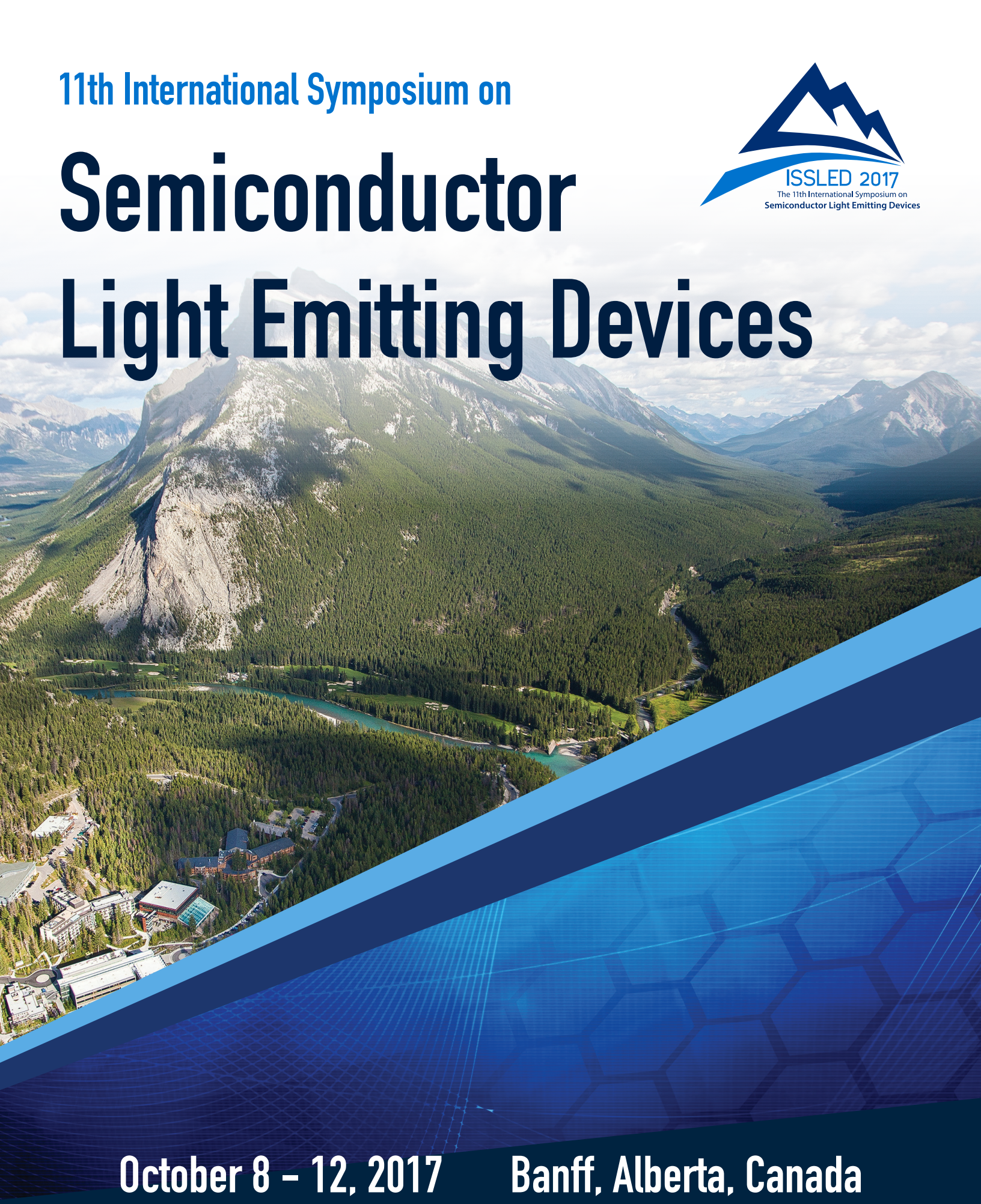
11th International Symposium on

Semiconductor Light Emitting Devices

ISSLED 2017
The 11th International Symposium on
Semiconductor Light Emitting Devices



October 8 – 12, 2017 Banff, Alberta, Canada

WELCOME TO ISSLED 2017!

It is our great pleasure to invite you to participate in the

11th International Symposium on Semiconductor Light Emitting Devices (ISSLED 2017)

CONFERENCE CO-CHAIRS

Zetian Mi
University of Michigan

George Wang
Sandia National Labs

Zlatko Sitar
North Carolina State University

CONFERENCE HIGHLIGHTS

11th ISSLED Conference: The ISSLED is a biannual international meeting for scientists and engineers worldwide, both in academia and in industry, to meet together to share and exchange the latest discoveries and progress on light emitting semiconductors, with a focus on III-nitride devices. It started in 1996/1998 in Chiba/Japan and went through Berlin/ Germany, Cordoba/ Spain, Gyeongju/ Korea, Montpellier/ France, Phoenix/ Arizona, Beijing/ China, Berlin/ Germany, and most recently Kaohsiung/ Taiwan in 2014.

ISSLED Plenary Speakers: Each morning of the conference will kick off with a plenary speaker. We are pleased to welcome Shuji Nakamura (UCSB), Hideki Hirayama (Riken), Michael Kneissl (TU Berlin) and Berthold Hahn (Osram) to Banff this year.

Welcome Reception: Join us for a welcome reception on Sunday evening at 18:00-20:00 in the KC 203. This is a great event to meet with long-time colleagues, create new connections and share information. Hors d'oeuvres will be provided along with two drink tickets per attendee.

Exhibit: Be sure to visit ISSLED exhibitors throughout the week in KC 103/105. Learn more about Adroit Materials and Hexatech.

Conference Banquet: Don't miss this year's conference reception on Wednesday evening in KC 101/103. Cocktails and hors d'oeuvres will be available at 18:45 with dinner beginning at 19:30. Full conference registration includes the conference banquet, and an extra ticket may be purchased during registration. A plated specialty five-course dinner and hosted bar will be provided for all guests in attendance.

Excursion: We are pleased to offer a Discover Lake Louise excursion at a negotiated rate for all interested ISSLED 2017 attendees. This event will run from 12:45 - 18:00 on Wednesday afternoon of the conference, and includes group transportation to/from Lake Louise, a guide, snacks on board, free time at Lake Louise and all gratuities. Guests can choose between a hike or high tea at Lake Louise.

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ISSLED 2017
The 11th International Symposium on
Semiconductor Light Emitting Devices

CONFERENCE SCHEDULE OVERVIEW

Registration Desk Open from 16:00 to 20:00 (KC200) & Welcome Reception from 18:00 (KC203) on Sunday, October 8

Time	Monday, October 9		Tuesday, October 10		Wednesday, October 11		Thursday, October 12	
7:00	Breakfast (Sally Borden Building)		Breakfast (Sally Borden Building)		Breakfast (Sally Borden Building)		Breakfast (Sally Borden Building)	
8:15								
8:30	Opening Remarks (KC201/203)		Plenary Session Tu1 M. Kneissl (KC201/203)		Plenary Session W1 S. Nakamura (KC201/203)		Plenary Session Th1 H. Hirayama (KC201/203)	
8:45	Plenary Session M1 B. Hahn (KC201/203)							
9:00								
9:15			Session Tu2 UV Lasers (KC201/203)	Session Tu3 Top-Down Nanostructures (KC205)	Session W2 LED Contacts (KC201/203)	Session W3 UV Nanowires (KC205)	Session Th2 Long Wavelength Emitters (KC201/203)	Session Th3 Novel Devices and Structures 1 (KC205)
9:30	Session M2 GaN Tunnel Junctions (KC201/203)	Session M3 Atom Probe Tomography (KC205)						
9:45								
10:00			Coffee Break (KC103/105)		Coffee Break (KC103/105)		Coffee Break (KC103/105)	
10:15	Coffee Break (KC103/105)							
10:30								
10:45	Session M4 Micro LEDs and VLC (KC201/203)	Session M5 IQE and Defects (KC205)	Session Tu4 AlN Growth and Templates (KC201/203)	Session Tu5 InGaN Nanostructures (KC205)	Session W4 Growth and Defects (KC201/203)	Session W5 UV Materials and Characterization (KC205)	Session Th4 InGaN Growth (KC201/203)	Session Th5 Novel Devices and Structures 2 (KC205)
11:00								
11:15								
11:30								
11:45								
12:00			Lunch (Sally Borden Building)		Lunch (Sally Borden Building)		Lunch (Sally Borden Building)	
12:15	Lunch (Sally Borden Building)							
12:30								
12:45					Excursion Shuttle (PDC Building)			
13:00					13:00 - 18:00 Lake Louise Excursion (optional)			
13:15								
13:30								
13:45	Session M6 Semipolar and Nonpolar GaN (KC201/203)	Session M7 LED Characterization (KC205)	Session Tu6 UV LEDs (KC201/203)	Session Tu7 Visible/InGaN-based Lasers (KC205)			Session Th6 Visible LEDs (KC201/203)	Session Th7 Nanowire Devices (KC205)
14:00								
14:15								
14:30								
14:45								
15:00								
15:15								
15:30			Late News Session Tu8 (KC201/203)				Coffee Break (KC103/105)	
15:45								
16:00	Poster Session (KC103/105)		Poster Session (KC103/105)				Session Th8 GaN Substrates and Growth (KC201/203)	Session Th9 Characterization of Nanostructures (KC205)
16:15								
16:30								
16:45								
17:00								
17:15								
17:30								
17:45								
17:15								
17:30							Closing Remarks (KC201/203)	
17:45							Closing Reception (KC103/105)	
					18:45 - 21:00 Banquet (KC101/103)			

TRAVEL RESOURCES

TRANSPORTATION

- The Banff Centre is a 90-minute drive from Calgary. Convenient shuttles are available for purchase via the Banff Airporter (www.banffairporter.com).

- For those attending the Lake Louise Excursion, bus transportation to/from Lake Louise is included in the overall purchase price.

PARKING

- Parking at the Banff Centre is included in your nightly rate and facility fee. The nearest parking areas are listed on the previous Campus Map page.

INTERNET ACCESS

- Banff Centre provides wireless Internet access as a part of your stay. Instructions on how to access the Internet will be provided at check-in.

DINING OPTIONS

- Breakfast and lunch will be provided each day in the Sally Borden building and covered by the registration fee. Dinner is the responsibility of the attendee, except Wednesday evening at the ISSLED banquet.

- Guests may eat in the Vista Dining Room at the Banff Centre or any number of restaurants in downtown Banff, a short drive away.

- Hors d'oeuvres and two drink tickets per attendee will be provided at each poster session on Monday and Tuesday. Hors d'oeuvres will also be provided at the closing reception on Thursday.

REGISTRATION

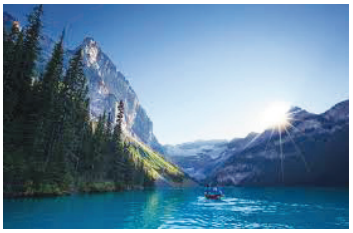
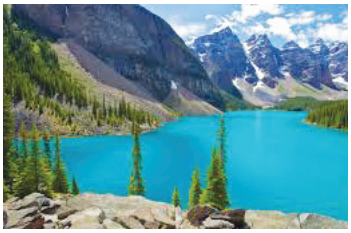
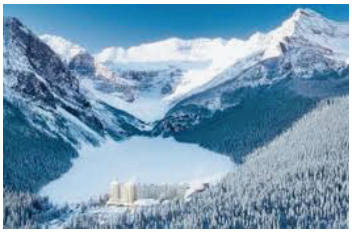
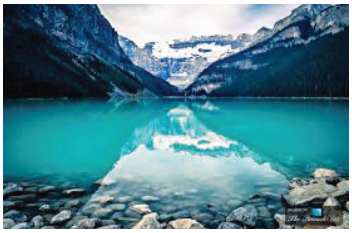
- All attendees must be registered to participate in all conference activities.

- Registration will open at 16:00 on Sunday in KC200 Galleria. Attendees should pick up their name badge before attending the welcome reception. The registration desk will be open during regular conference hours.

- Name badges should be worn for the duration of the conference, and will be required to gain access to breakfast and lunch in the Sally Borden building.

- For attendees that have not registered online, on-site registration will be available for credit cards only; rates subject to change.

ISSLED EXCURSION: LAKE LOUISE

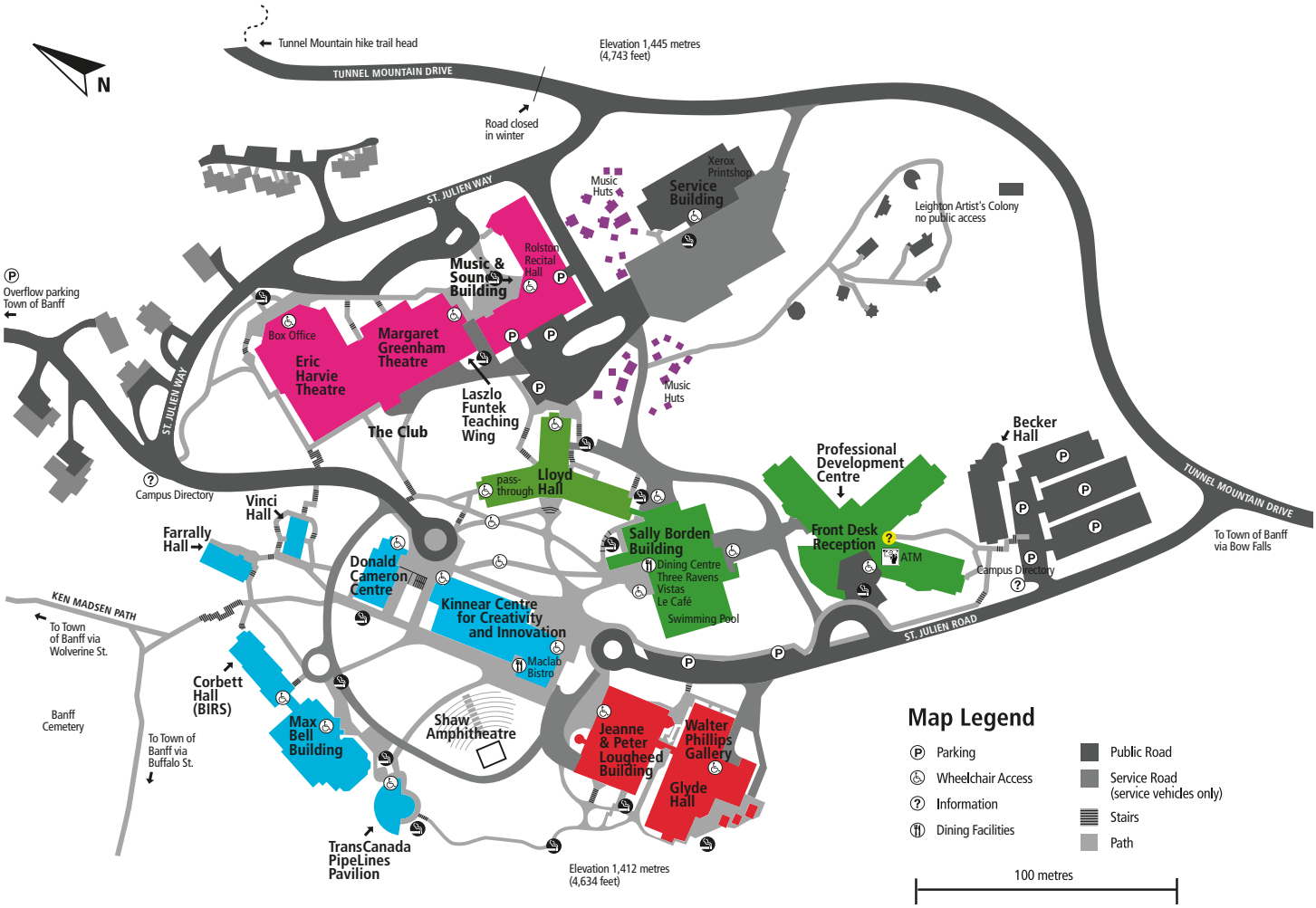
Lake Louise is a hamlet in Banff National Park in the Canadian Rockies, known for its turquoise, glacier-fed lake ringed by high peaks and overlooked by a stately chateau. Hiking trails wind up to the Lake Agnes Tea House for bird's-eye views. There's a canoe dock in summer, and a skating rink on the frozen lake in winter. The Lake Louise Ski Resort features a wildlife interpretive center at the top of a gondola.

Lake Louise Tour with Hike: For over a century, explorers have been making the trip to the incredible towering mountain peaks and icy blue glaciers, which are the highlights at Lake Louise. Your journey starts along the winding Bow Valley Parkway passing Hole-in-the-Wall, Johnston Canyon and magnificent Castle Mountain. At Lake Louise, enjoy a short, guided hike to discover this special place with outdoor pursuits. The rich history and beauty of Lake Louise will resonate for years to come. Hiking Trail, will be dependent on trail conditions and physical fitness levels. A moderate fitness level is required. Available to ISSLED guests for $95 CAD.

Lake Louise Tour with High Tea: For over a century, explorers have been making the trip to the incredible towering mountain peaks and icy blue glaciers, which are the highlights at Lake Louise. Your journey starts along the winding Bow Valley Parkway passing Hole-in-the-Wall, Johnston Canyon and magnificent Castle Mountain. At Lake Louise, enjoy high tea in a designated area of the historic hotel. If you prefer, the Château Lake Louise has various shops, lounges, restaurants and fabulous architecture that will impress you for hours. The rich history and beauty of Lake Louise will resonate for years to come. Available to ISSLED guests for $125 CAD.

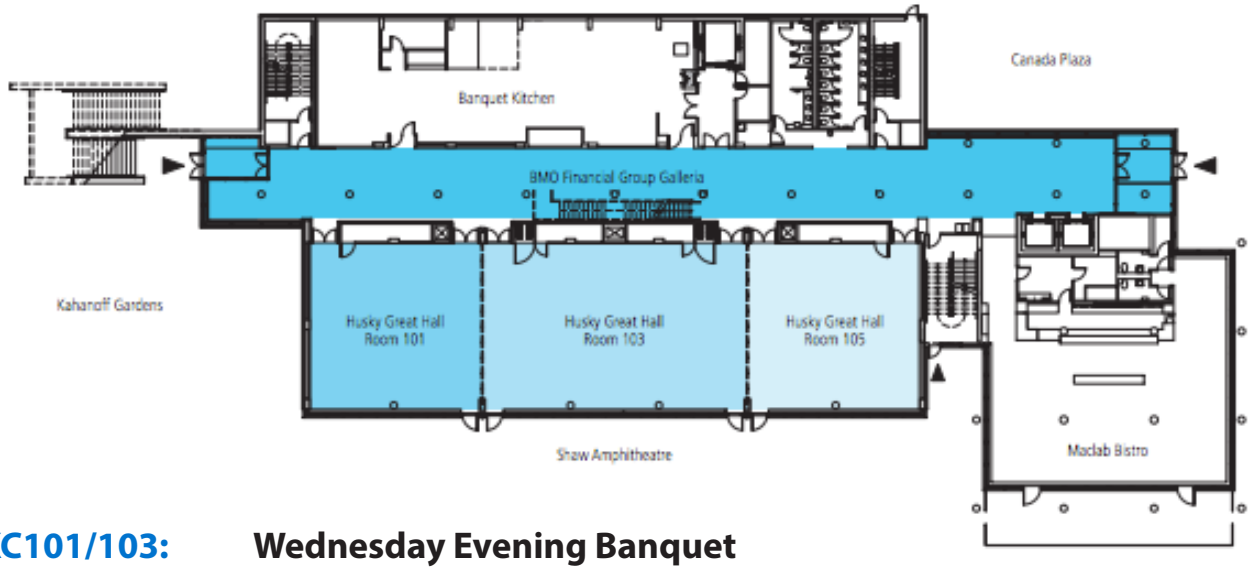
Lake Louise excursion is provided by Discover Banff Tours, and may be booked on the ISSLED website. Transportation is included in the price of the tour. Guests will be picked up in front of PDC at Banff Centre on Wednesday at 12:45.

CAMPUS MAP

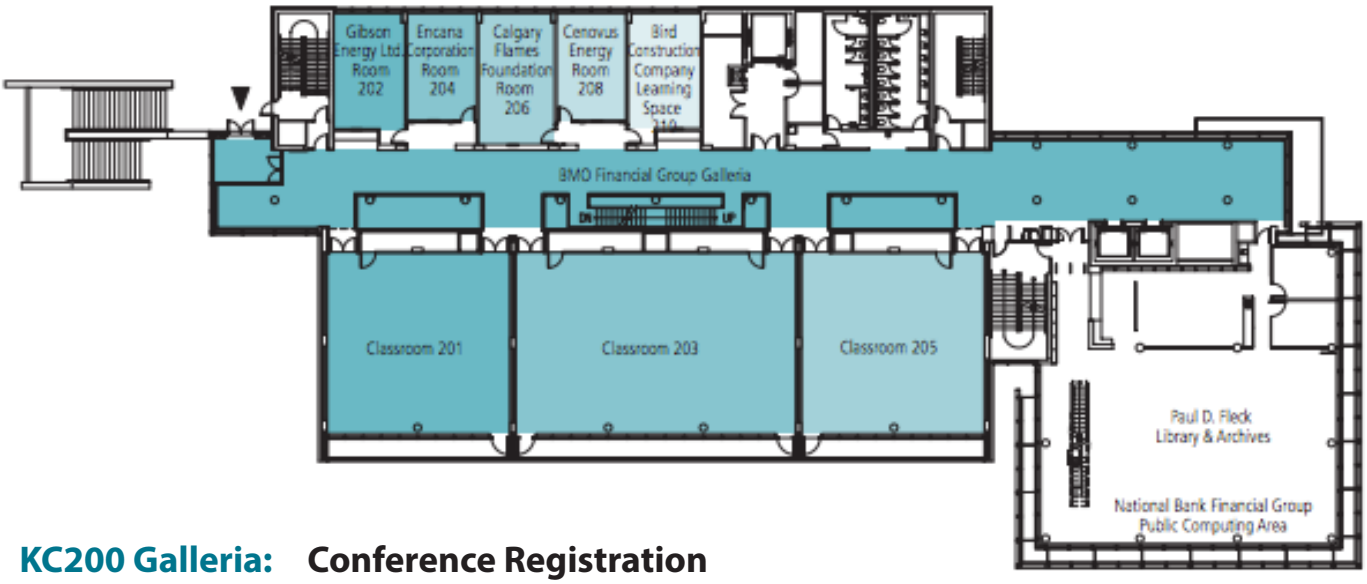


- **Professional Development Centre (PDC):** Hotel check-in for all guests
- **Lloyd Hall:** Additional Hotel Rooms
- **Kinnear Centre:** Main Conference Activities
- **Sally Borden Building:** Dining Facilities

FLOOR PLANS



KC101/103: **Wednesday Evening Banquet**
KC103/105: **Poster Sessions**
KC103/105: **Exhibit Booths**
KC103/105: **Coffee Breaks**



KC200 Galleria: **Conference Registration**
KC201/203: **Daily Plenary Sessions**
KC201/203: **Daily Even Sessions**
KC203: **Welcome Reception**
KC205: **Daily Odd Sessions**

AdroitMaterials

We provide state of the art crystal quality and client-specific material properties thanks to our unparalleled control of alloy composition and doping. We are focused on the development and deployment of III-nitride technology based on high quality native AlN and GaN substrates as well as sapphire.

Adroit Materials was spun out of North Carolina State University in 2012. Zlatko Sitar, President and CTO, has a proven track record of technology commercialization and of building teams that can bring sophisticated products to market.

The Adroit Materials portfolio encompasses epitaxial growth, doping, strain management, and contact control that can be leveraged by our clients for superior electronic and optoelectronic device performance. We are able to offer our customers access to the full AlGaN alloy composition range from AlN to GaN to within ±1% of the desired composition. With best in class dislocation densities films grown on native substrates, we are also able to provide conductive templates with free carrier concentrations suitable for a variety of applications.

HexaTech Inc. is a recognized world leader in the development and commercialization of the next-generation semiconductor material, aluminum nitride (AlN). This wide bandgap semiconductor offers unique properties which enable the fabrication of first-in-kind devices, including long life UV-C light emitting diodes (LEDs) for disinfection applications, deep UV lasers for biological threat detection, high voltage switching devices for efficient power conversion, and RF (radio frequency) components for satellite communications.

High-performance AlGaN semiconductor devices currently face a crucial challenge in terms of achievable device quality. Fabricating these devices on lattice-matched, highly thermally conducting, single crystalline AlN wafers enables sophisticated, next-generation AlGaN-based devices with vastly superior performance and device lifetimes.

HexaTech has developed a proprietary crystal growth process that yields single crystalline AlN boules of exceptionally high quality, ideally suited for the fabrication of AlN substrates.

By delivering substrates with 10,000 to 1,000,000 times fewer defects than competing technologies, HexaTech's AlN wafers enable breakthrough performance in the fabrication of high Al content AlGaN-based devices.

SPONSORS & SUPPORTING ORGANIZATIONS

ISSLED has been funded, in part, by the generous contributions of these organizations

HEXATECH

AdroitMaterials

OSRAM
Opto Semiconductors

Sandia National Laboratories

UNIVERSITY OF MICHIGAN

NC STATE UNIVERSITY

McGill

IEEE Photonics Society

Additional Support Provided By:

NSF

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PLENARY SPEAKERS

Monday, October 9

BERTHOLD HAHN

OSRAM OPTO SEMICONDUCTOR

Perspectives of Solid State Lighting

Berthold Hahn received his PhD in physics from Regensburg University at 1998.

He joined OSRAM in 1998 and was heading several epi and product development projects for InGaN high power LEDs in the blue/green spectral regin. Since 2006 he has been heading the InGaN LED chip and epi development at OSRAM.

In 2008, he took over responsibility also for the AlInGaP and AlGaAs material system and is today responsible for the global LED Chip and epi R&D within OSRAM OS.

Tuesday, October 10

MICHAEL KNEISSL

TU Berlin

Prospects and Challenges for AlGaN-Based Deep UV LED Technologies

Michael Kneissl is the executive director of the Institute of Solid State Physics and chair of “Experimental Nanophysics and Photonics” at TU Berlin, Germany. He holds a dual appointment at the Ferdinand-Braun-Institute (FBH) in Berlin, where he heads the “Joint Lab GaN Optoelectronics”. His interests include group III-nitride semiconductor materials, metal organic vapor phase epitaxy of wide bandgap semiconductors and nanostructures as well as novel optoelectronic devices, including UV LEDs and laser diodes. He has co-authored over 300 publications, five book chapters, and holds more than 55 patents. In 2016, Michael Kneissl was named Fellow of the Institute of Electrical and Electronics Engineers (IEEE) for his contributions to the development of wide bandgap semiconductor laser diodes and ultraviolet LEDs.

PLENARY SPEAKERS

Wednesday, October 11

SHUJI NAKAMURA

University of California, Santa Barbara

Invention of High Efficient Blue LED and Future Solid State Lighting

Shuji Nakamura obtained BE, MS, and PhD degrees in Electrical Engineering from the University of Tokushima, Japan in 1977, 1979, and 1994, respectively. He joined Nichia Chemical Industries Ltd in 1979.

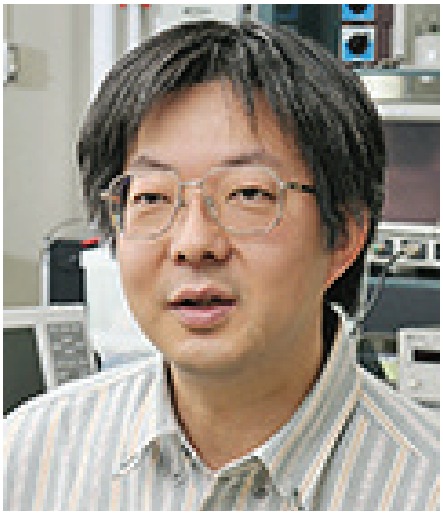
In 1993 and 1995 he developed the first group-III nitride-based high-brightness blue and green LEDs. He also developed the first group-III nitride-based violet laser diodes (LDs) in 1995.

Since 2000, he has been a professor of Materials and Electrical & Computer Engineering at the University of California, Santa Barbara. He is the 2014 Nobel Laureate in Physics for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources.

Thursday, October 12

HIDEKI HIRAYAMA

RIKEN



Progress of AlGaN UVC LED and Challenge to GaN THz-QCL

Hideki Hirayama received his PhD of engineering from Tokyo Institute of Technology (TIT) in 1994. Same year he became a research scientist at RIKEN. He became a team leader of Terahertz Quantum Device Team in 2005, and a chief scientist and director of Quantum Optodevice Laboratory in 2012. He was visiting professor of Saitama University from 2004. His research focuses on crystal growth of AlGaN based semiconductors and development of deep-ultraviolet (DUV) light-emitting diodes (DUV LEDs) and laser diodes (LDs), and terahertz quantum cascade lasers (THz-QCLs).

INVITED SPEAKERS

Yasuhiko Arakawa, Tokyo University, Japan
Progress in Single Photon Emitters Based on GaN Quantum Dots

Frank Bertram, Otto-von-Gueriche University, Germany
Highly Spatially Resolved Investigation Luminescence of III-Nitrides Nanostructures Using STEM-CL

Pallab Bhattacharya, University of Michigan, USA
III-Nitride Nanowire Monolithic Diode Lasers and Photonic Integrated Circuit on (001)Silicon

Gianluigi Botton, McMaster University, Canada
High-Resolution Transmission Electron Microscopy and Energy Loss Spectroscopy Applications to Semiconductor Nanostructures

Shigefusa Chichibu, Tohoku, Japan
Vacuum-Fluorescent-Display Devices Emitting Polarized Deep-Ultraviolet and Visible Lights Using m-Plane Al1-xInxN Epitaxial Nanostructures

Yong-Hoon Cho, KAIST, Korea
Highly Efficient Classical and Quantum Emitters Based on Nitride Semiconductor Nanostructures

Ramon Collazo, North Carolina State University, USA
Point Defect Control in III-Nitrides by Chemical Potential and Defect Quasi Fermi Level Control

Martin Dawson, Strathclyde University, UK
Gallium Nitride Micro-LEDs for Structured Illumination and Visible Light Communications

Phil Dawson, Manchester, UK
Optical Properties of InGaN Quantum Well Structures as a Function of Carrier Density

Gregory Garrett, U.S. Army Research Laboratory, *USA*
Interplay of Carrier Transport and Radiative Lifetime in Vertical III-Nitride Laser Structures

Nicolas Grandjean, EPFL, Switzerland
GaN Tunnel Junctions for Advanced Optoelectronic Devices

Jung Han, Yale, USA
Nonpolar and Semipolar GaN for Solid-State Lighting: Will This Ever Become Real?

Hongxing Jiang, Texas Tech, USA
Hexagonal Boron Nitride Epilayers for Deep UV Photonics

Jong Kyu Kim, POSTECH, Korea
Enhanced Light Extraction From AlGaN-Based Deep-Ultraviolet Light-Emitting Diodes

Emmanouil Kioupakis, University of Michigan, USA
Understanding and Mitigating Auger Recombination in Nitride LEDs

Ronny Kirste, Adroit Materials, USA
Development of Mid UV Laser Diodes

Katsumi Kishino, Sophia University, Japan
InGaN/(Al)GaN-Based Nanocolumn (NC) Arrays and Their Light-Emitter Applications

Yoshinao Kumagai, Tokyo University of Agriculture and Technology, Japan
Development of Bulk AlN Substrates for Deep-UV Optoelectronic Devices by HVPE Method

Maki Kushimoto, Nagoya University, Japan
Semipolar InGaN Optical Devices on Patterned Si Substrates

Kei May Lau, HK University of Sci & Tech, Hong Kong
Monolithic LED Micro-Display: LEDoS Technologies and Applications

Sheng Liu, Sandia National Laboratories, USA
Novel Light Emission Engineering Using III-V Dielectric Metasurfaces

Eva Monroy, CEA Grenoble, France
Intersubband Transitons in GaN Nanowires: Towards the Nanowire QWIP

Piotr Perlin, Unipress, Poland
Nitride Light Emitters - From Superluminescent Diodes to Semiconductor Optical Amplifiers

Lorenzo Rigutti, Université de Rouen, France
Assessing Advantages and Limitations of Atom Probe Tomography for the Nanoscale Interpretation of the Optical Properties of III-Nitride Heterostructures

Jong-In Shim, Hanyang University, Korea
A Measurement Method of Internal Quantum Efficiency in Light-Emitting Diodes at an Actual Operating Temperature

Qian Sun, Suzhou Institute of Nano-Tech and Nano-Bionics - CAS, China
III-Nitride LEDs and Laser Diodes Grown on Si

Tao Wang, University of Sheffield, UK
Non-Polar and Semi-Polar GaN for Photonics and Electronics

Xin-Qiang Wang, Beijing University, China
InGaN Monlayer: MBE Growth and Microstructure Analysis

Jonathan Wierer, Lehigh University, USA
Routes to Ultra-Efficient III-Nitride Emitters for Solid-State Lighting

Yuh-Renn Wu, National Taiwan University, Taiwan
Study of Carrier Transport and Recombination in Disordered InGaN Quantum Well Light Emitting Diode With Localization Landscape Theory

Atsushi Yamaguchi, Kanazawa Institute of Technology, *Japan Carrier Dynamics Studies of III-Nitride Materials Using Simultaneous Photo-Acoustic and Photoluminescence Measurements*

Rong Zhang, Nanjing University, China
Fabrication of GaN Nano-LED Devices by Nanoimprint Lithography

PROGRAM AT-A-GLANCE

SUNDAY

16:00 Registration Desk Opens in KC 200 Galleria

18:00 Welcome Reception – KC 203

MONDAY

7:00 Breakfast – Sally Borden Building

M1:OPENING REMARKS AND PLENARY SESSION (Chair: Zetian Mi) KC 201/203

8:30 Opening Remarks

8:45	Berthold Hahn	PL1	(Plenary) Perspectives of Solid State Lighting

M2: GaN TUNNEL JUNCTIONS (Chair: Erin Young) KC 201/203

9:30	Nicolas Grandjean	M2.1	(Invited) GaN Tunnel Junctions for Advanced Optoelectronic Devices
10:00	Abdullah Alhassan	M2.2	(Student) Low Efficiency Droop Green c-Plane III-Nitride LEDs Utilizing a GaN Tunnel Junction

M3: ATOM PROBE TOMOGRAPHY (Chair: Yuh-Renn Wu) KC 205

9:30	Lorenzo Rigutti	M3.1	(Invited) Assessing Advantages and Limitations of Atom Probe Tomography for the Nanoscale Interpretation of the Optical Properties of III-Nitride Heterostructures
10:00	Bastien Bonef	M3.2	Nanometer Scale Investigation of MOCVD Grown Green LED by Atom Probe Tomography and Scanning Transmission Electron Microscopy

10:15 Coffee Break – KC 103/105

M4: MICRO LEDs AND VC (Chair: George Wang) KC 201/203

10:45	Kei May Lau	M4.1	(Invited) Monolithic LED Micro-Display: LEDoS Technologies and Applications
11:15	Martin Dawson	M4.2	(Invited) Gallium Nitride Micro-LEDs for Structured Illumination and Visible Light Communications
11:45	Daniel Feezell	M4.3	Small-Signal Modulation Characteristics of Nonpolar and Semipolar InGaN/GaN Light-Emitting Diodes
12:00	Seungmin Lee	M4.4	Microchip-Sized GaN Growth on a Stripe Patterned Thin Al2O3 Membrane

M5: IQE AND DEFECTS (Chair: Phillip Dawson) KC 205

10:45	Erin Young	M5.1	Calcium Impurity as Non-Radiative Recombination Center in (In,Ga)N Alloys
11:00	Norihiko Kamata	M5.2	Nonradiative Recombination Centers in UV-LEDs Revealed by Below-Gap Excitation Light at Low Current Injection
11:15	Jong-In Shim	M5.3	(Invited) A Measurement Method of Internal Quantum Efficiency in Light-Emitting Diodes at an Actual Operating Temperature
11:45	Atsushi Yamaguchi	M5.4	(Invited) Carrier Dynamics Studies of III-Nitride Materials Using Simultaneous Photo-Acoustic and Photoluminescence Measurements

12:15 Lunch – Sally Borden Building

M6: SEMIPOLAR AND NONPOLAR GaN (Chair: Martin Dawson) KC 201/203

13:45	Jung Han	M6.1	(Invited) Nonpolar and Semipolar GaN for Solid-State Lighting: Will This Ever Become Real?
14:15	Yuji Zhao	M6.2	Valence Band States and Polarized Optical Emission From Nonpolar and Semipolar III-Nitride Quantum Well Optoelectronic Devices
14:30	Young-Woon Kim	M6.3	Luminescence Characteristics Originated From Structural Defects in Semipolar (11-22) InGaN/GaN Quantum Well
14:45	Tao Wang	M6.4	(Invited) Non-Polar and Semi-Polar GaN for Photonics and Electronics
15:15	Catherine Brasser	M6.5	(Student) Semipolar InGaN Quantum Well Structures for Long Wavelength Emission
15:30	Ousmane I Barry	M6.6	(Student) MOVPE Growth With N2 as Carrier Gas: A Method for Impurity Reduction in m-Plane (10-10) GaN Films
15:45	Can Bayram	M6.7	InGaN-based Flexible Light Emitting Diodes

M7: LED CHARACTERIZATION (Co-Chairs: Kei May Lau and Jong-In Shim) KC 205

13:45	Gerd Bacher	M7.1	Low Injection Losses in InGaN/GaN LEDs Probed by Quasi-Resonant Photoluminescence and Photocurrent Measurements
14:00	Gwénolé Jacopin	M7.2	Enhancement of Auger Recombination Induced by Carrier Localization in InGaN/GaN Quantum Wells
14:15	Philip Dawson	M7.3	(Invited) Optical Properties of InGaN Quantum Well Structures as a Function of Carrier Density
14:45	Michael Scarpulla	M7.4	Excess Carriers Effects on III-Nitrides for LEDs
15:00	Nicola Trivellin	M7.5	Temperature and Chip Size Dependance of Carrier Recombination Dynamics and Droop Behavior on High Power COTS-LEDs
15:15	Yuh-Renn Wu	M7.6	(Invited) Study of Carrier Transport and Recombination in Disordered InGaN Quantum Well Light Emitting Diode With Localization Landscape Theory
15:45	Xin Rong	M7.7	Mid-Infrared Photodetectors Based on Intersubband Transition in GaN Quantum Structure

16:00 Poster Session – KC 103/105

TUESDAY

7:00 Breakfast – Sally Borden Building

Tu1: PLENARY SESSION (Chair: Zlatko Sitar) KC 201/203

8:30	Michael Kneissl	PL2	(Plenary) Prospects and Challenges for AlGaN-based Deep UV LED Technologies

Tu2: UV LASERS (Chair: Zlatko Sitar) KC 201/203

9:15	Ronny Kirste	Tu2.1	(Invited) Development of Mid UV Laser Diodes
9:45	Motoaki Iwaya	Tu2.2	Acceleration Voltage Dependence of Threshold Power Density in AlGaN/GaN Based Electron Beam Pumped Laser

Tu3: TOP-DOWN NANOSTRUCTURES (Chair: Yong-Hoon Cho)			KC 205
9:15	Rong Zhang	Tu3.1	(Invited) Fabrication of GaN Nano-LED Devices by Nanoimprint Lithography
9:45	George Wang	Tu3.2	Top-Down Etching of Three-Dimensional, High Aspect Ratio GaN Nanostructures
10:00	***Coffee Break – KC 103/105***		

Tu4: AlN GROWTH AND TEMPLATES (Chair: Jong Kyu Kim)			KC 201/203
10:30	Kevin Lee	Tu4.1	(Student) MBE-Grown High Temperature AlN Epitaxy on Single Crystal AlN Substrate for Deep UV Photonics
10:45	Ryo Yoshizawa	Tu4.2	(Student) Fabrication of Highly Oriented c-Plane AlN Buffer Layer by Metalorganic Vapor Phase Epitaxy on Nucleation Layer Deposited by Sputtering
11:00	Yoshinao Kumagai	Tu4.3	(Invited) Development of Bulk AlN Substrates for Deep-UV Optoelectronic Devices by HVPE Method
11:30	Fujun Xu	Tu4.4	High-quality AlN Grown on Nano-Patterned Sapphire Substrates Prepared by Nano-Imprint Lithography
11:45	Dong-Sing Wuu	Tu4.5	Improved Internal Quantum Efficiencies of Deep-Ultraviolet LEDs Using a Low-Defect-Density Template Technique

Tu5: InGaN NANOSTRUCTURES (Chair: Tao Wang)			KC 205
10:30	Yong-Hoon Cho	Tu5.1	(Invited) Highly Efficient Classical and Quantum Emitters Based on Nitride Semiconductor Nanostructures
11:00	Yong-Ho Ra	Tu5.2	Bottom-up InGaN Nanowire Photonic Crystal Structures
11:15	Mohsen Nami	Tu5.3	Electro-Optical Characterization of Selectively-Grown GaN/InGaN Core-Shell Nanowire LEDs
11:30	Katsumi Kishino	Tu5.4	(Invited) InGaN/(Al)GaN-Based Nanocolumn (NC) Arrays and Their Light-Emitter Applications
12:00	***Lunch – Sally Borden Building***		

Tu6: UV LEDS (Chair: Ronny Kirste)			KC 201/203
13:30	Seiji Mita	Tu6.1	The Role of Surface Kinetics on AlN and Al-rich AlGaN
13:45	Dimiter Alexandrov	Tu6.2	Low Temperature Epitaxial Growth of AlGaN/GaN Hetero-Junctions on Sapphire Substrates
14:00	Jong Kyu Kim	Tu6.3	(Invited) Enhanced Light Extraction From AlGaN-Based Deep-Ultraviolet Light-Emitting Diodes
14:30	Shyam Bharadwaj	Tu6.4	(Student) 245 nm Electroluminescence From an MBE Grown GaN/AlN Deep-UV LED on a Bulk AlN Substrate
14:45	Yuewei Zhang	Tu6.5	(Student) Reflective Metal/Semiconductor Tunnel Junctions for AlGaN UV LEDs
15:00	Okhyun Nam	Tu6.6	Deep Ultraviolet Light Emitting Diodes Using Polarization Doped p-AlxGa1-xN/AlyGa1-yN Superlattice Structures
15:15	Koichi Okamoto	Tu6.7	Surface-Plasmon-Enhanced Light Emissions Extended to Deep-UV Spectral Regions

Tu7: VISIBLE/InGaN-BASED LASERS (Chair: Daniel Feezell)			KC 205
13:30	Qian Sun	Tu7.1	(Invited) III-Nitride LEDs and Laser Diodes Grown on Si
14:00	Daniel Becerra	Tu7.2	High Efficiency Semipolar InGaN Lasers for Solid State Lighting
14:15	Tadek Suski	Tu7.3	(Late News) Unexpected Behavior of Light Emission in Nitride Based Devices Under Hydrostatic Pressure

14:30	Maki Kushimoto	Tu7.4	(Invited) Semipolar InGaN Optical Devices on Patterned Si Substrates
15:00	Gregory Garrett	Tu7.5	(Invited) Interplay of Carrier Transport and Radiative Lifetime in Vertical III-Nitride Laser Structures

Tu8: LATE NEWS (Co-Chairs: Ronny Kirste and Daniel Feezell) — KC 201/203

15:30	Shun Washiyama	Tu8.1	(Late News, Student) Al-rich AlGaN/AlN Based Double Barrier Resonant Tunneling Diode
15:45	Keita Konishi	Tu8.2	(Late News) Influence of Ambient Oxygen on Si Incorporation During Hydride Vapor Phase Epitaxy of AlN at High Temperature

16:00 Poster Session – KC 103/105

WEDNESDAY

7:00 Breakfast – Sally Borden Building

W1: PLENARY SESSION (Chair: George Wang) — KC 201/203

8:30	Shuji Nakamura	PL3	(Plenary) Invention of High Efficient Blue LED and Future Solid State Lighting

W2: LED CONTACTS (Chair: Ramon Collazo) — KC 201/203

9:15	Dong-Sing Wuu	W2.1	Effects of Electron Retarding Electrodes on Semiconductor Light-Emitting Devices
9:30	Jung-Hong Min	W2.2	(Student) Very Thin ITO/Metal Mesh Hybrid Films for a High-Performance Transparent Electrode in GaN-Based LEDs
9:45	Jaehee Cho	W2.3	Mesa-Free Flat-Surface III-Nitride Light-Emitting Diodes

W3: UV NANOWIRES (Chair: Hongxing Jiang) — KC 205

9:15	Songrui Zhao	W3.1	AlGaN Nanowire Tunnel Junction Light Emitting Diodes and Lasers in the UV-C Band
9:30	Andreas Liudi Mulyo	W3.2	(Student) AlGaN/GaN Nanocolumn UV-A Light Emitting Diodes Grown on Graphene/Silica Glass
9:45	Pierre-Marie Coulon	W3.3	Hybrid Top-Down/Bottom-Up Fabrication of Regular Arrays of AlN/AlGaN Core-Shell Nanorods for UV Emission

10:00 Coffee Break – KC 103/105

W4: GROWTH AND DEFECTS (Chair: Lorenzo Rigutti) — KC 201/203

10:30	Douglas Irving	W4.1	Identification of Compensating Defects in AlN and AlGaN
10:45	Nathaniel Quitoriano	W4.2	High-Quality, Laterally Grown Ge Films on Si Utilizing a New Relaxation Mechanism
11:00	Ramon Collazo	W4.3	(Invited) Point Defect Control in III-Nitrides by Chemical Potential and Defect Quasi Fermi Level Control
11:30	Heon Lee	W4.4	Nano Patterned Sapphire Substrates for Improved GaN Growth and LED Performance

W5: UV MATERIALS AND CHARACTERIZATION (Chair: Gregory Garrett) — KC 205

10:30	Hongxing Jiang	W5.1	(Invited) Hexagonal Boron Nitride Epilayers for Deep UV Photonics
11:00	James LeBeau	W5.2	Picometer Precise Measurement of AlGaN Surfaces and Quantum Wells With Scanning Transmission Electron Microscopy
11:15	Jochen Bruckbauer	W5.3	Optical and Structural Properties of Semipolar (11-22) AlGaN Epilayers With High AlN Content

11:45 Lunch – Sally Borden Building

12:45 Lake Louise Excursion Buses will pick up registered attendees outside of PDC at 12:45 with a departure time of 13:00. Guests will return to PDC at 18:00.

18:45 Banquet – KC 101/103 Cocktails and hors d'oeuvres will be available starting at 18:45 with dinner beginning at 19:30.

THURSDAY

7:00 Breakfast – Sally Borden Building

Th1: PLENARY SESSION (Chair: Zetian Mi)			**KC 201/203**
8:30	Hideki Hirayama	PL4	(Plenary) Progress of AlGaN UVC LED and Challenge to GaN THz-QCL
Th2: LONG WAVELENGTH EMITTERS (Chair: Jonathan Wierer)			**KC 201/203**
9:15	Ray Hua Horng	Th2.1	AlGaInP-Based Flip Chip Micro LED Fabrication and Performance Study
9:30	Jianli Zhang	Th2.2	Efficient InGaN Based LEDs Within the "Green Gap" Grown on Silicon Substrate
9:45	Adam Bauer	Th2.3	High Efficacy Direct Green InGaN LEDs
Th3: NOVEL DEVICES AND STRUCTURES 1 (Chair: Eva Monroy)			**KC 205**
9:15	Shigefusa Chichibu	Th3.1	(Invited) Vacuum-Fluorescent-Display Devices Emitting Polarized Deep-Ultraviolet and Visible Lights Using m-Plane Al1-xInxN Epitaxial Nanostructures
9:45	Per Olof Holtz	Th3.2	(Late News) Small Size InGaN Pyramidal Quantum Dots to Reduce the Effects of Internal Fields

10:00 Coffee Break – KC 103/105

Th4: InGaN GROWTH (Chair: Matt Brubaker)			**KC 201/203**
10:30	Hisashi Murakami	Th4.1	Thick InGaN Layer With the Indium Solid Composition Over 10% Using Tri-Halide Vapor Phase Epitaxy
10:45	Armelle Even	Th4.2	(Student) Synchrotron X-ray Study of InGaN Layer Grown on Relaxed InGaN Substrate
11:00	Xinqiang Wang	Th4.3	(Invited) InGaN Monlayer: MBE Growth and Microstructure Analysis
11:30	Daichi Imai	Th4.4	Optical Characterization of Ordered InGaN Ternary Alloys Based on (InN)1/(GaN)n Short-Period Superlattices Grown by Dynamic Atomic Layer Epitaxy (D-ALEp)
11:45	Gintautas Tamulaitis	Th4.5	Origin of Green Emission in InGaN-Based MQWs
Th5: NOVEL DEVICES AND STRUCTURES (Chair: Shigefusa Chichibu)			**KC 205**
10:30	Piotr Perlin	Th5.1	(Invited) Nitride Light Emitters - From Superluminescent Diodes to Semiconductor Optical Amplifierss
11:00	Sheng Liu	Th5.2	(Invited) Novel Light Emission Engineering Using III-V Dielectric Metasurfaces
11:30	Yasuhiko Arakawa	Th5.3	(Invited) Progress in Single Photon Emittes Based on GaN Quantum Dots

12:00 Lunch – Sally Borden Building

Th6: VISIBLE LEDs (Chair: Xinqiang Wang)			**KC 201/203**
13:30	David Hwang	Th6.1	(Student) High Efficiency, Ultrasmall InGaN micro-LEDs for Displays and Solid State Lighting
13:45	Heonsu Jeon	Th6.2	Enhanced Fluorescence from Structurally Engineered Colloidal Quantum Dots and Its Application to Phosphor-Capped White LEDs

14:00	Jonathan Wierer	Th6.3	(Invited) Routes to Ultra-Efficient III-Nitride Emitters for Solid-State Lighting
14:30	Yong Seok Choi	Th6.4	High Power LEDs for Outdoor Luminaire Applications
14:45	Clayton Cozzan	Th6.5	(Student) High-Power and Directional Laser-Based White Lighting Using Computational Design and Thermally Stable Phosphor Morphologies
15:00	Emmanouil Kioupakis	Th6.6	(Invited) Understanding and Mitigating Auger Recombination in Nitride LEDs

Th7: NANOWIRE DEVICES (Chair: Frank Bertram) KC 205

13:30	Eva Monroy	Th7.1	(Invited) Intersubband Transitons in GaN Nanowires: Towards the Nanowire QWIP
14:00	Matt Brubaker	Th7.2	Core-Shell GaN Nanowire LEDs for Optically Active Scanned Probe Tips
14:15	Moab Rajan Philip	Th7.3	(Student) Phosphor-Free III-Nitride Nanowire Light-Emitting Diodes on Flexible Substrates
14:30	Pallab Bhattacharya	Th7.4	(Invited) III-Nitride Nanowire Monolithic Diode Lasers and Photonic Integrated Circuit on (001)Silicon
15:00	Bin Liu	Th7.5	Conversion Efficiency Enhancement in Polarization-Induced InGaN/GaN Nano-Photoelectrodes for Hydrogen Generation
15:15	Lung Hsing-Hsu	Th7.6	InN Nanopillar Photodetector With Enhanced Infrared Response Using Indium-Tin Oxide Nanorods

15:30 Coffee Break – KC 103/105

Th8: GaN SUBSTRATES AND GROWTH (Chair: Piotr Perlin) KC 201/203

16:00	Je Won Kim	Th8.1	(Late News) Nanorod Array Shaping and Formation Through Nano-Mold Process
16:15	Yulong Fang	Th8.2	Stress Modulation of GaN Epilayer on Sapphire With Graphene Interlayer
16:30	Tohru Honda	Th8.3	GaN Growth on Al Template by MBE for the Fabrication of Micro Displays
16:45	Zongliang Liu	Th8.4	Growth of GaN Single Crystal by LPE-Na Flux Method Adding Nitrogen-Doped Additives
17:00	Jianfeng Wang	Th8.5	Low-Dislocation Density and 6 Inch GaN Substrates Grown by Hydride Vapor Phase Epitaxy

Th9: CHARACTERIZATION OF NANOSTRUCTURES (Chair: Pallab Bhattacharya) KC 205

16:00	Frank Bertram	Th9.1	(Invited) Highly Spatially Resolved Investigation Luminescence of III-Nitrides Nanostructures Using STEM-CL
16:30	Gianluigi Botton	Th9.2	(Invited) High-Resolution Transmission Electron Microscopy and Energy Loss Spectroscopy Applications to Semiconductor Nanostructures
17:00	Takao Oto	Th9.3	Optical Properties in InGaN/AlGaN Quantum Wells on GaN Nanocolumns Fabricated by Selective Area Growth
17:15	Wolf Quitsch	Th9.4	Sub-µm Correlation of Optoelectronic and Photoelectric Performance of GaN/InGaN Nanorod LEDs

17:30 Closing Remarks – KC 201/203

17:45 Closing Reception – KC 103/105

FRIDAY

7:00 Breakfast – Sally Borden Building

POSTER SESSION

MONDAY PM 16:00–18:00 — KC 103/105

POSTER #	PRESENTER	TITLE
MP1	**Fayzah Alhamed**	(Student) Effect of Gd2O3 Additives on the Microstructure and Electrical Properties of ZnO Varistor
MP2	**Alexander Usikov**	A Fractal Organization in III-N LED Structures
MP3	**Ray Hua Horng**	Performance Improvement of Light-Emitting Thyristor Using GaInP Active Layers and a GaP Window Layers
MP4	**Norah Alwadai**	(Student) Fabrication of a High Brightness UV-Blue Light-Emitting Diode Based on High Quality Gd Doped ZnO-Nanotube Array Grown on p-GaN
MP5	**Jeonghwan Jang**	(Student) Selective Area Growth of GaN Layer on Partially Crystallized Cavity Engineered Sapphire Substrate
MP6	**Sheng-Yuan Chu**	Investigation of the Photoelectric Characteristics of the MoO3/Ag/MoO3 Tri-Layer Photodetector
MP7	**Sheng-Yuan Chu**	Luminescence Properties of Ca6BaP4O17:Sm3+ Phosphor and Its Thermal Stability
MP8	**Kubonaka Yuuto**	(Student) Growth of Nitrogen – Polar InN on Sapphire Substrate by DERI Method
MP9	**Bei Ma**	C Exciton and A Exciton Dynamic of m-Plane GaN Film
MP10	**Su-Jung Yoon**	(Student) Electrical Characteristics of Ti/ITO Schottky Contacts on p-Type GaN
MP11	**Semi Oh**	Self-Assembled Indium Tin Oxide Nanoball-Embedded Omnidirectional Reflectors for High Photon Extraction Efficiency in III-Nitride Ultraviolet Emitters
MP12	**Janghwan Han**	(Student) Enhanced Optical Output Power of InGaN/GaN Multiple Quantum Wells Light-Emitting Diodes by Vertical Magnetic Fields of Co/Pt Multilayers
MP13	**Jong-In Shim**	Systematic Study on the Trade-Off Relationship Between the Forward Voltage and the Internal Quantum Efficiency of Light-Emitting Diodes
MP14	**Jeonghwan Jang**	(Student) Study on Solid-Phase Epitaxy of Stripe-Shaped Al2O3 Membrane
MP15	**Donghyun Lee**	(Student) Fabrication of Nano-Cavity Patterned Sapphire Substrates and their Application to the Growth of GaN
MP16	**Minkyung Baek**	(Student) Oblique-Angle Deposited ITO/Silver Nanowire Transparent Conductive Electrodes for GaN-Based Light-Emitting Diodes
MP17	**Tae-Hoon Chung**	High Efficient InGaN/GaN Blue Light-Emitting Diodes by Using the p-Type InGaN Layer for V-Pit Passivation
MP18	**Yongjin Kim**	(Student) Study of Polarity-Controlled ZnO Films and Nanorods on the Light Extraction Efficiency of Semipolar (11-22) GaN-Based Light-Emitting Diodes
MP19	**Jinho Ahn**	Enhanced Optical Properties by Two-Dimensional Photonic Quasicrystal Layers on a Y2O3:Eu3+ Thin-Film Phosphors
MP20	**Jochen Bruckbauer**	Optical and Structural Properties of Semipolar GaN on Patterned Si Substrates
MP21	**Seiji Mita**	Reduction of Carbon in MOCVD-Grown GaN for Power Devices by Supersaturation Control
MP22	**Felix Kaess**	Suppression of Mg Migration and Surface Accumulation by Fermi Level Control in GaN Grown by MOCVD
MP23	**Yulong Fang**	Influence of Initial Pretreatment on GaN Growth on Graphene

MP24	**Margaret Hopkins**	Indium-Free Transparent Ohmic Contacts to N-polar n-type GaN
MP25	**Jongmyeong Kim**	(Student) Linearly Polarized Photoluminescence of c-Plane GaN Grown on Stripe-Shaped Cavity-Embedded Al2O3 Membrane on c-Plane Sapphire Substrate
MP26	**Christophe Rodriguez**	(Student) Bio-Inspired Light Emitting Diodes With Optimized Structuration for High Light Extraction Efficiency
MP27	**Dae-Hyun Kim**	(Student) Improved Light Output of AlGaInP-Based Light Emitting Diode Fabricated With Thermally Stable NiZn-Based Ohmic Contacts
MP28	**Andrew Klump**	(Student) Resistivity of Mg-Doped GaN Grown by MOCVD: Compensation Control

TUESDAY PM 16:00–18:00 – KC 103/105

POSTER #	PRESENTER	TITLE
TP1	**Kun Wang**	(Student) Performance Improvement of Near-UV LED by Carbon Nanotube Assisted Nanoheteroepitaxy
TP2	**Xianghua Kong**	First-Principles Investigation of Artificial Photosynthesis on Ga(In)N Surface
TP3	**Kang Bok Ko**	(Student) Lateral Epitaxial Overgrowth of High Quality AlN on Patterned h-BN Using Metal Organic Chemical Vapor Deposition
TP4	**Min Han**	(Student) A Study on Quality Variation Characteristics of AlN Layer According to Types of h-BN Buffer Using MOCVD
TP5	**George Wang**	Quantum Size Controlled Etching of InGaN Quantum Dots
TP6	**Masataka Imura**	Microstructure of In0.20Ga0.80N Nanowires on Si (111) Substrate Evaluated by Aberration-Corrected Scanning Transmission Electron Microscopy
TP7	**Si-Young Bae**	Selective Area Growth of III-Nitride Core–Shell Nanorod Array on Quartz Substrates by Combined Epitaxy of MBE and MOCVD
TP8	**Jochen Bruckbauer**	Hybrid White Inorganic/Organic LEDs using Organic Colour Converters
TP9	**Tomohiro Inaba**	(Student) Enhanced Light Output From Eu-Doped GaN Red LED by a Microcavity.
TP10	**Wanxin Zhu**	(Student) Color Tunablility of Eu-Doped GaN LEDs Achieved Through a Re-Excitation Driven Up-Conversion Process
TP11	**Shun Washiyama**	(Student) Point Defect Reduction Via Supersaturation Based Chemical Potential Control in High Al-Content AlGaN Grown by Metalorganic Chemical Vapor Deposition
TP12	**Donghyun Lee**	(Student) Enhanced Light Output Power of AlGaN-Based Deep Ultraviolet Light-Emitting Diodes With Nano-Patterned AlN/Sapphire Substrates
TP13	**Karan Mehta**	(Student) High Reflectivity Ultraviolet AlGaN-Metal Hybrid Distributed Bragg Reflectors
TP14	**David Arto Laleyan**	(Student) AlN/h-BN Nanowire Heterostructures for Deep Ultraviolet Photonics
TP15	**Xianhe Liu**	(Student) Deep Ultraviolet AlGaN Nanowire Light Emitting Diodes by Selective Area Epitaxial Growth
TP16	**Hua Zong**	(Student) Flexibly and Repeatedly Modulating Lasing Wavelengths in Single Core-Shell Semiconductor Microrod
TP17	**Mohsen Asad**	(Student) Light Extraction Efficiency Enhancement of InGaN Nanowire Light-Emitting Diodes on Flexible Substrates

POSTER SESSION

POSTER #	PRESENTER	TITLE
TP18	**Yusuke Namae**	(Student) Characterization of InGaN/GaN Ultra-Fine Nanopillars Fabricated by Hydrogen-Assisted Thermal Decomposition Etching
TP19	**Sharif Sadaf**	(Student) Molecular Beam Epitaxial Growth and Characterization of n-GaN/Al/p-AlGaN Tunnel Junction Nanowire Heterostructure
TP20	**Biplab Sarkar**	Performance Improvement of Contacts to Optoelectronic Devices Grown on Single Crystal AlN Substrate
TP21	**Yuta Yamaki**	(Student) Annealing and Sputtering of AlN Films on Sapphire for Deep-Ultraviolet LED
TP22	**Taro Mitsui**	(Student) Characterization of Threading Dislocations in HVPE-Grown AlN Substrates by Wet Chemical Etching
TP23	**Dae-Woo Jeon**	Control of Bowing in Free-Standing GaN Substrate by Using Selective Etching
TP24	**Akira Mishima**	Characterization of AlN Layer on 4 Inch Sapphire Substrate by High Temperature Annealing in Nitrogen Atmosphere
TP25	**Mingxing Wang**	Improvement of AlN Crystalline Quality by Combination of High Temperature Annealing and MOCVD Growth
TP26	**Jinho Ahn**	(Late News) Enhanced Optical Properties by Two-Dimensional Photonic Quasicrystal Layers on a Y2O3:Eu3+ Thin-Film Phosphors

11th International Symposium on

Semiconductor Light Emitting Devices

October 8 – 12, 2017 Banff, Alberta, Canada

ISSLED 2017
The 11th International Symposium on
Semiconductor Light Emitting Devices

MONDAY ORAL PRESENTATIONS

11th ISSLED Conference

*Invited talk, **Student talk

8:45 *PL1

Perspectives of solid state lighting Berthold Hahn; OSRAM Opto Semiconductors GmbH, Leibnizstr. 4, 93055 Regensburg, Germany

Optoelectronic devices based on group III nitrides (i.e., LEDs) provided a completely new technology in the lighting sector, the solid state lighting. For about one decade, the brightness and efficiency has been the figures of merit for such devices. However, the recent improvements of its design and in doping strategies yielded efficiencies close to the fundamental limit reaching internal quantum efficiencies of more than 90 % and corresponding wall-plug efficiencies well above 70%. Meanwhile it is recognized that LED offer a big variety of opportunities beyond efficient lighting. Fortunately, there are many applications that could only be addressed by the unique characteristics of semiconductor LED light sources. Thus, it is much more than cost cutting triggering further research on group III nitride optoelectronics. An introduction to OSRAM Opto Semiconductors' numerous activities in research and development of next generation LEDs / Lasers and future trends for lighting applications will be given. Examples of technology and products for various application fields will illustrate the claimed technology leadership that is based on the close interplay of material development, thorough understanding of scientific background and of technological solutions yielding.

9:30 *M2.1

GaN tunnel junctions for advanced optoelectronic devices Nicolas Grandjean; Institute of Physics, École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

GaN tunnel junctions (TJs) have recently attracted a lot of interest as they can be used in a wide range of optoelectronic devices. A straightforward and promising application of TJs is to achieve transparent contacts on light emitting diodes (LEDs) or lasers. To this aim, a thin n+-GaN layer is deposited on top of the p+-GaN cap-layer, similarly to the deposition process of a transparent conductive oxide. Such a transparent conductive nitride (TCN) contact offers a lot of advantages compared to commonly used ITO thanks to reduced absorption at short-wavelengths. Another application of TJs is concerned with current confinement in micro-LEDs and vertical cavity surface emitting lasers. TJs could also enable LEDs in series allowing this way to reduce the efficiency droop. In this presentation, we first study GaN TJs entirely grown by MBE and investigate their electrical properties. The specific resistance is in the low 10-4 Ω.cm2 and strongly depends on the current density. Such TJs are further used in LEDs grown by metal organic chemical vapor deposition (MOCVD). The influence of the surface preparation and p-type doping level will be discussed. Then buried TJs are implemented in micro-LEDs with excellent current confinement properties. Finally, we demonstrate current injection through a buried TJ in an edge emitting laser. Lasing at 400 nm with output powers of 100 mW is demonstrated in continuous-wave operation at a threshold current density of 2.4 kA.cm-2.

9:30 *M3.1

Assessing advantages and limitations of atom probe tomography for the nanoscale interpretation of the optical properties of III-nitride heterostructures Lorenzo Rigutti, L. Mancini, F. Moyon, D. Hernandez-Maldonado, I. Blum, J. Houard, W. Lefebvre, F. Vurpillot, D. Blavette, E. Giraud, J. F. Carlin, R. Butté, N. Grandjean, C. Durand, J. Eymery; Groupe de Physique des Matériaux, Normandie University, France; SuperSTEM STFC Daresbury Laboratories, United Kingdom; Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland; Université Grenoble Alpes, France; Nanophysique et Semiconducteurs, France

Atom probe tomography (APT) has recently emerged as a nano-analysis technique allowing for the reconstruction of the three-dimensional distribution of chemical species with sub-nanometer resolution. The recorded compositional maps allow assessing features such as alloy distributions or heterostructure compositions, shapes and interfaces. It becomes thus possible to interpret the electronic and the optical properties of semiconductor heterostructures [1]. Nevertheless, the technique also has several limitations due to the physical processes of field evaporation on which it is based, e.g.: (i) the degradation of the spatial resolution induced by the presence of materials with different evaporation behaviors within the same specimen (e.g., AlN and GaN) and (ii) the degradation of both spatial resolution and compositional accuracy related to the relatively low and sometimes species-specific detection efficiency [2]. These effects occur in the measurements under typical conditions of analysis. In this contribution we will show how APT may provide invaluable information for the interpretation of the optical properties of selected systems, i.e., AlGaN epitaxial layers GaN/AlGaN and InGaN/GaN quantum wells. These results will be critically discussed in order to assess what is the impact of the above-mentioned non-ideal features affecting APT measurements, and what strategies can be adopted in order to reduce it. [1] L. Rigutti et al. NanoLett. (2014) [2] L. Rigutti et al. JAP (2016)

10:00 **M2.2

Low efficiency droop Green c-plane III-Nitride LEDs utilizing a GaN tunnel junction Abdullah Alhassan; Erin C. Young, Robert M. Farrell, Steven P. DenBaars, and Shuji Nakamura, and James S. Speck; Materials Department,

University of California Santa Barbara, CA 93106 USA; Department of Electrical and Computer Engineering, University of California Santa Barbara,USA

The remarkable progress in white LEDs for solid state lighting has been driven by phosphor converted LEDs. Color mixed LEDs produce white light from red, green, blue, and amber (RGBA) LEDs and have a fundamental efficiency limit of ~400 lm/W. The lack of efficient LEDs in the green and amber spectral range, known as the "green gap", is mainly due to the combined effects of high indium compositions, piezoelectric-polarization fields, and possibly higher Auger recombination. One strategy for improving the efficiency of long wavelength devices is to add and optimize an AlGaN capping layer in the active region. Additionally, the growth of GaN tunnel junction on green LEDs can improve the device

10:00 M3.2

Nanometer scale investigation of MOCVD grown green LED by atom probe tomography and scanning transmission electron microscopy; Bastien Bonef, Papan Li, Hongjian Li, James S Speck; Department of Materials Science and Engineering; University of California Santa Barbara, USA; Department of Physics, Low Dimensional Materials Research Centre (LDMRC); University of Malaya

The luminance efficiency of InGaN LEDs drops rapidly as emission wavelength goes into the green region (λ=510~570 nm). Understanding the carrier localization effect and carrier recombination dynamics due to alloy disorder in InGaN based green LEDs is off great importance to solve the "green gap" issue. Atom probe tomography (APT) has the ability to analyze semiconductors with the application of laser pulses which trigger the evaporation of atoms. It is now possible to directly obtain alloy compositions and fluctuations with a nanometer resolution. In this study, APT is used to evidence In clustering in a [0001] green LED grown with metal-organic chemical vapor deposition. The sample structure is composed of a n-GaN layer, a strain releasing InGaN/GaN super-lattice, 15 InGaN/GaN quantum wells/barriers, an electron blocking layer and the p-GaN top layer. The APT specimen is imaged in scanning transmission electron microscopy (STEM) to allow for the optimization of the reconstruction of the APT volume. From the APT 3D volume, the experimental distribution of In in the quantum wells is compared to the distribution expected in the case of random alloys. Failures in $\chi 2$ test performed in each quantum wells revealed the presence of In rich clusters. Photoluminescence (PL) and electroluminescence (EL) measurements revealed the presence of several radiative recombination centers in good agreement with the presence of clustering effects in the wells.

10:45 *M4.1

Monolithic LED Micro-display: LEDoS Technologies and Applications Kei May Lau; Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Hong Kong

The use of LED in micro-displays is attracting more attention recently, for direct view or projection applications. LEDs have advantages in terms of efficiency, brightness, lifetime, temperature stability and robustness, compared with other existing micro-display technologies. Fabrication of high resolution truly monolithic micro-display with decent visual quality is challenging. Non-optimized bumping technology and bowing of micro-LED array causing difficulty in flip-chip bonding are the major issues. We have developed two different approaches to illustrate high resolution micro-displays with much better bonding yield. A 1700 pixel per inch (PPI) passive-matrix and a 400 × 240 active-matrix micro-LED arrays bonded on ASIC have been demonstrated. Realization of full color LED micro-display is also a big challenge because it is not practical to selectively grow three different epi-layers emitting at different wavelengths on a single substrate for three primary colors. Dedicated for projection display application, we demonstrated a novel 3LED light engine that can project full color video on screen. 3LED consists of a trichroic prism that combines RGB images generated from three LED micro-displays based on AlGaInP (Red) and GaN (Green and Blue) materials. For near-to-eye display application, RGB quantum dots were printed on micro-LED array by aerosol jet printing, achieving full color LED micro-display with high image quality.

10:45 M5.1

Calcium impurity as non-radiative recombination center in (In,Ga)N alloys Erin Young, Nicolas Grandjean, Tomas Uzdavinys, Saulius Marcinkevicius, Thomas E Mates, James S. Speck; University of California Santa Barbara; Ecole Polytechnique Federale de Lausanne; KTH Royal Institute of Technology Sweden

We have recently have discovered that (In,Ga)N alloys grown by molecular beam epitaxy (MBE) both at UCSB and in other laboratories systematically contains high levels (up to ~1e18 /cm3) of an impurity element, calcium, as demonstrated by secondary ion mass spectroscopy. Experimental evidence suggests that this defect may act as a Shockley Read Hall recombination center in MBE alloys. We have investigated the incorporation of Ca as a function of MBE growth conditions and demonstrated a method to grow multi quantum well (QW) active regions with reduced Ca concentration via low temperature buffer layers. Preliminary light emitting diodes grown with Ca reduction in the QWs show higher output power than those with high Ca concentration in in the QWs. In addition, photolumines-

cence studies (PL) show stronger room temperature PL intensity and longer PL decay times for samples with Ca reduction. We will give an overview of these studies and the potential implications for light emitting devices grown by MBE.

11:00 M5.2

Nonradiative Recombination Centers in UV-LEDs Revealed by Below-Gap Excitation Light at Low Current Injection Norihiko Kamata, Ken Matsuda, Takeshi Fukuda, and Zentaro Honda; Dept. of Functional Materials Science, Saitama University

Though the external efficiency of blue LEDs exceeds 80%, efficient emission of UV light is still difficult as the increased density of crystalline defects acting as nonradiative recombination (NRR) centers deteriorates electroluminescence (EL) intensity as well as operating lifetime. We detected NRR centers by utilizing a below-gap excitation (BGE) light under extremely low current condition.
Ten UV-LED chips of 365nm peak wavelength, 1,300mW output at operating current of 1,000mA are used. A BGE light (hvB=1.17eV) was switched on and off for each 500s interval to the chip driven by 0.15mA. The EL intensities with and without the BGE, IE+B and IE, respectively, are recorded to define the normalized EL intensity as IN = IE+B / IE. All chips showed initially the IN values larger than unity, implying a NRR center activated by the BGE energy of 1.17eV. Operation at 1,000mA for 75h turned the IN values lower than unity for all chips, indicating the formation of additional NRR centers. The IN value is related to the density of NRR centers. We observed also a μA-order current increase during the BGE irradiation. We interpret it as the BGE of carriers from the NRR centers since the increased amount was proportional to the density of the NRR centers. The BGE energy dependence gives us the energy distribution of NRR centers. The technique is proven to be effective for characterizing defects in actual LED structures.

11:15 *M4.2

Gallium nitride micro-LEDs for structured illumination and visible light communications Martin D. Dawson, J. Herrnsdorf, J.J.D. McKendry, E. Xie, M.J. Strain, I.M. Watson, and E. Gu; Department of Physics, Institute of Photonics,, University of Strathclyde, UK

High density arrays of micro-pixel gallium nitride inorganic light-emitting diodes (GaN micro-LEDs) can be successfully bonded to CMOS electronic driver arrays to provide pattern-programmability and high-speed modulation. We overview the capabilities and potential of this technology for a range of digital and structured lighting applications. Specifically, we will focus on applications in visible light communications (VLC) and object location and tracking. For VLC, the small pixel format of micro-LEDs is favourable for increasing the modulation bandwidth by between 10X and 100X over conventional chip GaN LEDs (to 100's MHz) and has led to a series of world record demonstrations of optical wireless and polymer optical fiber data communications links with multi-Gb/s capability. A variety of spatial and spectral multiplexing schemes for VLC are enabled by the array format of the micro-LEDs. For object location and tracking we utilise the so-called structured illumination capability of these arrays, where rapid switching of the micro-LEDs permits complex spatio-temporal structuring of illumination fields, which can be used to locate and track objects in the field of view, to direct illumination at those objects once located (to send separate communications channels to different locations for example, or to control autonomous systems), and to enable ultra-low light level imaging in conjunction with single photon (SPAD) photodetectors.

11:15 *M5.3

A Measurement Method of Internal Quantum Efficiency in Light-Emitting Diodes at an Actual Operating Temperature Jong-In Shim, Dong-Pyo Han, Dong-Soo Shin, and Hyundon Jung; Hanyang University; Etamax Co.

The separate and accurate measurement of the internal quantum efficiency (IQE) of a light-emitting diode (LED) has been intensely pursued for the last six-decades. For widely usable IQE measurement, it is desirable to use easily measurable physical quantities such as current and light output power without assuming any physical parameters. In this sense, the temperature-dependent electroluminescence (TDEL) has been considered as a standard method, where the maximum external quantum efficiency (EQE) point is found by changing temperature and current, and the IQE at that point is considered as 100% with assuming that both the radiative efficiency (RE) and the injection efficiency (IE) are 100%.

In this paper, we present a method of measuring the IQE of LEDs as a function of current at an actual operating temperature. The proposed method is theoretically based on the semiconductor carrier rate equation. The measurement procedure starts to find an exact value of the IQE at the reference point where the IE is considered as 100% and the RE is calculated from the relative EQE curve. Once the IQE at the reference point is exactly known, the IQE at any other point is calculated by the relative ratio of EQE values to the reference one. We show the theoretical formalism of the proposed method and demonstrate its validity using a commercial InGaN blue LED as an example. The comparison with the IQE obtained by the conventional TDEL is also given.

11:45 M4.3

Small-Signal Modulation Characteristics of Nonpolar and Semipolar InGaN/GaN Light-Emitting Diodes Daniel Fezzell, Morteza Monavarian, Arman Rashidi, An-

drew Aragon, Mohsen Nami; Center for High Technology Materials, Department of Electrical and Computer Engineering, University of New Mexico, USA

The increasing demand for wireless data communication and popularity of solid-state lighting has prompted research into visible-light communication (VLC) systems based on InGaN/GaN light-emitting diodes (LEDs). To support multi-Gb/s data rates, VLC systems will require efficient LEDs with large modulation bandwidths. Conventional c-plane LEDs suffer from polarization-related electric fields, which reduce the overlap between the electron and hole wave functions and lower the carrier recombination rate. Since modulation bandwidth is proportional to the carrier recombination rate, the overlap between the wave functions should be maximized. Nonpolar and semipolar orientations have significantly reduced polarization effects and offer a potential path to realize high-efficiency LEDs with large modulation bandwidths. In this work, we grow and fabricate nonpolar (10-10) and semipolar (20-2-1) InGaN/GaN micro-LEDs on free-standing GaN substrates and investigate their small-signal modulation characteristics as a function of current density, device area, quantum well number, and quantum well thickness. We demonstrate 3-dB modulation bandwidths in excess of 500 MHz for both nonpolar and semipolar orientations. We also present a small-signal method for determining the RC characteristics and differential carrier lifetimes of the LEDs under electrical injection by fitting the frequency response and impedance data to the transfer function and input impedance of a small-signal circuit model.

11:45 *M5.4

Carrier dynamics studies of III-nitride materials using simultaneous photo-acoustic and photoluminescence measurements Atsushi A. Yamaguchi, N. Shimizu, S. Sakai, T. Nakano, H. Fukada, Y. Kanitani, and S. Tomiya; Kanazawa Institute of Technology; Sony Corporation

Internal quantum efficiency (IQE) in III-nitride materials is usually estimated from temperature dependence of photoluminescence (PL) intensity by assuming that IQE at cryogenic temperature is unity. III-nitride samples, however, usually have large density of non-radiative defects, and the assumption is not necessarily valid. Photo-acoustic (PA) measurement is a good method to directly detect the heat generation by non-radiative recombination, and can be a complementary approach to reveal the recombination processes. Recently, we developed a new method to estimate accurate IQE values by simultaneous PA/PL measurements. The IQE values can be estimated by analyzing the correlation between PA and PL signals in nonlinear behavior of their excitation-power dependence, by considering that these signals are proportional to the amounts of heat and light generation in the non-radiative and radiative recombination, respectively. In this study, we have applied the method to InGaN quantum-well active layers and have measured the IQE values and their excitation carrier-density dependence in the layers. Also, we have performed temperature-dependent time-resolved measurements for the same samples, which enable us to accurately estimate the radiative and non-radiative lifetimes of photo-excited carriers by the combination with the PA/PL simultaneous measurements. Finally, we will discuss the carrier dynamics in the InGaN quantum-well layers and their temperature dependence.

12:00 M4.4

Microchip-sized GaN growth on a stripe patterned thin Al2O3 membrane Seungmin Lee, Daeyoung Moon, Daehan Choi, Hyejin Lim, Yongjo Park, Euijoon Yoon; Dept. of Materials Science and Engineering, Seoul National University, Korea; Energy Semiconductor Research Center, Advanced Institutes of Convergence Technology (AICT), Seoul National University, Korea

Micro-LEDs have attracted much attention due to high pixel density, high light intensity flexible displays. In this study, we demonstrate a new, simple and cost-effective scheme combining the growth of a microchip-sized GaN film array and subsequent direct transfer of the array to a Si substrate by a mechanical lift-off. Discrete GaN layers of various LED chip sizes (14 μm x 14 μm, 50 μm x 50 μm and 100 μm x 100 μm) were successfully grown on a stripe-patterned thin sapphire membrane by metalorganic vapor phase deposition. First, photoresist (PR) pattern of a stripe with the width and the spacing of 2 μm was formed on a sapphire substrate. Then, an amorphous Al2O3 layer with a thickness of 120 nm was deposited by atomic layer deposition (ALD). Then, the substrate was annealed at 1100 °C for 2 hours to oxidize PR, leaving stripe-shaped cavities, and to crystallize the ALD alumina into sapphire membranes for the GaN growth. The stripe length and the number of arrays determine the sizes of GaN microchip. The wafer with a chip-sized GaN array was flipped over on a Si substrate and the GaN layers were successfully transferred by a mechanical lift-off process. Also, we found that the threading dislocation density of discrete GaN layers was 1.2x108 cm-2, which was 40% lower than that of GaN grown on the planar sapphire substrate. In the presentation, more details of the results including the growth behavior of GaN on sapphire membrane and potential applications will be discussed.

13:45 *M6.1

Nonpolar and Semipolar GaN for solid-state lighting: will this ever become real? Jung Han; Department of Electrical Engineering, Yale University, New Haven, USA

Non-polar and semipolar orientations of gallium nitride (GaN) have the possibility to address long-standing problems in III-Nitride light emitting diodes (LEDs). They have

drawn substantial attentions 2000. In the past several years, high output power green and blue LEDs and laser diodes (LDs) have been demonstrated on (202$\bar{1}$), (20(21$\bar{}$), and several other oriented GaN. However, all of the high-performance semipolar GaN devices have only been grown on bulk GaN substrates. These bulk GaN substrates are produced by cross-slicing GaN crystals into tiny strips and are not yet compatible with mass production. In this talk we will review the effort in heteroepitaxy of nonpolar and semipolar GaN on large-area substrates. This field has gone through several generations of development including planar epitaxy, ELO growth, and growth on patterned sapphire substrates. Focus will be given to the understanding and control of stacking faults in semipolar GaN, which has been a most challenging issue due to the formation of nitrogen-polar (0001$\bar{}$) facet in heteroepitaxy. There has been recent progress in reducing the density of stacking faults. The availability of high-quality semipolar GaN-on-sapphire templates will enable high-performance, next generation GaN LEDs with economic feasibility. This work is partially supported by Saphlux Inc (http://www.saphlux.com/). JH is a cofounder of Saphlux and acknowledges that he has a significant financial interest with Saphlux.

13:45 M7.1

Low injection losses in InGaN/GaN LEDs probed by quasi-resonant photoluminescence and photocurrent measurements Gerd Bacher, Daniel Sager, Wolf Quitsch,-Tobias Meyer, Berthold Hahn; Werkstoffe der Elektrotechnik and CENIDE, Universität Duisburg-Essen, Germany; OSRAM Opto Semiconductors GmbH, Germany

In spite of established and widely spread applications, high power InGaN/GaN based light emitting diodes (LEDs) still suffer from an efficiency droop at high injection currents. To avoid this loss process, current approaches intend to increase the emissive area for getting high photon fluxes at reduced current densities. Hereby, however, low injection losses come into play, which detailed operation mechanism is still under discussion. We used a combined approach of photoluminescence and photocurrent measurements under quasi-resonant excitation in open- and closed circuit configuration to address this issue. Clear signatures of carrier leakage out of the active area are observed in the low injection regime: A decrease in luminescence intensity and reduced charge carrier lifetimes are correlated with an enhanced photocurrent. We demonstrate that these losses are related to the voltage drop across the p-n junction, controlled either by an external voltage or by a light-induced photovoltage. Comparing photoluminescence measurements under quasi-resonant excitation with electroluminescence measurements, we conclude that this mechanism strongly impacts the low injection losses in InGaN/GaN LEDs.

14:00 M7.2

Enhancement of Auger recombination induced by carrier localization in InGaN/GaN quantum wells Gwénolé Jacopin, M. Shahmohammadi, W. Liu, G. Rossbach, L. Lahourcade, A. Dussaigne, C. Bougerol, R. Butté, N. Grandjean, B. Deveaud; Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland; University of Grenoble Alpes, France; University of Grenoble Alpes, France

State-of-the-art GaN based light emitting diodes have their peak quantum efficiency at low current density. Under high injection, these devices suffer from a strong decrease of efficacy called the efficiency droop. In this work, the origin of efficiency droop in state-of-the-art quality InGaN/GaN and GaN/AlGaN quantum wells (QWs) grown on various crystal planes is studied by means of time-resolved photoluminescence spectroscopy associated with a precise determination of the QW carrier density [1]. In a first set of experiments, we show that a polar InGaN/GaN QW under high optical excitation exhibits clear signatures of Auger loss mechanism and thus behaves quite differently compared to its binary based GaN/AlGaN QW counterpart, where no Auger signature is observed. In order to get rid of the impact of the built-in polarization field and illustrate the dominant role of carrier localization, similar experiments have been conducted on two m-plane InGaN/GaN QWs with similar In composition but a different degree of disorder. We demonstrate that carrier localization strongly enhances the Auger recombination process in nonpolar InGaN/GaN QWs. The relaxation of the k-selection rule during the Auger recombination process, resulting from QW potential disorder, can account for the enhancement of the efficiency droop in InGaN/GaN QWs.

[1] Shahmohammadi et al., Phys. Rev. B 95, 125314 (2017)

14:15 M6.2

Valence band states and polarized optical emission from nonpolar and semipolar III-nitride quantum well optoelectronic devices Yuji Zhao; School of Electrical, Computer, and Energy Engineering, Arizona State University

Nonpolar and semipolar III-nitride quantum wells (QWs) and devices have been extensively studied due to their unique valence band (VB) structure and polarized optical emission. Unlike conventional c-plane oriented III-nitride QWs, the low crystal symmetry and unbalanced biaxial stress in nonpolar and semipolar QWs separates the topmost VBs and gives rise to polarized optical emission. Since the first experimental reports on nonpolar devices, research on this topic has progressed very rapidly and has covered nonpolar m-plane and a-plane QWs and devices as well as semipolar (11-22), (20-21), and (20-2-1) QWs and devices. Issues such as strain, plane inclination angle (with respect to the c-plane), indium composition, tempera-

ture, and their impact on QW VB structure and device performance have been extensively studied. In this talk, I will review the physical background and theoretical analysis of the VB states and polarized optical emission of nonpolar and semipolar structures and discuss their potential impacts on optoelectronic devices. Experimental results for nonpolar and semipolar light-emitting diodes and laser diodes will be covered along with additional discussions on the potential applications and challenges related to their unique physical properties.

14:15 *M7.3

Optical Properties of InGaN Quantum Well Structures as a Function of Carrier Density Philip Dawson, G Christian, S Schulz, R A Oliver M Kappers, C J Humphreys; University of Manchester; Tyndall National Institute Ireland; University of Cambridge

Low temperature photoluminescence (PL) studies of InGaN quantum well structures (QWs) are useful tools for revealing the underlying physics of recombination that can impact on LED performance. At low temperatures and for low excited carrier densities (- 1011 cm-2) in c-plane InGaN QWs the PL internal quantum efficiency (IQE) can approach 100%, the absence non radiative pathways is attributed to the effects of carrier localisation. The effects of carrier localisation are responsible for the PL line widths, recombination times and so-called Stokes shifts. Although there is still debate about the nature of the localisation centres the localisation of holes at random In fluctuations dominate the optical properties. In this paper we will report on the optical properties at much greater excited carrier densities, in the range 1011 cm2 to 1014cm-2 when efficiency droop occurs. As the density increases the intensity of the recombination pathway observed at low excitation carrier densities saturates and we observe the emergence of a high energy emission band. The recombination dynamics of this band are particularly revealing in that, in general, the PL decay curves exhibit long lived plateau regions followed by a rapid single exponential decays. This behaviour is very similar to the effects of state blocking reported [1] in InAs quantum dot structures which correlates with the saturation of the localised state recombination.

P Buckle et al, J. App. Phys. 86, 2555, 1999.

14:30 M6.3

Luminescence characteristics originated from structural defects in semipolar (11-22) InGaN/GaN quantum well Young-Woon Kim, Mi-Hyang Sheen, Yong-Hee Lee, Sung-Dae Kim, Jongjin Jang, Okhyun Nam; Seoul National University; Korea Polytechnic University

Conventional polar InGaN/GaN quantum wells (QWs) for light-emitting diodes (LEDs) has strong internal electrical field, leading to separations of carriers and thus low internal quantum efficiency (IQE). For last decade, growth of semi- and non-polar GaN has been studied to reduce this quantum-confined stark effect (QCSE). Unfortunately, although the QCSE was decreased in semi- and non-polar InGaN/GaN QWs, reduced crystal symmetry of GaN along the growth axis cause high density of structural defects, deteriorating the efficiency of LEDs. The extended defects such as basal plane stacking faults (BSFs) accompanying partial dislocations (PDs) are an optically active defects, which can drastically disturb and modify optical properties of LEDs. Therefore, it is important for developing high performance LED to investigate the luminescence properties of the defects according to their type and to evaluate the effects of the growth process on the defect reduction. In this presentation, we will report microstructural and optical analysis results on (11-22) semi-polar InGaN/GaN QWs by using home-built cathodoluminescence (CL) stage for transmission electron microscopy. The CL maps clearly identify the type of the BSFs and visualize their distribution depending on a substrate pattern. In addition, we will discuss the correlation between surface morphology of the epitaxial layer and facet dependent emissions of the QWs.

14:45 *M6.4

Non-polar and Semi-polar GaN for photonics and electronics Tao Wang; Department of Electronic and Electrical Engineering, University of Sheffield, United Kingdom

The last twenty years have seen major progresses on developing III-nitride based photonics and electronics, which are unfortunately mainly limited to c-plane III-nitrides. In terms of III-nitride based optoelectronics current c-plane GaN technology has approached its limits, while both theoretical and experimental studies suggest that (11-22) GaN is becoming increasingly important due to its advantages of reducing the polarizations and exhibiting higher indium incorporation efficiency than either c-plane surface. In this presentation, I will demonstrate high performance semi-polar (11-22) LEDs with an emission wavelength of up to amber overgrown on such GaN templates. III-nitrides have also attracted wide attention due to an increasing demand on high frequency and high temperature electronics. So far, AlGaN/GaN high-electron-mobility transistors (HEMTs) have been developed mainly based on c-plane GaN, where it is difficult to achieve normally-off operation. The growth of an AlGaN/GaN heterostructure along non-polar orientations is a simple and promising solution to overcome the problem. In this talk, I will demonstrate nonpolar (11-20) GaN with significantly improved crystal quality and an atomically smooth surface achieved by employing the above similar cost-effective patterning approach for overgrowth on sapphire. It has been found that there exist significant differences between them in terms of the overgrowth mechanisms and the mechanisms for defect reduction.

14:45 M7.4

Excess carriers effects on III-nitrides for LEDs Michael Scarpulla, Kirstin Alberi; University of Utah; National Renewable Energy Laboratory

It is well-known that the formation energy of charged point defects in semiconductors is dependent on the Fermi level. Especially for wide bandgap ionic semiconductors in which the Fermi level has large range, this can lead to compensation of dopants by native defects, extrinsic impurities, or defects involving the dopant itself. The presence of non-equilibrium carrier concentrations during growth or operation alters the quasi Fermi levels of band carriers and thus modifies populations of charged defects in ways very different from thermal equilibrium predictions. Herein we describe a rigorous theory of the dependence of defect formation energy on the quasi Fermi levels and apply it to nitrides used in light emitting diodes. To illustrate the theory we first investigate how a single donor-like level is affected by excess carriers in the presence of excess carriers. The most important findings are that such donor states will be suppressed for p-type doping but is unchanged or actually enhanced in the case of n-type doping. The implications of excess carriers on the concentrations of relevant defect states during processing and also during high-injection LED operation are then investigated in III-nitrides.

15:00 M7.5

Temperature and chip size dependence of Carrier recombination dynamics and droop behavior on high power COTS-LEDs Nicola Trivellin, Matteo Buffolo, Matteo Meneghini, Gaudenzio Meneghesso, Enrico Zanoni; Department of Information Engineering, University of Padova, Italy

With this work we report on the study of recombination dynamics, carrier lifetime and droop behaviour of commercial LEDs from the same manufacturer as a function of chip size, junction temperature and Indium composition, resulting in a variation of the emission wavelength. The analysis has been carried from absolute spectral and optical carrier lifetime measurements in order to extrapolate External Quantum Efficiencies, Internal quantum efficiencies, non radiative lifetime (tau_nr) and A,B and C parameters. By analysing tau_nr on different LED chip size (0.5, 1, 2 and 4 mm2) we report that tau_nr has a greater dependence on temperature for smaller devices, thus suggesting that recombination mechanisms strongly depend on device size also when they operate at the same current density. Results are consistent also analysing LEDs from the same manufacturer based on different processing technology (flip-chip and buried contacts). Droop as a function of junction temperature (Tj) under high injection is analysed for different chip size at the same current density. Results indicate that, while in general bigger devices have a higher maximum IQE values, they suffer of a sensible increase of droop as Tj increases. Droop dynamics evaluated on smaller chip devices, instead, are more thermally stable and in some cases droop incidence decreases as temperature increases. In conclusion, several possible solution on droop management are discussed as a function of LED operating conditions.

15:15 **M6.5

Semipolar InGaN Quantum Well structures for long wavelength emission Catherine Brasser, J. Bruckbauer, Z. Li, L. Jiu, J. Bai, P. R. Edwards, T. Wang and R. W. Martin; Department of Physics, SUPA, University of Strathclyde, United Kingdom; Department of Electronic and Electrical Engineering, University of Sheffield, United Kingdom

Semipolar growth of III-nitrides provides a route to increasing device efficiency by reducing the inbuilt electric fields present in polar directions. This orientation provides a way to bridge the ‘green gap,’ as the strain from the increased InN content is alleviated by the reduced spontaneous polarisation. However, semipolar growth introduces a new range of defects, including basal-plane stacking faults and chevron-shaped features. The latter form due to irregularities in coalescence and propagate to the surface of the material. We report on their impact on the optical properties and conductivity of devices. Semipolar InGaN QW samples, with emission wavelengths from the blue to yellow spectral region, were grown using ELOG methods. Templates with nanorod and microrod structures were explored for overgrowth of the QW structures. Cathodoluminescence hyperspectral imaging was used to map the light emission, which was correlated with the conductivity and non-radiative recombination in the region of chevrons by simultaneous measurement of Electron Beam Induced Current. Shifts in the emission energy,and the dominance of non-radiative recombination along the ‘arms’ of the chevron were observed. As the wavelength of the QW emission increases this shift changes from a red- to a blueshift. The topography of the chevrons were analysed using AFM to provide further insight. The complementary microscopy techniques are shown to provide important details of the properties of the chevrons.

15:15 *M7.6

Study of carrier transport and recombination in disordered InGaN quantum well Light emitting diode with Localization landscape theory Yun-Renn Wu, Chi-Kang Li, Marco Piccardo, Svitlana Mayboroda, Lucio Martinelli, Jacques Peretti , James S. Speck,Claude Weisbuch, Marcel Filoche; Graduate Institute of Photonics and Optoelectronics and Department of Electrical Engineering, National Taiwan University, Taiwan; Laboratoire de Physique de la Matière Condensée, Ecole Polytechnique, CNRS, Univer-

sité Paris, France; Materials Department, University of California, Santa Barbara, USA; Department of Mathematics, University of Minnesota, USA

In this paper, we introduced a novel method to account for quantum disorder effects into the classical Poisson and drift-diffusion model through the localization landscape theory to analyze nitride-based structures. The landscape model solves the carrier dynamics with quantum effects self-consistently and provides an efficient solver when compared with the Schrödinger equation eigen value solver. By using the landscape theory to analyze the carrier states due to the random indium fluctuations, in-plane quantum confinement and tunneling effects can be modeled in an efficient way while solving equations self-consistently. With the landscape model, computations are much faster than the conventional Schrödinger eigensolvers, especially in 3D modeling, typically by a factor 100-1000x, allowing self-consistent calculations. The I-V characterization of LEDs matches very well experimental results and the landscape maps for electrons and holes give us a good estimate of electron and hole overlap, leading to good simulation of LED IQE. Although the landscape theory cannot give the exactly same result of the Schrödinger solution, it does capture the wave nature of the carriers and provide an excellent approximation compared to the classical models, which could be widely incorporated in future device modeling to account for disorder effects.

15:30 **M6.6

MOVPE growth with N2 as carrier gas: a method for impurity reduction in m-plane (10-10) GaN films Ousmane I Barry, Kaddour Lekhal, Si-Young Bae, Ho-Jun Lee, Atsushi Tanaka, Kentaro Nagamatsu, Markus Pristovsek, Yoshio Honda, Hiroshi Amano; Department of Electrical Engineering and Computer Science, Nagoya University, Japan; Institute of Materials and Systems for Sustainability, Nagoya University, Japan; Akasaki Research Center, Nagoya University, Japan

The growth of GaN-based electronic devices in non-polar orientations eliminates the spontaneous polarization and piezoelectric fields along the growth direction. This technology is of great interest for normally-off enhancement mode transistors and also for very stable light emitters due to the suppression of the quantum confined Stark effect. However, the higher unintentional impurity incorporation in non-polar layers during metal-organic vapor phase epitaxy (MOVPE) is a challenge for device performance and reliability. To understand the influence of carrier gas on the impurity incorporation in m–plane (10-10) GaN homoepitaxial films, secondary ion mass spectrometry (SIMS) analysis was performed on m–GaN samples grown on nominally on-axis bulk GaN substrates by MOVPE at identical temperature set-points (ca. 1050 °C at the surface), total pressures of 400 hPa and V/III ratios of 1800 using pure conventional H2 carrier gas or reaction inert N2 carrier gas. SIMS depth profiles revealed a clear dependence of the impurity levels on the choice of carrier gas. Oxygen (O), carbon (C) and silicon (Si) concentrations were all nearly one order of magnitude lower in the samples grown with N2 as compared to that in the samples grown with H2. Thus, in this study MOVPE growth with N2 carrier gas is proposed as a method for reducing the impurity contamination in m-plane (10-10) GaN and the mechanism of impurity reduction is discussed.

15:45 M6.7

InGaN-based Flexible Light Emitting Diodes Can Bayram; Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, USA; Micro and Nanotechnology Laboratory, University of Illinois at Urbana-Champaign, USA

Novel layer release and transfer technology of single-crystalline GaN semiconductors is attractive for enabling many novel applications including flexible photonics and hybrid device integration. To date, LED research has been primarily focused on rigid devices due to the thick growth substrate. This prevented fundamental research in flexible inorganic LEDs, and limited the applications of LEDs in the solid state lighting (due to the substrate cost) and in optogenetics (due to LED rigidness). In the literature, a number of methods to achieve layer transfer have been reported including the laser lift-off, chemical lift-off, and Smartcut. However, the release of films of GaN semiconductors has been challenging since their elastic moduli and chemical resistivity are much higher than most conventional semiconductors. In this talk, we are going to review the existing technologies and propose a new mechanical release technique to overcome these problems.

15:45 M7.7

Mid-infrared photodetectors based on intersubband transition in GaN quantum structure Xin Rong, Xinqiang Wang, Ping Wang, Xiantong Zheng, Guang Chen, Fujun Xu, Bo Shen; State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, China

GaN quantum structure is an excellent candidate for high speed infrared photodetectors based on intersubband transition (ISBT). However, fabrication of GaN based quantum structure suffers from the polarization induced internal electric field, which suppresses not only the ISBT probability but also the carrier vertical transport. These issues can be overcome by using non-polar GaN quantum structures or cubic ones if their crystalline qualities can be largely promoted [1,2]. Here, we propose a polarization engineering method used in c-plane GaN-based ISBT structure. A spacer barrier layer with thickness less than 2 nm was adopted to balance the polarization in the quantum wells (QW),

resulting in a step-QW structure with a nearly flat conduction band potential profile[3]. As such, a B-to-QC type ISBT structure can be achieved. This can also be proved by solving the self-consistent Schrödinger-Poisson equations. Further, considering the influence of spacer barrier layer cannot be completely neglected although it is narrow for carrier tunneling, we designed and grew a novel graded barrier ISBT structure, predicted to be more favorable for the carrier vertical transport. At last, the intersubband prototype device with detectable photocurrent at atmosphere window (3-5 μm) is achieved in GaN quantum structure.

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MONDAY POSTER ABSTRACTS

11th ISSLED Conference
Monday Poster Session
4:00-6:00 PM
Room KC 103/105

MP1

(Student) Effect of Gd2O3 additives on the microstructure and electrical properties of ZnO varistor F. H. Alhameda, M. A. Al-issab, S. M. Al-bashirc; Physics Department, Faculty of Science and Arts, Najran University, Saudi Arabia; Physics Department, Physics and Astronomy Department, King Saud University, Saudi Arabia

The influence of Gd2O3 (0, 0.2, 0.5, 1, 1.5) mol% additives on microstructure and electrical properties of ZnO – Pr6O11 – Co3O4 – Cr2O3 – Gd2O3 (ZPCCG) – based varistors were studied. Samples were prepared by using the standard ceramic technique (traditional thermal chemistry method). The grain size of prepared samples was obtained by SEM. The DC measurements (nonlinear properties, capacitance – voltage characteristics) were determined. Increasing the concentration of Gd2O3 led to increased density, nonlinear properties and breakdown field, whereas it decreased the average grain size of the samples. The density was in the range of 5.32–5.42 g/cm3. The average grain size decreased from 7.80 to 5.40µm. The nonlinear coefficient value of the samples doped with Gd2O3 increased remarkably in the range of 3.2 – 48.2 and the breakdown field (EB) increased from 15.9 to 3210.5 Vcm-1. The increase of the concentration of Gd2O3 led to increases the potential barrier height (B). As for the C–V characteristic parameters, it has been found that the increase of Gd2O3 content at room temperature led to the decrease of the donor concentration (ND) and density of interface states (NS) in the range of (55.651018 – 0.441018/cm3) and (15.371012 –1.931012/cm2), respectively.

MP2

A fractal organization in III-N LED structures Alexander S. Usikov, V. N. Petrov, A. P. Kartachova, N. A. Talnishnikh, A. E. Chernyakov, E. I. Shabunina, N. M. Shmidt, H. Helava, Yu. Makarov, A. Y. Polyakov, N. B. Smirnov, and In-Hwan Lee; Ioffe Physical–Technical Institute, Russian Academy of Sciences, Russia; Submicron Heterostructures for Microelectronics Research and Engineering Center, Russia; Nitride Crystals Inc., Virginia, USA; National University of Science and Technology MISiS, Russia; School of Advanced Materials Engineering, Chonbuk National University, Korea

A fractal nanomaterial ordering (FNO) observed in III-N LED structures is due to an existence of the extended defects system and 3D random compositional fluctuation in an active region. These disturbances can be quantified by a multifractal parameter that is degree of disorder. A comprehensive study of MOCVD- and HVPE-grown 360-530 nm LEDs by means of low frequency noise, I-V characteristics, electroluminescence spectra, and a disorder of the III-N structure allow revealing a relationship of FNO to LED properties. In addition, complex dynamic of the LED characteristics under injection current demonstrates a formation of random percolation paths (RPP) in the extended defects system and the alloy fluctuations which leads to the current crowding effect and transport of charged carriers along and across layers in the structure (lateral and vertical transport). An impact of FNO and RPP the efficiency droop and lifetime of LEDs is considered. A mechanism among others responsible for the external quantum efficiency (EQE) degradation and the unpredictable failure of LEDs is a multi-phonon carrier recombination (MCR) under injection current at the percolation paths. The MCR mechanism dues the In and Ga local migration and undulating changing of the EQE values that appears as flickering radiation during the aging test. The contribution of RPP is changed at different stages of aging that can be identified by specific of I-V characteristics at low bias.

MP3

Performance Improvement of Light-Emitting Thyristor Using GaInP active layers and a GaP Window Layers Ray-Hua Horng, Ching-Ho, Chen, Jia-Jhen Jhan, Dong-Sing Wuu; Department of Materials Science and Engineering, National Chung Hsing University, Taiwan; Graduate Institute of Precision Engineering, National Chung Hsing University, Taiwan; Institute of Electronics, National Chiao Tung University, Taiwan; Advanced Optoelectronic Technology Center, National Cheng Kung University, Taiwan

Light-emitting thyristors (LET) with a GaInP active layer have been fabricated on n-type GaAs substrates. These thyristors of GaInP exhibited the excellent performance than conventional thyristors with AlGaAs active layer on p-type GaAs substrates. The measured internal quantum efficiencies (IQE, by PL) of thyristors with a GaInP active layer is about 17%. It was much greater than 4% of conventional thyristors of AlGaAs. It could be attributed that the thyristors with GaInP did not consist of aluminum atoms, so it is not easy to oxidize at growth and operational process. Moreover, the external quantum efficiencies (EQE) of LETs, which result in increasing the output light intensity and thermal stability of the LET using GaP windows. At an injection current of 250 mA, the LETs with GaP windows obtained a higher light intensity of 75 mcd compared to that of 45 mcd of the LETs without GaP windows. It could be attributed that GaP could improve the current spreading and droop efficiency. Therefore the npnp structure had been grown on n-type GaAs substrates to thyristor application and this process reduces the cost of substrates compared with conventional pnpn of thyristors on p-type GaAs substrates.

MP4

(Student) Fabrication of a high brightness UV-Blue Light-Emitting Diode based on high quality Gd doped ZnO-nanotube array grown on p-GaN Norah Alwadai, Tahani Felemban, Somak Mitra, Idris ajia, Mufasila Mumthazmuhammed, Bilal Janjua, Boon Ooi, and Iman Roqan; King Abdullah University of Science and Technology (KAUST); Semiconductor and Material Spectroscopy Group,Physical Science and Engineering Division, Saudi Arabia

The unique optical and electrical properties of ZnO nanotubes (NTs), due to their high aspect ratio and confinement effect, can lead to high optical UV efficiency light emitting diodes (LED). Furthermore, self-assembled ZnO NTs are easier to form, with larger exciton binding energy (60 meV) and inexpensive compared to GaN materials. In this study, to fabricate high-brightness ZnO/GaN NTs-based UV-Blue LED, high optical and structural quality vertical n-ZnO NTs without catalyst doped with Gadolinium (Gd) (2 wt%) were grown on MOCVD p-GaN films with c-sapphire substrate using pulsed laser deposition. X-ray diffraction and scanning electron microscopy confirmed highly textured single crystal hexagonal-shaped ZnO NT with thin wall (>20 nm) and wide hollow (>200 nm diameter) and 800-1000 nm height grown along c-axis. We show an intense UV–blue electroluminescence emission at room temperature arising from our ZnO NT-based LEDs. Micro-photoluminescence (μPL) reveals an intense bandedge emission with a very weak defect band, indicating high optical quality. The strong blue emission can be due to donor presence as a result of Gd doping. Electrical measurements performed show distinct diode characteristics. We demonstrate that Gd dopants significantly improve the device performance due to donor injection.We investigate carrier dynamics by time resolved PL spectroscopy using femtosecond Ti:sapphire laser with a frequency tripled wavelength (266 nm), that is attached to a streak camera.

MP5

(Student) Selective area growth of GaN layer on partially crystallized cavity engineered sapphire substrate Jeonghwan Jang, Seungmin Lee, Daeyoung Moon, Giwoong Kim, Duyoung Yang, Jehong Oh, Yongjo Park, and Euijoon Yoon; Department of Materials Science and Engineering, Seoul National University, Korea; Energy Semiconductor Research Center, Advanced Institutes of Convergence Technology, Seoul National University, Korea

Recently, we have reported a new growth scheme of using a cavity engineered sapphire substrate (CES), in which well-defined air-cavity patterns were formed on a sapphire for the fabrication of more efficient and less strained LEDs. During the growth of GaN layer on the CES, it was found that undesired GaN crystal was deposited on the top area of the cavity patterns, generating the additional threading dislocations during the coalescence of GaN layer. This is because the cavity shell was crystallized into single crystalline a-phase, the phase of sapphire substrate, by solid-phase epitaxy during the fabrication process of the CES. To suppress the growth of the parasitic GaN, we investigated selective area growth of GaN layer on partially crystallized CES (PCCES) in which the cavity shell is remained in nanocrystalline g-phase, another phase of alumina, rather than a-phase. By carefully controlling the crystallization process, we successfully obtained g-phase cavity shell while the area between the cavities were crystallized into a-phase for the GaN growth. Transmission electron microscopy analysis revealed that the parasitic GaN growth on top of the cavity patterns was successfully suppressed and the GaN layer from the planar area was coalesced on top of the pattern without generating additional dislocations. As a result, threading dislocation density in the GaN layer grown on the PCCES was reduced up to ~ 30 % compared to that on CES with a-phase cavity shell.

MP6

Investigation of the photoelectric characteristics of the MoO3/Ag/MoO3 tri-layer photodetector Sheng Yuan Chu, Chen Tao Wang, Shan Rong Li, Cheng-Shong Hong; Department of Electrical Engineering, National Cheng Kung University, Taiwan; Institute of Microelectronics, National Cheng Kung University, Taiwan; Department of Electronic Engineering, National Kaohsiung Normal University, Taiwan

In past years, the photodetectors (PDs) has attracted significant interest for the popular application in many fields such as biotechnology, semiconductor, environment…etc. Many researchers have paid numerously effort to improve the absorption of the PDs, suppress the dark current…etc. Recent years, tri-layer PDs, have been investigated popularly. The structure of tri-layer PDs structures include semiconductor and a thin metal film such as ZnO/Ag/ZnO, ITO/Ag/ITO, O/Cu/ITO, GZO/Ag/GZO. Molybdenum oxides have been widely investigated for their broad applications ranging from electronics to energy storage. Photodetectors based on molybdenum trioxide (MoO3) were usually fabricated with Au film. However, the most drawback of Au is high cost which limited the application in PDs. In this paper the authors improve the PDs by the silver film which is more conductive and cheaper than gold film. The authors will investigate the optical and electronic characteristics of this PDs then compared with the references.

MP7

Luminescence properties of Ca6BaP4O17:Sm3+ phosphor and its thermal stability Chung-Hao Chiang, Sheng-Yuan Chu; Department of Electrical Engineering, National Cheng Kung University, Taiwan

In this study, Ca6BaP4O17:Sm3+ phosphors were synthesized via a conventional solid-state reaction method. These phosphors can be excited by near-ultraviolet (NUV) at 405 nm. The luminescence properties of the obtained orange-red emission phosphors were characterized. The Sm3+ doped barium phosphate phosphor can be excited by near-NUV and blue light, and the emission spectrum consists of three main emission spectra, between 550-580 nm, 585-638 nm, and 640-675 nm, respectively. The thermal stability was investigated systematically and corresponding mechanisms were proposed. Based on the results, the as-prepared Ca6BaP4O17:Sm3+ phosphors are promising orange-red-emitting phosphors for NUV-based white light-emitting diodes (WLEDs). The phosphor exhibits the three classical emission bands of Sm3+. The 4G5/2 - 6H7/2 (585-638 nm) transition has the strongest intensity. The X-ray diffraction patterns, PL properties, thermal quenching, and decay time were discussed in detail. The excitation spectrum shows absorption from 340 to 500 nm, which can be attributed to the 4f-4f transition of Sm3+ ions. Sm3+-doped Ca6BaP4O17 phosphors exhibited very stable thermal stability of orange-red emission. The integrated emission intensity of Ca6BaP4O17 doping with 12 mol% Sm3+ at a phosphor temperature of 200 °C was still 84% of that at room temperature. This study shows that these phosphors can be excited by NUV chips for potential applications in phosphor converted WLEDs.

MP8

(Student) Growth of Nitrogen –polar InN on sapphire substrate by DERI method Kubonaka Yuuto, Mouri Shinichiro, Araki Tsutomu, Nanishi Yasushi; Ritsumeikan Univ.

We reported the DERI method as a new growth method of InN. This method enabled reproducible growth of high-quality InN films. So far, we have applied this growth method for growth of In–polar InN. In this study, we have investigated availability of DERI method for N-polar InN growth, expecting higher growth temperatures and resulting higher quality films. C-plane sapphire was used as a substrate. After nitridation of substrate at 300- for 2h, using nitrogen flow rate of 2.0sccm and rf power of 200W, InN buffer layers were grown at 300- for 10min under N rich conditions. DERI process with N-polar growth mode then followed on these buffer layers for 1 hour with various growth temperatures ranging from 425- to 530-. By using in-situ RHEED intensity monitoring, it was found that DERI process worked well even for N-polar InN growth under growth temperatures up to 480-. However, at growth temperatures higher than 500-, under which In-polar growth cannot be carried out due to dissociation, we have found that DERI process under N-polar growth also did not worked well.
Differences of growth mode in atomic scale on N-polar surface or wetting of the In-solution on N-polar surfaces are considered to be as possible causes for these results. Measures to realize growth of N-polar InN films at higher temperatures will be extensively discussed.
Acknowledgements: This work was supported by JSPS KAKENHI Grant Number JP16H03860, JP16H06415, JP26600090, JP15H03559

MP9

C exciton and A exciton dynamic of m-plane GaN film Bei Ma, Tsubasa Yamakawa, and Yoshihiro Ishitani; Chiba University

The clear reason of electron-hole plasma state becoming dominant in the GaN laser devices at temperatures higher than 150K has not yet been obtained even at present. Exciton dissociation could be considered to cause the reduction of the radiation by inelastic exciton-exciton collisions. As the quality of GaN film getting better, the photoluminescence spectrum of the C excitons can be obtained by a time-resolved photoluminescence measurements using non-polar GaN film. We have investigated the A excitonic dynamics of GaN at LT in the previous study. In this study, we focus on the energy transport among A exction, C exction, and LO phonon, by analyzing the total energy of exciton-carrier-phonon system. The sample was a non-polar GaN film grown on a freestanding GaN substrate by MOVPE method. Eexciton dynamics between A excitons with the principal quantum numbers n = 2 (FA(2)) and n = 1 (FA(1)), B (FB) and C excitons (FC) after a pulse excitation were analyzed. It was found that the effective temperature of FC excitons is approximately the same as that of FA(2), while the population density of the C exciton is thought to decay faster than that of the FA(2) exciton on the basis of the intensities of 1-LO phonon replicas. These results suggest that the population transport between the A and C exciton states is negligible, and that the C exciton states have a strong interaction with the continuum states.

MP10

(Student) Electrical Characteristics of Ti/ITO Schottky Contacts on p-type GaN Su-Jung Yoon, Dae-Hyun Kim, Daesung Kang, Tae-Yeon Seong; Department of Nanophotonics, Korea University, Korea; Department of Materials Science and Engineering, Korea University, Korea; LED Division, LG Innotek Co., Ltd, Korea

GaN-based semiconductors are of technological importance for their applications in optoelectronic and electronic devices. Particularly, the wide band gap, high breakdown field, and high saturation velocity of nitride semiconductors make them suitable for high power electronic devices, including metal-insulator-semiconductor field effect transistors, heterostructure field effect transistors, and high electron mobility transistors. To improve the performance of these devices, the formation of reliable Ohmic and Schottky contacts is crucial. Thus, it is important to understand

the relationship between interfacial, electrical, and optical properties. In this study, we investigated the electrical characteristics of Ti/ITO Schottky contacts on p-GaN by means of current-voltage and capacitance-voltage measurements. The Schottky barrier height (SBH) and ideality factor were found to depend on the annealing temperature. The SBHs increased with increasing temperature, whereas the ideality factor decreased. This behavior was explained in terms of barrier inhomogeneity model, by which effective Richardson constant was estimated to be of 130–136 Acm-2K-2. To understand the electrical behavior of the Schottky contacts, transmission electron microscopy and energy dispersive X-ray spectroscopy measurements will be performed. Furthermore, the effect of sulphur passivation on the Schottky behavior will be also presented.

MP11

Self-assembled indium tin oxide nanoball-embedded omnidirectional reflectors for high photon extraction efficiency in III-nitride ultraviolet emitters Semi Oh, Kwang Jae Lee, Sang-Jo Kim, Kab Ha, Jongyeul Jeong, Dongjun Kim, Kyoung-Kook Kim, and Seong-Ju Park; School of Materials Science and Engineering, Gwangju Institute of Science and Technology, Korea; Department of Advanced Convergence Technology and Research Institute for Advanced Convergence Technology, Korea Polytechnic University, Korea

The control of refractive index and electrical conductivity in dielectric layer of onmidirectional reflectors (ODRs) is essential to improve the low efficiency of AlGaN-based ultraviolet (UV) emitters. The air-embedded porous ODR that contained a porous electrically conductive film was fabricated to decrease the refractive index of the conductive dielectric layer. However, these ODRs have some critical problems for application to UV light emitters because current cannot be easily injected from an ODR to the p-type AlGaN layer owing to the high electrical resistance of the dielectric layer with low refractive index. In this study, we report self-assembled indium tin oxide (ITO) nanoball-embedded omnidirectional reflectors (NODRs) for use in high-efficiency AlGaN-based UV emitters of 365 nm. The NODR was able to realize both high electrical conductivity and reflectivity by decreasing the average refractive index of the ITO nanoball layers. We observed diffuse reflection as well as omnidirectional reflection from the NODR UV emitters because of the corrugated interfaces of the nanovoids, ITO nanoball layer, and Al layer. These structural and optical properties of the NODRs remarkably increased the output power of a UV emitter by a Lambertian enhancement factor of 57% at an injection current of 50 mA at all emission angles compared with that of an ITO film/Al UV emitter.

MP12

(Student) Enhanced optical output power of InGaN/GaN multiple quantum wells light-emitting diodes by vertical magnetic fields of Co/Pt multilayers Janghwan Han, Jae-Joon Kim, Young-Chul Leem, and Seong-Ju Park; School of Materials Science and Engineering, Gwangju Institute of Science and Technology, Korea

Recently, GaN-based LEDs with high internal quantum efficiency (IQE) have attracted a lot of attention for high efficiency light-emitting diodes (LEDs). Therefore, various methods, such as surface plasmon, electron blocking layer, and epitaxial growth techniques have been used to achieve high IQE. However, it was only until recently that the effect of magnetic film on GaN-based LEDs has been reported, even though the external magnetic field can change the radiative recombination rate in GaAs/AlGaAs heterostructures and and InGaN/GaN multi-quantum wells (MQWs) structures.

In this study, we investigated the effect of vertical magnetic field gradient on the performance of InGaN/GaN MQWs flip-chip blue LEDs by using cobalt/platinum (Co/Pt) multilayer. The film and dot pattern of Co/Pt multilayer, which can supply the vertical magnetic field to the MQWs, were deposited on p-ohmic reflector to provide a magnetic field gradient to MQWs. The optical output powers of LEDs with Co/Pt multilayer film and dot patterns were increased by 20 % and 28 %, respectively at 20 mA, compared to LEDs without Co/Pt multilayer. The time resolved-photoluminescence (TR-PL) decay time also decreased by a vertical magnetic field. These results indicate that more carriers are localized in the potential fluctuations in InGaN/GaN MQWs under vertical magnetic field and the enhancement of optical output power is attributed to the increased IQE by gradient of vertical magnetic field from Co/Pt multilayer.

MP13

Systematic study on the trade-off relationship between the forward voltage and the internal quantum efficiency of light-emitting diodes Jong-In Shim, Dong-Pyo Han, Dong-Soo Shin, Hyundon Jung; Hanyang University; Eta-Max Co.

Improving the wall-plug efficiency (WPE) of light-emitting diodes (LEDs) requires enhancing the internal quantum efficiency (IQE) and reducing the forward voltage (VF) simultaneously. It has been empirically recognized that there is a trade-off relationship between two characteristics of the IQE and VF from the long history of epitaxial growth. However, more systematic research on this topic is still needed. In this presentation, the relationship between the IQE and VF of blue LEDs is investigated both experimentally and theoretically. Recently, we have introduced an analysis technique of combining the IQE with the current-volt-

age curve, in which the radiative and nonradiative recombination currents are analyzed separately. It is found that the radiative recombination current does follow the ideal Shockley diode equation with an ideality factor of 1 and a constant series resistance Rs. Moreover, Rs shows a close relationship with the IQE rather than the metallic ohmic properties. In order to clarify the issue, we analyze various energy-loss mechanisms of carriers such as Joule heating, optical absorption, Shockley-Read-Hall (SRH) recombination, and carrier heating/cooling effects. Analysis results reveal that the carrier accumulation and subsequent spillover from the multiple-quantum-well to the outside region due to insufficient carrier recombination rates is the most probable mechanism for explaining the trade-off relationship between the IQE and VF.

MP14

(Student) Study on solid-phase epitaxy of stripe-shaped Al2O3 membrane Jeonghwan Jang, Daeyoung Moon, Giwoong Kim, Duyoung Yang, Yongjo Park, and Euijoon Yoon; Department of Materials Science and Engineering, Seoul National University, Korea; 2Energy Semiconductor Research Center, Advanced Institutes of Convergence Technology, Seoul National University, Korea

Recently, we have reported growth of high quality GaN layer on an ultra-thin (26 nm) a-Al2O3 membrane, which is used as a compliant substrate. This results in 28% reduction of misfit dislocation density compared to that on a planar sapphire substrate. Fabrication of the membrane involved the formation of a 3-dimensional (3-D) amorphous Al2O3 membrane structure on a sapphire substrate (a-Al2O3) by atomic layer deposition and its subsequent solid phase epitaxial (SPE) transformation into a-phase. Thus, understanding the phase transformation of the Al2O3 membrane structure is crucible to the quality improvement of the GaN layers. In this research, we fabricated a stripe-shaped amorphous Al2O3 membrane structure on a sapphire substrate and then performed an annealing to crystallize it into the single crystalline a-phase. SPE of the Al2O3 membrane structure proceeds in two step transformation of amorphous to metastable g-phase and then subsequently into a-phase. After phase transition into g-phase, the volume of Al2O3 contracted, resulting in inward bending of the membrane wall. This bending induced compressive stress at the bottom region of the membrane wall, leading to the enhanced SPE rate of the subsequent transition to a-phase at the region. After annealing at 1063 C for 2.5 hrs, the whole membrane structure was crystallized into a single crystalline a-phase. Details of the SPE behavior in the 3-D Al2O3 membrane structure, including the geometrical effect, will be presented.

MP15

(Student) Fabrication of nano-cavity patterned sapphire substrates and their application to the growth of GaN Donghyun Lee, Seungmin Lee, Jeonghwan Jang, Jongmyeong Kim, Giwoong Kim, Jehong Oh, Daeyoung Moon, Yongjo Park, and Euijoon Yoon; Seoul National University; 2Advanced Institutes of Convergence Technology

GaN-based light-emitting diodes (LEDs) have been investigated intensively due to various applications such as full-color display, and general lighting. Although GaN-based LEDs have already been commercialized via significant technology advancement such as patterned sapphire substrate, the efficiency and cost competitiveness must be improved. Recent studies using hollow nanosphere-coated substrate1 and cavity-engineered substrate2 have been reported to show that air-voids inserted in GaN not only improve the LED performance but also relax the film stress. We have fabricated a nano-cavity patterned sapphire substrate (NCPSS), which has periodic nano-cavity patterns on sapphire, using polystyrene (PS) sphere patterning. Coating of self-assembled PS (1 um in diameter) spheres by spin coating and O2 reactive ion etching enabled the fabrication of nanoscale non-close-packed hexagonal PS array on sapphire substrate. Subsequently, 60 nm-thick alumina was deposited by atomic layer deposition and the substrate was annealed at 1100 C for two hours in air ambient, resulting in NCPSS. Then, GaN layer was grown on NCPSS by metal-organic chemical vapor deposition. The embedded air-voids enhanced the diffuse reflectance by 33% at 460 nm by breaking the total internal reflection. In addition, Raman spectroscopy reveals that the stress of GaN on NCPSS was 20% relaxed by the inserted nano-cavities.

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MP16

(Student) Oblique-Angle Deposited ITO/Silver Nanowire Transparent Conductive Electrodes for GaN-Based Light-Emitting Diodes Minkyung Baek, Munsik Oh, and Hyunsoo Kim; Chonbuk National University

The development of next-generation transparent conductive electrodes (TCEs) overcoming the conventional indium tin oxide (ITO) TCEs is of significant importance in designing superior optoelectronic semiconductor devices. Recently, silver nanowires (Ag NWs) displayed an excellent TCE performance including high optical transmittance, a low sheet resistance, and improved mechanical flexibility, which has resulted in practical use of Ag NWs in flexible displays. Nevertheless, Ag NWs still cannot be directly used in III-nitride LEDs because of their relatively poor Ohmic contact to p-GaN associated with reduced contact area. In this

study, hybrid transparent conductive electrodes consisting of oblique-angle deposited indium tin oxide (OAD ITO) and silver nanowires (Ag NWs) were developed for GaN-based LEDs. 100 nm thick OAD ITO acted as an Ohmic contact to p-GaN with negligible light absorption, and Ag NWs acted as a favorable current spreader with sheet resistance as low as 19.9 /sq. Consequently, the hybrid TCEs consisting of OAD ITO and Ag NWs yielded an optical transmittance of 93% at 450 nm, a sheet resistance of 18.9 /sq, and a specific contact resistance of 2.1 102 ·cm2. LEDs fabricated with hybrid TCEs demonstrated improved electrical properties and 20% greater output power than the reference LEDs. This was due to the combined effects of improved optical transparency, enhanced current spreading, and the surface roughening effect.

MP17

High efficient InGaN/GaN blue light-emitting diodes by using the p-type InGaN layer for V-pit passivation Tae-Hoon Chung, Sung Hoon Jung, Jong Hyeob Baek, Kwang Jae Lee, June Key Lee; LED R&D Division, Korea Photonics Technology Institute (KOPTI); Department of Materials Science and Engineering Chonnam National University

Recently, III-nitride-based light emitting diodes (LEDs) have been extensively used for various applications such as outdoor light, display, traffic signal, and automobile. However, the optical output power of LEDs is still low because of the low external quantum efficiency (EQE). To enhance the EQE, various methods have been suggested in LED structure in terms of internal quantum efficiency (IQE) and light extraction efficiency (LEE). In particular, many researchers have focused on the band-gap engineering of n-type, p-type GaN layer, and InGaN/GaN-based multiple quantum wells (MQWs) to further enhance the IQE considering on carrier dynamics, quantum confined Stack effect (QCSE), and Auger recombination rate. Generally, the grown LEDs have hexagonal structured V-pit defects in those epitaxial layer. To date, as an alternative way to enhance the IQE, using V-pit defects has been newly emerged and the reported results on V-pit technics in LEDs clearly show the enhancement of light output power owing to the higher potential barrier of defects, resulting in the decrease in non-radiative recombination rate. In this report, we investigate the effect on V-pit structures with and without the p-type InGaN insertion layer before the growth of p-type GaN layer for V-pit passivation. Since the V-pit structures are practically maintained up to p-type GaN surface, inserting the p-type InGaN layer would play an important role as leakage current blocking layer.

MP18

(Student) Study of polarity-controlled ZnO films and nanorods on the light extraction efficiency of semipolar (11-22) GaN-based light-emitting diodes Yongjin Kim, Sung-Nam Lee; Department of Nano-Optical Engineering, Korea Polytechnic University, Korea

ZnO thin film and nanorods have been attractive to achieve high extraction efficiency of GaN-based light-emitting diodes (LEDs) as a transparent conductive electrode to replace ITO. Since ZnO films and NRs have mostly reported to the c-axis, it represented spontaneous and piezoelectric polarizations. Therefore, some research groups have focused on nonpolar ZnO. However, there is no systematic report on the applications of nonpolar ZnO films and NRs. In this study, we investigated polar/nonpolar ZnO films/NRs to improve the light extraction efficiency (LEE) of semipolar (11-22) GaN-based LEDs by using atomic layer deposition and electrochemical deposition, respectively. We prepared high quality polar (0001) and nonpolar (10-10) ZnO films on c- and m-sapphire substrates, respectively. And then, ZnO NRs were grown on polar and nonpolar ZnO seed layers. The crystal direction of ZnO NRs would be significantly affected by that of ZnO seed layer. From HR-XRD, it found that polar [0001] and semipolar [10-11] ZnO NRs were grown on polar and nonpolar ZnO films, respectively. And then, we fabricated two types of semipolar LEDs with [0001] and [10-11] ZnO NRs as TCEs using polar and nonpolar ZnO films. The light output power of semipolar GaN-based LEDs with [10-11] ZnO NRs was superior to that of LED with [0001] ZnO NRs. It implied that the inclined [10-11] ZnO NRs is more effective to increase LEE than vertical [0001] NRs increased by using polar and semipolar ZnO NRs.

MP19

Enhanced optical properties by two-dimensional photonic quasicrystal layers on a Y2O3:Eu3+ thin-film phosphors Hyojun Kim, Ki-Young Ko and Jinho Ahn; Department of Materials Science and Engineering, Hanyang University, Korea; Institute of Nano Science and Technology, Hanyang University, Korea; Korea Invention Promotion Association, Korea

Recently there has been growing interest in the use of thin-film phosphors in flat panel displays (FPD) such as field-emission displays (FED) and plasma display panels (PDP). Even though thin film phosphor shows superiority over the powder phosphors in many aspects, it shows limited light extraction efficiency of ~7% (Eu3+-doped Y2O3, Y2O3:Eu3+) due to total internal reflection (TIR) and waveguide effect. In order to resolve this drawback, two-dimensional (2D) photonic crystal layers (PCLs) have been applied to various light emitting devices incorporating luminescent film materials. However, this 2D PCLs show improvement of extraction efficiency only at specific angles, and this causes a light dazzling optical effect produced by Bragg diffraction. In this study, we fabricated various 2D photonic quasicrystal (PQC: non-periodic but ordered) layers using nano-sphere lithography (NSL) and their optical

effects have been evaluated. Quasicrystals were formed by NSL using mixture of two different size polystyrene (PS) spheres of 1um/420nm or 600nm/150nm. We examined the optical effects of 2D PQC layers on the photoluminescence property of annealed Y2O3:Eu3+ TFPs fabricated by sol-gel method. The 2D PQC layer improves the light extraction efficiency by 8.7 times compared to the conventional Y2O3:Eu3+ TFPs with uniform emission distribution along the angle.

MP20

Optical and structural properties of semipolar GaN on patterned Si substrates Jochen Bruckbauer, G. Naresh-Kumar, X. Yu, J. Pugh, P. R. Edwards, M. J. Cryan, T. Wang, C. Trager-Cowan, and R. W. Martin; Department of Physics, SUPA, University of Strathclyde, United Kingdom; Department of Electronic and Electrical Engineering, University of Sheffield, United Kingdom; Department of Electrical and Electronic Engineering, University of Bristol, United Kingdom

GaN on Si opens up several new device possibilities. Si offers low cost substrates and CMOS compatibility for optoelectronic devices. Patterning of the Si substrate enables different crystal orientations for GaN growth to be accessed and the defect density to be controlled. Accessing the semipolar crystal orientations offers the benefits of a reduced quantum-confined Stark effect and higher incorporation of InN to achieve longer wavelength emitters. (10-11)-oriented GaN has been overgrown by MOCVD on Si substrates which have been patterned into stripes. InGaN multiple quantum well (MQW) structures emitting around 470 nm are grown on top. Cathodoluminescence (CL) hyperspectral imaging at room temperature revealed several features. Black spots associated with non-radiative recombination at threading dislocations (TDs) appear in the GaN CL intensity image. The MQW CL intensity image showed dark lines and mode structures overlaying the MQW emission peak. Electron channelling contrast imaging confirmed the presence of TDs at the dark spots. The dark lines are associated with misfit dislocations induced during the semipolar growth. Finite difference time domain simulations of the mode structure revealed that the peak spacing originates from Fabry-Perot type resonances from the Si sidewalls. The source was a dipole at the position where the two GaN growth fronts from the opposite sidewalls of the Si meet. These structures show promise for longer wavelength emitters and laser diodes.

MP21

Reduction of Carbon in MOCVD-grown GaN for Power Devices by Supersaturation Control Seiji Mita, Felix Kaess, Jingqiao Xie, Luis H. Hernandez-Balderrama, Shun Washiyama, Pramod Reddy, Andrew Klump, Alexander Franke, Ronny Kirste, Axel Hoffmann, Erhard Kohn, Tomasz Sochack, Michal Bockowski, Ramón Collazo, Zlatko Sitar; Adroit Materials, Inc., North Carolina State University, Technical University Berlin, Institute of High Pressure Physics

It was identified that carbon was the main defect attributed to the sudden reduction of the electron mobility, the electron mobility collapse, in n-type MOCVD-GaN. SIMS has been performed to determine the C concentration to compare with our Ga supersaturation model. Our base growth conditions consisted of a TEGa flow rate of 134 μmol/min and a growth temperature of 1040 °C in a low growth pressure of 20 Torr at a constant total mass flow of 7.5 slm. Both H2 and N2 were used as diluent gases. By controlling the ammonia flow rate, the input partial pressure of the Ga precursor, and the diluent gas within the Ga supersaturation model, the C concentration in Si-doped GaN was controllable from 6x1019 cm-3 to values as low as 2x1015 cm-3. It was found that the electron mobility collapsed as a function of free carrier concentration, once the Si concentration closely approached the C concentration. Lowering the C concentration to around 1015 cm-3 by choosing the appropriate Ga supersaturation achieved a controllable free carrier concentration down to 5x1015 cm-3 with a peak electron mobility of 820 cm2/Vs without observing the mobility collapse. The highest electron mobility of 1170 cm2/V s was obtained even in MOCVD-grown GaN on sapphire substrates by optimizing growth parameters in terms of Ga supersaturation to reduce the C concentration. This growth condition also led the GaN homoepitaxial growth GaN on HVPE/ammonothermal GaN substrates to a narrow PL DBX peak of 100 μeV.

MP22

Suppression of Mg Migration and Surface Accumulation by Fermi Level Control in GaN grown by MOCVD Felix Kaess, Andrew Klump, Pramod Reddy, Dorian Alden, Ronny Kirste, Axel Hoffmann, Ramón Collazo, and Zlatko Sitar; Department of Materials Science and Engineering, North Carolina State University, USA; Technical University Berlin, Solid State Physics Institute, Germany

The creation of an electron blocking layer in c-plane Ga-polar GaN grown by metal-organic chemical vapor deposition (MOCVD) was achieved by using a GaN:Mg layer and an unintentionally doped spacer layer. Two n-type layers with a large difference in free carrier concentration, namely an n- layer with n=5x10^16 cm-3 on top of an n+ layer with n=1x10^19 cm-3, could be isolated from each other and independently measured with Hall. The Hall free electron mobility in the top n- layer was above 600 cm2/Vs, indicating a good structural quality and a low concentration of compensating defects. The carry forward of Mg, also called memory effect, makes it difficult to obtain sharp doping profiles in GaN grown by MOCVD that involve p-type doping. Here, we show that the memory effect in GaN grown by MOCVD can be reduced significantly by illumination with

above bandgap light during epitaxy. This Fermi-level controlled reduction of Mg was necessary for confining the Mg in the designated insulation layer, which could be confirmed independently by Hall, PL, and SIMS measurements. Blue or violet light can be used for this due to the Varshni shift of the GaN bandgap at MOCVD growth temperatures. Our results reveal that without illumination, there is a significant accumulation of Mg that is advanced towards the sample surface, whereas in areas with low or high light intensity this transport mechanism can be suppressed significantly.

MP23

Influence of Initial Pretreatment on GaN Growth on Graphene Yulong Fang, B. Wang, J. Y. Yin , Z. R. Zhang , Y. M. Guo , J. Li, W. L. Lu, Z. H. Feng; National Key Laboratory of ASIC, China

Due to the absence of dangling bonds on the surface of graphene, GaN epilayer grown on graphene is bound by the weak van der Waals interactions. However, due to the low surface energy of graphene, direct epitaxy of GaN materials on graphene suffers the formation of 3D clusters, and subsequently leads to poor crystal quality. In this paper, the effect of ammonia pretreatment on the performance of GaN epilayer grown on graphene by MOCVD is characterized. The graphene is deposited on sapphire by CVD. The AFM spectra show that, the graphene is etched by the ammonia. With the increase of the ammonia flow rate, the graphene is first etched at the wrinkle, and the etched pits appear along the direction of the winkles. The appearance of etch pits relaxes the residual stress, resulting in more winkles. Finally, graphene is almost etched out and small fragments of about 100 nm are formed. SEM shows that, GaN is initially nucleated on the winkles and the etch pits of graphene, and recombined by lateral over growth. The results of XRD test show that the rocking curve FWHM of GaN epilayer on graphene is related to ammonia flow rate during the pretreatment process, decreasing first and then increasing with the increase of ammonia flow rate. The appropriate ammonia flow was used for the pretreatment of graphene, which changed the stress and surface morphology of the graphene, and control the nucleation density of GaN on graphene.

MP24

Indium-free Transparent Ohmic Contacts to N-polar n-type GaN Margaret A Hopkins, S. Thornley, J. Dutson, G. Christmann, S. Nicolay, J. Niemela, M. Creatore, J. Ellis, D.W.E. Allsopp; Department of Electrical and Electronic Engineering, University of Bath, UK; Plasma Quest Ltd, UK; CSEM, Switzerland; Department of Applied Physics, Eindhoven University of Technology, Netherlands; Plessey Semiconductors Ltd.,UK

Low resistance transparent contacts to N-face n-type GaN have the potential to greatly simplify the processing of high-brightness flip-chip or vertical light-emitting diodes (V-LEDs). To date work on forming transparent contacts to the top N-face n-GaN layer in V-LEDs has focused on using indium tin oxide (ITO)1 . However, a technology based on earth-abundant elements is preferred for cost, supply and environmental reasons. Such Indium-free wide band gap transparent materials typically form Schottky diodes on n-GaN2 and methods for overcoming this limitation are required. In this paper we report a study of the electrical properties of transparent Aluminium or Boron-doped Zinc oxide (AZO or BZO) contacts to moderately doped (n - 3 x 1018 cm-3) N-polar n-GaN for vertical LEDs. These contacts are non-ohmic, displaying leaky Schottky barrier behaviour. However, exposure of the n-GaN surface to a hydrogen or oxygen plasma prior to deposition of the transparent conducting oxide gives ohmic contacts with contact resistances below 2 x 10-5 Ωcm2, which is close to state of the art. The mechanisms by which these contacts are formed has been investigated through the temperature dependence of the contact resistances and XPS measurements of the interfaces. The thermal stability of these contacts has also been investigated up to 250°C. This technique opens the door to creating In-free transparent conducting electrodes for efficient large-area V-LEDs.

MP25

(Student) Linearly Polarized Photoluminescence of c-plane GaN Grown on Stripe-Shaped Cavity-Embedded Al2O3 Membrane on c-plane Sapphire Substrate Jongmyeong Kim, Daeyoung Moon, Seungmin Lee, Jeonghwan Jang, Donghyun Lee, Yongjo Park, Euijoon Yoon; Seoul National University, Korea; Advanced Institutes of Convergence Technology, Korea

Polarized emission of GaN-based devices has attracted great interest due to potential applications in liquid crystal display (LCD) backlight source. If it is possible to inherently generate the polarized emission with high efficiency, it will be beneficial to the improvement in efficiency of LCD. However, c-plane GaN on c-plane sapphire substrate, a typical growth scheme, exhibits unpolarized emission due to isotropic in-plane strain. We realized polarized photoluminescence (PL) of c-plane GaN on c-plane sapphire substrate by using a stripe-shaped cavity-engineered sapphire substrate (SCES), which is expected to induce anisotropic in-plane strain in the GaN grown on SCES. The fabrication process of SCES and GaN growth on SCES were described elsewhere [1]. X-ray reciprocal space mapping experiment revealed the GaN on SCES was under anisotropic strain of -0.023% and -0.196% along the direction perpendicular (-) and parallel (||) to the stripe pattern, respectively. The PL peak shift of -16 meV and 1.6 times higher PL intensity was observed along the direction of E || stripe compared to E-stripe. The experimental results were compared with theoretical value based on k-p perturbation theory. It was found that the anisotropic PL was attributed to anisotro-

pic in-plane strain. In this presentation, mechanism for the anisotropic strain of GaN on SCES and the modification of the band structures will be discussed.

[1] D. Moon et al., J. Cryst. Growth 441, 52 (2016).

MP26

(Student) Bio-inspired light emitting diodes with optimized structuration for high light extraction efficiency

Christophe Rodriguez, Alexandre Mayer, Annick Bay, Abdelatif Jaouad, Nicolas André, Laurent A. Francis, Hassan Maher, Vincent Aimez; UMI-LN2 CNRS 3463 / 3IT, Université de Sherbrooke, Canada; Laboratoire de Physique du Solide, Université de Namur, Belgium; ICTEAM/ELEN, Université catholique de Louvain-UCL, Belgium

Despite their great advantages, GaN based LEDs suffer from a limitation in terms of Light Extraction Efficiency (LEE). The top surface of the conventional LED is planar and a portion of the created light is trapped inside the device due to the reflection at the interface GaN/Air. In the literature, several techniques have been demonstrated to improve the LEE such as induced roughness or microlenses on the top of the LED. We suggest a structuration on the top surface inspired from fireflies. In our previous work, we showed an improvement of the LEE (@425nm) from 3.7% for a planar LED to 5.7% with the non-symmetric pyramidal structuration (factory–roof shape). In this previous study, we patterned a photoresist (AZ9245®) while in the current work we propose to pattern a high refractive index dielectric material instead. Simulations have shown a LEE of 10.5% (@524nm) by patterning a dielectric material with a refractive index of 2.43. The new model has shown that the optimal cross-section for the structuration is a symmetrical pyramid with a period of 4.4µm and a height of 3.5µm. In order to demonstrate experimentally this improvement, we fabricate a classical device emitting at 524nm and add the structuration on the top by patterning 3.5µm of Silicon Nitride (SiN) with a refractive index of 2.43. The SiN with high refractive index is deposited by PECVD and its structuration is achieved by transferring a patterned photoresist (UV-lithography and re-flow technique) by dry etching.

MP27

(Student) Improved light output of AlGaInP-based light emitting diode fabricated with thermally stable NiZn-based ohmic contacts

Dae-Hyun Kim, Tae-Yeon Seong; Department of Nanophotonics, Korea University, Korea; Department of Materials Science and Engineering, Korea University, Korea

High-power AlGaInP-based LEDs, emitting light from red to yellow-green, have various applications such as traffic light lamps, automobile tail lamps, biotherapy, and outdoor displays. In particular, for outdoor display applications, the enhancement of the performance of AlGaInP LEDs is essential. AlGaInP LEDs suffer from severe current crowding because p-AlGaInP layers contain low hole concentrations. To solve the problem, a thick wide-bandgap p-GaP window layer has been used as a current spreading layer (CSL). To maximize the output efficiency of AlGaInP-based LEDs, the formation of low resistance and thermally stable ohmic contacts to the p-GaP CSL is imperative. Thus, in this study, to develop AuBe-free ohmic schemes for AlGaInP-based LEDs, NiZn-based contacts were investigated and their electrical properties were compared with conventional AuBe/Au contacts. It was shown that after annealing at 500 °C, both AuBe/Au and NiZn solid-solution/Ni contacts were degraded, while the NiZn/Ta/Ni contacts were electrically improved. LEDs with the NiZn/Ta/Ni contact exhibited higher output than LEDs with AuBe/Au contact. On the basis of X-ray photoemission spectroscopy and Auger electron spectroscopy, and electrical results, the annealing-induced ohmic contact formation mechanisms are described. Furthermore, the Schottky characteristics of metals to p-GaP are described to understand carrier transport mechanisms.

MP28

(Student) Resistivity of Mg-Doped GaN Grown by MOCVD: Compensation Control

Andrew Klump, Felix Kaess, Pramod Reddy, Biplab Sarkar, Seiji Mita, Ronny Kirste, Ramón Collazo, and Zlatko Sitar; Department of Materials Science and Engineering, North Carolina State University, USA

As the only p-type dopant widely used in gallium nitride devices, magnesium is key for power and optoelectronic applications. However, Mg doping in GaN has many complications when grown by metalorganic chemical vapor deposition. During growth, hydrogen passivates Mg and forms of neutral Mg-H complexes, requiring post-growth dissociation by annealing. At elevated Mg doping concentrations, increased incorporation of other defects leads to overcompensation. Because of these effects, resistivity values at room temperature have been limited to slightly below 2 Ω cm for GaN:Mg grown on sapphire. In this study, two methods are employed during MOCVD growth to reduce compensating point defects. The first is to vary the gallium supersaturation, either by choice of N2 or H2 diluent gas or the group V/III ratio. At elevated V/III ratios and H2 diluent conditions, GaN:Mg shows a reduction in the blue luminescence at 2.8 eV. Which is explained as a reduction in the triply ionized nitrogen vacancies-the main compensators in high Mg doping regime. The second is to illuminate the samples during growth with above bandgap light as a Fermi level point defect control. Secondary ion mass spectrometry reveals a reduction in H incorporation, while not affecting the Mg incorporation. A similar reduction in blue luminescence is also observed. As a result, resistivity values of < 1 Ω cm are demonstrated, showing the importance of limiting of compensating defects in GaN:Mg.

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8:30 *PL2

Prospects and challenges for AlGaN-based deep UV LED technologies Michael Kneissl, J. Enslin, M. Guttmann, C. Kuhn, F. Mehnke, C. Reich, L. Sulmoni, T. Wernicke, J. Jeschke, J. Glaab, S. Hagedorn, A. Knauer, T. Kolbe, M. Lapeyrade, N. Lobo-Ploch, C. Netzel, J. Raß, C. Stölmacker, U. Zeimer, S. Einfeldt, M. Weyers; Institute of Solid State Physics, TU Berlin, Germany; Ferdinand-Braun-Institut, Germany

Light emitting diodes in the deep UV spectral range (UV-LEDs) are of great interest for the realization of compact and highly sensitive optical sensors, e.g. for the detection of toxic gases, multi-drug-resistant germs, and the monitoring of medical conditions. [1]. For example, many organic compounds, like tryptophan as well as number of gas molecules, like ammonia and NO, exhibit distinct absorption bands in the UVC (280nm – 200nm) wavelength region [2]. This presentation will provide an overview of recent advances in the development of deep UV-LEDs including metalorganic vapor phase epitaxy of low defect density AlN layers on sapphire substrates by epitaxial lateral overgrowth (ELO). We will also investigate the limits of Si-doping of AlGaN alloys over the entire aluminium composition range including systematic studies of Si activation energies and the formation of DX centers. We will present efficient carrier injection into UVC-LEDs based on Mg-doped AlGaN electron blocking heterostructures and explore how the optical polarization of light emission from deep UV-LEDs can be controlled by the AlGaN quantum well design and strain. Finally, we will demonstrate AlGaN multiple quantum well LEDs emitting near 230 nm and illustrate how these UV-LEDs are being already successfully applied for NO gas sensing.

1] M. Kneissl, J. Rass (Eds.), “III-Nitride Ultraviolet Emitters - Technology & Applications” (Series on Material Science, Vol. 227), Springer (2016).

9:15 *Tu2.1

Development of mid UV laser diodes Ronny Kirste, Biplab Sarkar, Seiji Mita, Alexander Franke, Pramod Reddy, Qiang Guo, Zachary Bryan, Isaac Bryan, James Tweedie, Ramon Collazo, Zlatko Sitar; Adroit Materials, NCSU

Design and fabrication of AlGaN based laser diodes is the most promising pathway for next generation UV lasers. Challenges for these devices include low n- and p-conductivity, absorbing injection layers, and non-ohmic contacts. Here, we present recent advances in the growth and fabrication of UV laser diodes. As advancement over existing approaches, we pursue the growth on single crystalline AlN substrates. Any such device fabrication starts with the growth of an AlN homoepitaxial layer. It is demonstrated that this epitaxial layer can be grown with a dislocation density that follows that of the substrate. Subsequent growth of AlGaN layers with Al content ranging 50-85% is shown to be pseudomorphic. MQWs for emission at wavelengths ranging 240-300 nm are discussed and optically pumped lasing is demonstrated. In order to achieve electrically injected UV lasing, Al-rich AlGaN is doped and free electron concentrations for the n-cladding with 80% Al-content is shown to be around 8x1018 cm-3. In contrast, p-doping of AlGaN is much more challenging because of the high activation energy of the Mg acceptor. Consequently, free hole concentration and conductivity of the p-cladding are low. Experimental work is supported by simulations and used to direct the UV laser design. Finally, we present electrical data and electroluminescence spectra from fabricated diodes and discuss the challenges that need to be addressed to demonstrate the first electrically injected UV laser diode.

9:15 *Tu3.1

Fabrication of GaN Nano-LED Devices by Nanoimprint Lithography Rong Zhang, Bin Liu, Tao Tao, Zhe Zhuang, Ting Zhi, Zili Xie, Peng Chen, Yugang Zhou, Dunjun Chen, Hai Lu, Youdou Zheng; Nanjing University

Using nano-structure is an important way to promote the efficiency of light emitting diodes (LEDs). In this talk, we will demonstrate several novel GaN-based nanostructured LED devices. Highly ordered InGaN/GaN nanorod, nanohole, and nano-grating structures on a wafer scale can be fabricated by UV-soft nanoimprint lithography(NIL), top-down dry etching. By means of nano-fabrication, blue and green nanorod array LEDs have been also obtained. Besides, a single nanorod green InGaN/GaN LED with extremely small illumination size (0.3 μm × 0.2 μm) and low leakage current has been developed. It also shows polarized electroluminescence emission with a considerable linear polarization degree of ~50% parallel to c axis. We developed hybrid III-nitride/nanocrystal nanohole LEDs utilizing efficient nonradiative resonant energy transfer (NRET) between violet/blue emitting InGaN/GaN multiple quantum wells (MQWs) and various wavelength emitting nanocrystals (NCs) as color conversion mediums, which exhibit high efficiency, good color rendering indexs(CRI), and suppressed droop effect.

9:45 Tu2.2

Acceleration voltage dependence of threshold power density in AlGaN/GaN based electron beam pumped laser Motoaki Iwaya, Takafumi Hayash, Noriaki Nagata, Takashi Senga, Sho Iwayama, Tetsuya Takeuchi, Satoshi Kamiyama, Isamu Akasaki, Takahiro Matsumoto; Meijo University; Akasaki Research Center, Nagoya University; Graduate School of Pharmaceutical Sciences, Nagoya City University

AlGaN-based UV lasers have a great potential in the fields of laser processing especially surface processing, medical, biotechnology and so on. However it is difficult to realize the current injection in deep UV laser because it is difficult to obtain high hole concentration p-AlGaN with high AlN molar fraction at RT. Therefore, one promising technique is the electron beam excitation AlGaN-based UV lasers. We reported that GaN/AlGaN based electron beam pumped laser, but detailed characteristics and mechanism are unclear. In this study, we investigated the acceleration voltage dependence of threshold power density in AlGaN-based electron beam pumped laser. After growth of a 500-nm-thick GaN layer on GaN substrate, a 500-nm-thick Al0.15Ga0.85N cladding layer, a 100-nm-thick Al0.07Ga0.93N guide layer, GaN (3nm)/Al0.07Ga0.93N (12nm) 10QW active layer, a 100-nm-thick Al0.07Ga0.93N, and a 100-nm-thick Al0.15Ga0.85N cladding layer were stacked in that order. The cavity length of the laser was ~50 μm. We investigated the dependence of the integrated light intensity on the excitation power density with different acceleration voltages. Despite measuring the same sample, we found clearly difference in the threshold power density required for laser oscillation. Also, the threshold excitation power density was minimized at 20 kV. This result almost matched with the simulation result. The threshold power density and wavelength were ~ 160 kW/cm2 and 352.8 nm, respectively.

9:45 Tu3.2

Top-Down Etching of Three-Dimensional, High Aspect Ratio GaN Nanostructures George T. Wang, Benjamin Leung, Miao-Chan Tsai, Changyi Li, Ganesh Balakrishnan; Sandia National Laboratories; University of New Mexico

Chemical etch processes for GaN materials and devices are significantly underdeveloped due to its apparent inertness to common wet etchants. Here, we explore the etch characteristics of GaN using the general geometric principles of crystallographic dissolution processes to enable the prediction of facet-determined etch structures. Significant etch rates albeit with extremely high crystallographic anisotropy are observed in KOH-based etchants. Fabricating novel GaN based devices requires understanding the consequences of this extremely high etch rate anisotropy for the resulting etch geometries. For silicon, full knowledge of orientation-dependent etch rates and geometry evolution has enabled design of silicon MEMS structures. Here, we use the same framework (Wulff-Jaccodine method) for understanding and predicting the geometry of the facet evolution and final structure, and apply it to GaN. We perform the first complete orientation-dependent etch rate measurements, clearly showing fast a-plane etch rate relative to m-plane, and use them to predict the faceting of pillar structures with good agreement with experiment. Finally, we use these developments in GaN wet etching to go beyond the current paradigm of bottom-up grown hexagonal nanowires to fabricate functional optical nanowire and microcavity structures with controlled three-dimensional cross-sectional shapes, where faceting enables smooth sidewalls for a high-quality cavity structure.

10:30 **Tu4.1

MBE-grown High Temperature AlN Epitaxy on Single Crystal AlN Substrate for Deep UV Photonics Kevin Lee, SM Islam, Shyam Bharadwaj, Huili Grace Xing, Debdeep Jena; Cornell University, USA

Deep UV photonics (sub-280 nm LEDs) based on nitride semiconductors is popular recently due to applications in disinfection, security, food-preservation etc. These devices are usually grown on non-native template substrates such as AlN on Sapphire with a threading dislocation density (TDD) of ~10^10 cm-2. High TDD degrades the internal quantum efficiency of photonic devices. Recently, low TDD (~10^4 cm-2) native bulk AlN substrates have been developed. Epitaxial growth of AlN on such bulk substrates is therefore of fundamental interest for high efficiency LEDs. We have performed high temperature (>900oC) AlN epitaxy on bulk AlN substrates using plasma-assisted MBE. The high growth temperature ensures good nucleation and subsequent AlN growth with few extended dislocations and defects. The growth conditions have been optimized on both bulk single crystals and AlN on Sapphire templates for comparison. Two different growth rates, 300 nm/hr and 600 nm/hr, were investigated. A 300 nm AlN layer grown on a bulk crystal exhibited atomic steps and smooth surface (0.18 nm RMS roughness over 2X2 μm2). 500 nm AlN films grown on AlN templates are rougher (~0.5 nm RMS roughness over 2X2μm2). X-ray diffraction based rocking curve analysis shows a FWHM of ~10 arcsec along the (002) and (012) directions for epitaxial AlN films on bulk crystals. Further structural characterization and defect analysis using transmission electron microscopy is under investigation.

10:30 *Tu.5.1

Highly Efficient Classical and Quantum Emitters Based on Nitride Semiconductor Nanostructures Yong-Hoon Cho; Department of Physics and KI for the NanoCentury, Korea; Advanced Institute of Science and Technology (KAIST)

Group III-nitride semiconductor nanostructures have attracted a lot of attention owing to their their versatile classical and quantum photonic applications. Here, we present nitride-based quantum structures grown on various three-dimensional nano- and micro-structures as a template. First, we demonstrated phosphor-less white light emitting diodes (LEDs) based on three-dimensional GaN structures. The annular and double concentric truncated pyramidal LEDs provide broad-band, white light genera-

tion from the QWs formed on various planes. Second, we demonstrated the self-aligned deterministic coupling of single quantum dot (QD) to nanofocused plasmonic modes, showing strong spontaneous emission enhancement as high as ~ 22 of QDs over a wide spectral range. Third, we found that the majority of the extracted light from single QD is guided toward the bottom of the pyramid with high directionality. Nano-pyramidal structures were detached from a substrate and the far-field radiation pattern was measured using Fourier microscopy. This approach overcomes the major hurdles in the implementation of practical solid-state quantum devices and shows great promise for versatile applications including quantum cryptography, quantum logic gates, integrated on-chip nano-emitters, and energy-harvesting devices.

10:45 **Tu4.2

Fabrication of highly oriented c-plane AlN buffer layer by metalorganic vapor phase epitaxy on nucleation layer deposited by sputtering Ryo Yoshizawa, Hideto Miyake, Kazumasa Hiramatsu; Department of Electrical and Electronic Engineering. Mie University, Japan; Graduate School of Reginal Innovation Studies, Mie University, Japan

To obtain low-dislocation-density c-plane AlN on sapphire, we have studied the annealing of AlN films at 1700 oC. The orientation of AlN films is important because the AlN grains are grown by a solid-phase reaction based on c-plane rotation. Hence, we fabricated a highly oriented c-plane AlN layer by metalorganic vapor phase epitaxy (MOVPE) using a nucleation AlN layer deposited on sapphire by sputtering. We prepared an AlN film with a thickness of 20 nm by radio-frequency (RF) sputtering, on which an AlN epilayer with a thickness of 280 nm was grown by MOVPE at a different growth temperature. Finally, the AlN layer on sapphire was annealed in N2 at 1700 oC using a face-to-face setup. The full widths at half maximum (FWHM) of the X-ray rocking curves (XRCs) for AlN(0002) were approximately 50 arcsec for all samples, whereas those for AlN(10-12) significantly decreased from 6500 to 350 arcsec after thermal annealing. A surface morphology with atomic steps and a terrace structure was clearly obtained after thermal annealing. From these results, we concluded that a high-quality AlN layer can be obtained by annealing of AlN on sapphire grown by MOVPE on a highly oriented c-plane AlN nucleation layer deposited by sputtering.

11:00 *Tu4.3

Development of bulk AlN substrates for deep-UV optoelectronic devices by HVPE method Yoshinao Kumagai, Rie Togashi, Toru Nagashima, Toru Kinoshita, Reo Yamamoto1,3, Rafael Dalmau, Raoul Schlesser, Hisashi Murakami, Ramón Collazo, Akinori Koukitu, Bo Monemar, and Zlatko Sitar; Department of Applied Chemistry, Tokyo University of Agriculture and Technology, Japan; Institute of Global Innovation Research, Tokyo University of Agriculture and Technology, Japan; Tsukuba Research Laboratories, Tokuyama Corporation, Japan; HexaTech, Inc., USA; Department of Materials Science and Engineering, North Carolina State University, USA; Department of Physics, Chemistry and Biology (IFM), Linköping University, Sweden

AlN substrates with low dislocation densities and deep-UV transparency are needed for production of deep-UV LEDs. We have developed such AlN substrates by hydride vapor phase epitaxy (HVPE) using starting AlN substrates prepared by physical vapor transport (PVT). HVPE growth of AlN, properties of the prepared HVPE-AlN substrates, and performance of deep-UV LEDs fabricated on the HVPE-AlN substrates will be presented. Thick AlN layers were grown at 1450 ºC on PVT-AlN substrates (dislocation density < 1E4 cm^-2) using an atmospheric-pressure HVPE system. AlCl3 and NH3 source gases were supplied onto the PVT-AlN substrate placed on a heating susceptor using a carrier gas (H2/N2 = 7/3). Owing to the high structural quality of the PVT-AlN substrates, the HVPE-AlN substrates prepared from thick AlN layers grown at a growth rate of 25 μm/h were found to possess high structural quality. Furthermore, the HVPE-AlN substrates showed deep-UV transparency with an optical transmission cutoff at 206.5 nm due to low impurity concentration of carbon [1]. An emission peaking at around 265 nm from deep-UV LEDs fabricated on the HVPE-AlN substrates could be extracted through the HVPE-AlN substrates [2]. This work was partly supported by JSPS KAKENHI Grant Number 15H03555.

[1] Kumagai et al., Appl. Phys. Express 5 (2012) 055504, [2] Kinoshita et al., Appl. Phys. Express 6 (2013) 092103.

11:00 Tu5.2

Bottom-up InGaN Nanowire Photonic Crystal Structures Yong-Ho Ra, Roksana Rashid, Ishiang Shih, Zetian Mi; Department of Electrical and Computer Engineering, McGill University, Canada; Department of Electrical Engineering and Computer Science, University of Michigan, USA

Highly stable and efficient LEDs are essentially required for a broad range of applications. While GaN-based LEDs exhibit efficient operation in the blue range, their efficiency and stability degrades considerably with increasing wavelengths due to polarization fields and defects. Internal quantum efficiency can be potentially enhanced by modifying the optical density of states via Purcell effect. Such photonic crystal (PhC) structure also allows for the efficient extraction of the guided modes. Bottom-up nanowire structures provide inherent advantages compared to the top-down method. In this context, we have investigated

the epitaxy and optical performance of bottom-up InGaN nanowire PhC structures fabricated by selective area epitaxy using PAMBE. We have demonstrated two unique properties of InGaN nanowire PhC structures for LED operation, including extremely stable operation vs. temperature and excitation power and scalable optical mode confinement. PhC arrays exhibit significantly enhanced light intensity (~505 nm) and narrow spectral linewidth (~ 12 nm). It is measured that the emission properties, including both the spectral linewidth and wavelengths remained virtually unchanged in various temperature range and under various excitation densities, suggesting the elimination of heating and QCSE effects. Detailed spectrally resolved CL mapping studies further suggest that the confined optical modes are scalable in InGaN nanowire PhC arrays for large area LED application.

11:15 Tu5.3

Electro-Optical Characterization of Selectively-Grown GaN/InGaN Core-Shell Nanowire LEDs Mohsen Nami, Isaac E. Stricklin, Ashwin K. Rishinaramangalam, Steve R. J. Brueck, Igal Brener, and Daniel F. Feezell; Center for High Technology Materials University of New Mexico, USA; Center for Integrated Nanotechnologies Sandia National Laboratories, USA

III-nitride based light-emitting-diodes (LEDs) suffer from reduced external quantum efficiency at longer wavelengths (green gap) and high current densities (efficiency droop). This motivates work on more energy efficient LED structures for solid-state lighting. GaN/InGaN core-shell nanowire LEDs are promising candidates to mitigate efficiency droop due to their large active region surface area. Nanowire LEDs also offer an approach to monolithically integrated RGB-based white LEDs by simply modifying the growth template. Bottom-up selective-area epitaxy using a dielectric growth mask and metal-organic chemical vapor deposition (MOCVD) on c-plane sapphire substrates can be used to realize core-shell nanostructure GaN/InGaN LEDs with nonpolar m-plane InGaN active regions on the sidewalls. This approach provides access to polarization-free active regions on inexpensive c-plane sapphire substrates. In this work, GaN nanowire cores with diameter of 600 nm and height of 1.2 μm were grown using pulsed-mode MOCVD. Four pairs of InGaN/GaN quantum wells were then grown around the cores, followed 150 nm of p-GaN, using conventional continuous MOCVD growth. We will present the light and voltage versus current density (L-J-V), electroluminescence (EL) spectra, peak EL wavelength and full-width at half maximum (FWHM) at different current densities, internal quantum efficiency, room temperature and low temperature carrier lifetimes, and small-signal RF characterization for the nanowires.

11:30 Tu4.4

High-quality AlN grown on nano-patterned sapphire substrates prepared by nano-imprint lithography Fujun Xu, Lisheng Zhang, Mingxing Wang,Nan Xie, Zhixin Qin, Xinqiang Wang, and Bo Shen; State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, China

Generally, the surface morphology and defect density of AlN template have a crucial influence on the crystalline quality of AlGaN and upper active layer in deep ultraviolet (DUV) devices. Therefore, it is essential to obtain AlN template with flat surface and low threading dislocation density. In this work, high-quality AlN grown on nano-patterned sapphire substrates (NPSS) has been investigated. The crystalline quality of AlN was greatly improved by using the optimized NPSS. The X-ray diffraction omega-scan full width at half maximum (FWHM) values for (002) and (102) reflections of AlN are 79 and 206 arcsec, respectively. The optimized NPSS contributes to eliminate almost entirely the threading dislocations (TDs) originating from the AlN/sapphire interface via bending the dislocations by image force from the void sidewalls before coalescence. In addition, reducing the misorientations of the adjacent regions during coalescence adopting the low lateral growth rate is also essential for decreasing TDs in the upper AlN epilayer.

11:30 *Tu5.4

InGaN/(Al)GaN-based nanocolumn (NC) arrays and their light-emitter applications Katsumi Kishino, Jun Yoshida, Yuzo Matsui, Takao Oto, K. Kikushi, and Kai Motoyama; Department of Engineering and Applied Sciences, Sophia University, Japan; Sophia Nanotechnology Research Center, Sophia University, Japan

The selective area growth (SAG) of InGaN/(Al)GaN-based nanocolumns (NC) arrays were performed on GaN templates, Si, and Graphene/SiO2 substrates [1-3], fabricating visible light-emitting diodes [4–7]. The periodic arrangement of NCs led the photonic crystal (PC) effect, which provided optically excited lasing operations of NC arrays [8-10] and a high directional beam radiation from NC LEDs [7]. A novel arrangement of nanocolumns, cluster array of NC-PCs has been presented, where clustered neighboring 3 to 7 thin NCs are arranged in triangular lattice. At the same time, regularly arranged InGaN/GaN/AlGaN heterojunction NCs have been prepared, where the optical waveguide was integrated in the NC system, enhancing the NC-PC effect. And the deposition of Au film on the side surface of periodically arranged InGaN NCs has enhanced 5.2 times the emission intensity at 600 nm through the surface plasmonic effect.

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et al., Appl. Phys. Express 7 (2014) 112102. [7] H. Hayashi et al., Photonic. Tech. Lett. 27 (2015) 2343. [8] T. Kouno et al., Optics Express 17 (2009) 20440. [9] S. Ishizawa et al., Appl. Phys. Express 4 (2011) 055001. [10] K. Kishino et al., Appl. Phys. Lett. 109, (2016) 071106.

11:45 Tu 4.5

Improved internal quantum efficiencies of deep-ultraviolet LEDs using a low-defect-density template technique Dong-Sing Wuu, Tzu-Yu Wang, Guan-Wei Fu, Ching-Ho Tien, Ray-Hua Horng; National Chung Hsing University, Taiwan

In this study, we demonstrate a 2.6 μm-thick AlN epilayer as a low-defect-density template where the AlN superlattices structure with alternation of high (100) and low (25) V/III ratios was grown on a nano-patterned sapphire substrate (NPSS) under a low growth temperature (1130oC). The NPSS exhibited a funnel-shape pattern with the diameter of 700 nm and hole depth of 250 nm. From the X-ray diffraction measurement, the full width at half maximum value of (102) in AlN/NPSS showed a dramatic decrease from 1640 arcsec to 714 arcsec than AlN layer grown on flat sapphire. The transmission electron microscopy analysis was utilized to understand the dislocation behavior of AlN epilayer. From the bright field cross-sectional TEM images, the key holes were formed in AlN epilayer upon NPSS with hole regions. It can notable that only few dislocations propagated to layer surface owing to most dislocations obstructed by the key holes. The dislocation density was estimated about 1×108 cm-2. Finally, the 7-pairs Al0.5Ga0.5N/Al0.6Ga0.4N multi-quantum-wells (MQWs) structure with wavelength of 260 nm was prepared on Al0.6Ga0.4N/AlN/NPSS. From photoluminescence (PL) measurement, the internal quantum efficiency of the MQWs was about 50% from the ratio of intrgrated PL intensity at 300K and 10K (I 300K/I 10K). Details of the feasibility and improved quantum efficiencies of deep-ultraviolet LEDs on this template will be described.

13:30 Tu6.1

The role of surface kinetics on AlN and Al-rich AlGaN Seiji Mita, Isaac Bryan, Zachary Bryan, Shun Washiyama, Ronny Kirste, Anthony Rice, Lindsay Hussey, James Tweedie, Ramón Collazo, Zlatko Sitar; Adroit Materials, Inc.; North Carolina State University

AlN based AlGaN technology offers a great potential as materials for deep UV optoelectronic and high-power electronic devices. In order to realize such devices, high quality epitaxial films with controlled surface morphology are necessary. We have developed a surface kinetic framework for the control of surface morphology of AlN epitaxial thin films grown on both vicinal (0001)-oriented native single crystal AlN substrates and AlN templates grown on vicinal (0001)-oriented sapphire. A Burton, Cabrera, and Frank theory-based model is utilized to understand the dependence of the surface kinetics on the vapor supersaturation and substrate misorientation angle. The critical misorientation angle for the onset of step-bunching was determined to be ~0.2° for a growth rate of 500 nm/h and temperature of 1250 °C. Transitioning from a surface with 2D nuclei to one with bilayer steps required an increase in the vapor supersaturation or a decrease in substrate misorientation angle, whereas the suppression of step-bunching required a decrease in the vapor supersaturation or an increase in substrate misorientation angle. We extended the same framework of surface kinetic model in AlN growth to the case of Al-rich AlGaN growth. The composition of bilayer stepped AlGaN was uniformed, while step-bunching resulted in strong compositional inhomogeneity as observed by Z-contrast STEM. These results demonstrate a control scheme for consistently obtaining smooth Al-rich AlGaN epitaxial thin films.

13:30 *Tu7.1

III-Nitride LEDs and Laser Diodes Grown on Si Qian Sun; Key Laboratory of Nano-devices and Applications, Chinese Academy of Sciences (CAS), China; Suzhou Institute of Nano-Tech and Nano-Bionics (SINANO), Chinese Academy of Sciences (CAS), China; Lattice Power Corporation, China

There is a great potential in cost reduction for light emitting devices by epitaxially integrating III-Nitride semiconductors on large diameter Si. However, hetero-epitaxial growth of Ga(Al)N on Si encounters a large mismatch in both lattice constant and coefficient of thermal expansion, often resulting in a high density of defects and even micro-crack networks. By carefully engineering Al-composition step-graded AlN/AlGaN multilayer buffer between Si and GaN, we have not only successfully eliminated the crack formation, but also significantly reduced dislocation density. This talk presents the R&D progress of Ga(Al)N-on-Si blue/UVA LEDs and blue/violet laser diodes. Upon the Ga(Al)N-on-Si template, InGaN/AlGaN UVA multiple quantum well (MQW) active region is overgrown and caped by p-AlGaN electron blocking layer and a thin p-GaN cap-layer, which are processed into vertical structure UVA LEDs. Besides blue and UVA LEDs, we have achieved continuous-wave electrically injected blue/violet InGaN-based laser diodes with a ridge structure on Si at room temperature. In addition, InGaN-based electrically injected microdisk lasers have also been realized on Si. GaN-based laser could be a useful alternative on-chip light source for monolithically integrated Si photonics.

13:45 Tu6.2

Low temperature epitaxial growth of AlGaN/GaN hetero-junctions on sapphire substrates Dimiter Alexandrov, Jonny Tot, Robert Deubroil; Lakehead University, Low temperature epitaxial growths of AlGaN/GaN hetero-junctions

were performed by MOCVD techniques with TMGa and TMAl precursors and nitrogen DC plasma in a direct exposure configuration. The traditional continuous precursor flow in MOCVD has been modified to separately introduce each precursor to the chamber, allowing increased lateral migration of adatoms and reduced vapour phase parasitics. The growth temperatures were chosen to be 540°C for all samples. Each growth consists of two parts – growth of GaN layer and its characterization and subsequent growth of AlGaN layer and characterization of the entire hetero-structure. For the GaN (002) layers XRD measurements show variation of FWHM's in interval 0.18–0.27 degrees and the positions of the XRD peaks vary in range 34.67–34.83 degrees. For the AlGaN (002) layers XRD measurements show variation of FWHM's in interval 0.24–0.38 degrees and the positions of the XRD peaks vary in range 35.21-35.38 degrees. It was found significant heights of the XRD peaks for different samples for the layer thicknesses that are 187-230 nm for GaN layers and 151-170 nm for AlGaN layers. SEM measurements show uniform GaN layers and uniform AlGaN layers. EDX measurements were used to determine the presence and the amounts of aluminum, gallium and nitrogen throughout the structure. It was found that the hetero-junctions are sharp and that the developed technology can have further applications in HEMT and in UV Light Emitting Sources technologies.

14:00 *Tu6.3

Enhanced light extraction from AlGaN-based deep-ultraviolet light-emitting diodes Jong Kyu Kim, Jong Won Lee, Dong Yeong Kim, Gabisa Bekele Fayisa; Department of Materials Science and Engineering POSTECH

AlGaN-based deep ultraviolet (DUV) light-emitting diodes (LEDs) are being developed for their numerous applications, however, their external quantum efficiency (EQE) remains very poor particularly due to low hole concentration and light extraction efficiency (LEE). Conventional LEE-enhancing techniques used for GaInN-based visible LEDs turned out to be ineffective for DUV LEDs due to a strong absorption of DUV light by p-GaN contact layer, and ii) predominant transverse-magnetic (TM) polarized anisotropic emission from Al-rich AlGaN multi-quantum well (MQW) active region grown on c-plane sapphire substrate. Therefore, a new LEE-enhancing approach addressing the unique intrinsic property of AlGaN DUV LEDs is strongly desired. In this study, we present DUV LEDs having various arrays of mesa structures including stripes, truncated cones, and micro-rings with inclined sidewalls covered by MgF2/Al omni-directional mirrors. These sidewall-emission-enhanced DUV LED breaks through the fundamental limitations caused by the intrinsic properties of AlGaN, thus shows a remarkable improvement in light extraction as well as operating voltage simultaneously. Furthermore, an analytic model is developed to understand and precisely estimate the extraction of DUV photons from AlGaN DUV LEDs, and hence to provide promising routes to maximize the power conversion efficiency.

14:00 Tu7.2

High Efficiency Semipolar InGaN Lasers for Solid State Lighting Daniel L. Becerra, Daniel Cohen, Shlomo Mehari, Kareem Hamdy, Tal Margalith, Steven DenBaars, and Shuji Nakamura; Materials Department, University of California Santa Barbara, USA; Department of Electrical and Computer Engineering, University of California Santa Barbara, USA

Solid state lighting using InGaN laser diodes (LDs) is gaining popularity due to the ability of LDs to operate at high current densities and provide high brightness while maintaining a very low beam divergence and small chip size. However, the wall plug efficiency (WPE) of InGaN LDs remains lower than that of InGaN LEDs. We present here work towards improving the WPE of InGaN LDs using the semipolar (20-2-1) plane. We have previously reported improvements to threshold current and differential efficiency after developing a 2 quantum well active region and chemically assisted ion beam etching (CAIBE) for the formation of mirror facets, but the operating voltage remained high. New LDs with reduced voltage at high current will be presented in this work. The decrease in voltage was accomplished by the reduction of impurities in the LD growth, optimization of the metal to p-GaN contact, and moving to wider LD ridges (8-15 μm). These changes enabled continuous-wave (CW) operating voltages of 6.5 V at 3 A compared with 10 V at 1 A reported in our prior work. Advances in thermal management will also be shown which lead to high power CW operation. Further work includes further optimization of the active region and reduction of internal loss for improved differential efficiency.

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14:15 Tu7.3

Unexpected behavior of light emission in nitride based devices under hydrostatic pressure Tadek Suski, P. Wisniewski, K. Pieniak, G. Staszczak, S. Grzanka, A. Kafar, S. Stanczyk, D. Schiavon, A. Bercha, W. Trzeciakowski and P. Perlin; Institute of High Pressure Physics UNIPRESS, Institute of High Pressure Physics UNIPRESS and TopGaN

Light emitters with InGaN/GaN QWs grown along the polar c-direction operate often in the strong electric field, FTot, consisting of built-in and p-n junction related contributions. Applied driving current, ID, introduces carriers to the active region of the devices which causes a screening of FTot.

Resulting magnitude of the Quantum Confined Stark Effect is not well understood, e.g., we observe that with increasing ID in LEDs, LDs and superluminescent diodes the emission energy EEL increases non-monotonically. Significant rise is observed at low ID and with increasing of ID a tendency to saturation of EEL occurs. We applied hydrostatic pressure to examine the microscopic mechanisms responsible for such behavior. We found that pressure shift dEEL/dp shows analogous tendency as the evolution of EEL versus ID, i.e: a strong increase of dEEL/dp at low ID and saturation at high Id towards the bandgap value of dEG/dp. In nitride LDs, pressure evolution of lasing energy, dEL/dp stabilizes after approaching lasing threshold due to clamping of carrier density. The above findings for nitride emitters are in contrast to cubic arsenides where in LEDs and LDs, dEEL/dp and dEL/dp show always evolution corresponding to pressure variation of their QW band gap. We discuss the above described effects characteristic for nitride emitters in terms of the QCSE screening and the band-tail filling effect. We acknowledge support from the Polish National Scientific Center Grant 2013/11/B/04263.

[1] Jinwan Kim, Jaedo Pyeon, Minhwan Jeon, and Okhyun Nam. Jpn. J. Appl. Phys. 54, 081001 (2015)
[2] Comparison of UVC LEDs with polarization doped and conventional EBLs by electroluminescence measurement. (not published)

14:30 **Tu6.4

245 nm Electroluminescence from an MBE grown GaN/AlN Deep-UV LED on a Bulk AlN substrate Shyam Bharadwaj, SM Islam, Kevin Lee, Vladimir Protasenko, Huili (Grace) Xing, and Debdeep Jena; Cornell University, USA

Deep UV LEDs are used for UV curing, imaging, water purification, and sterilization. For sterilization and water purification, UV-C emission (sub-280 nm) is ideal due to strong absorbance by pathogenic DNA in this regime. In this work, we demonstrate 245 nm electroluminescence from an LED grown on bulk AlN substrates with a low threading dislocation density (TDD) of ~1x10^4/cm^2. This emission is produced by 4 periods of 2 monolayer GaN quantum discs separated by 2.5 nm AlN barriers. Both impurity based doping (Si as the donor, Mg as the acceptor) and polarization-induced doping via compositional AlGaN grading are applied for enhanced carrier concentrations in the LED injection regions. TEM analysis confirms desired structural growth of the sample. 100x100 μm^2 mesas were fabricated to perform electrical and optical characterization. A control sample was grown on an AlN template on sapphire substrate (TDD ~1x10^10 cm^-2) to evaluate the effects of bulk substrates on device performance. Both samples were co-loaded in the MBE system to ensure structural consistency. Strong EL at 245 nm was observed from both samples, with a narrower FWHM (11 nm vs 14 nm) and higher current rectification (suggesting lower leakage) from the sample grown on bulk AlN. A comparison of external quantum efficiency and angle resolved polarization measurements of emission are under investigation for further assessment of the advantages afforded by high quality bulk AlN substrates.

14:30 *Tu7.4

Semipolar InGaN optical devices on patterned Si substrates Maki Kushimoto, Takafumi Suzuki, Daiki Ito, Yoshio Honda, and Hiroshi Amano; Graduate School of Engineering, Nagoya University, Japan; Center for Integrated Research of Future Electronics (CIRFE), Institute of Materials and Systems for Sustainability (IMaSS), Japan; Akasaki Research Center, Nagoya University, Japan

Si has an advantage over the other materials in that its wafer can be obtained in large sizes at a relatively low cost. In addition, GaN on Si is capable of monolithic integration of optoelectronic devices with ICs. In recent times, stimulated emissions by optical pumping and current injection LDs have been reported. However, the LDs were grown on Si(111); hence, it is difficult to integrate them with conventional ICs on Si (001). In this study, a combination of Si micromachining technology with selective-area MOVPE was used to grow semipolar GaN(1-101) on Si(001). In the c-plane, emission efficiency was suppressed owing to QCSE. This effect, which is pronounced on the high-Indium-content InGaN active layer, hinders the fabrication of long-wavelength LEDs and LDs with good temperature characteristics for an RGB light source as well as light sources for visible light communications. The effect can be reduced by inclining the crystal plane of GaN. Additionally, it is possible to increase the growth temperature and, grow high-quality crystals by selecting an appropriate crystal plane. By using GaN(1-101) on Si(001), lasing via photoexcitation was observed in this study. In addition, successful growth of high-In-content InGaN using a relaxation mechanism in a semipolar plane was reported; and this may be applicable for a full nitride semiconductor RGB light source. This research is supported by “Knowledge Hub Aichi”, Priority Research Project from Aichi Prefectural Government.

14:45 **Tu6.5

Reflective Metal/Semiconductor Tunnel Junctions for AlGaN UV LEDs Yuewei Zhang, Sriram Krishnamoorthy, Fatih Akyol, Zane Jamal-Eddine, Jared M. Johnson, Andrew Allerman, Michael W. Moseley, Andrew Armstrong, Jinwoo Hwang, and Siddharth Rajan; Department of Electrical and Computer Engineering, Ohio State University, USA; Department of Materials Science and Engineering, Ohio State University, USA; Sandia National Laboratories, USA

III-Nitride UV LEDs currently have poor efficiency due to light absorption losses in the p-type contact layers. In this work, we demonstrate a novel tunnel junction structure

based on hole injection from metal into wide band gap p-AlGaN using polarization engineering. We show that UV-reflective Aluminum layers can be directly used to form p-type contact.

Devices were grown by plasma assisted molecular beam epitaxy. The UV LEDs contain three periods of 2.5 nm Al0.2Ga0.8N quantum wells, 50 nm p-AlGaN, and 4 nm unintentionally doped In0.25Ga0.75N capping layer. The high polarization sheet charge at AlGaN/InGaN interface leads to the formation of abrupt metal/semiconductor tunnel junction.

Devices with different top metal stacks were compared. The device with Al-based top contact showed higher output power because of high reflectivity to UV light as compared to the device with Ni-based top contact. Efficient tunneling hole injection was confirmed by light emission at 326 nm with on-wafer peak EQE and WPE of 2.65% and 1.55%, respectively. A high power density of 83.7 W/cm2 was measured at 1200 A/cm2. The metal/semiconductor tunnel junction structure could provide significant advantages for efficient and manufacturable device topologies for high power UV emitters.

15:00 Tu6.6

Deep ultraviolet light emitting diodes using polarization doped p-AlxGa1-xN/AlyGa1-yN superlattice structures Jinwan Kim, Byeongchan So, Taemyung Kwak, Eunyoung Shin, Taeyoung Kim, and Okhyun Nam; CANS (Convergence Center for Advanced Nano Semiconductor), Department of Nano-optical engineering, Korea Polytechnic University

Light emitting diodes (LEDs) with short emission wavelength in the range of 200-320nm have been demonstrated to be promising for applications in environmental purification. Because AlGaN has direct band gaps between 3.4 and 6.2eV, Al-rich AlGaN alloys are prime candidate for realization of UVC LEDs. In this paper, we report on growth of high efficiency AlGaN based UVC LEDs using high temperature metal organic chemical vapor deposition (HT-MOCVD). The structures of grown UVC LEDs are same but p-electron blocking layers (EBLs). To enhance doping efficiency and injection rate of hole into multiple quantum wells (MQWs), graded AlxGa1-xN/AlyGa1-yN superlattice structures (SLs) were inserted as EBLs. According to the results from electroluminescence(EL), the emission intensity of wavelength about 275nm from UVC LED with graded EBL increased about factor of 2 compared to the single p-AlGaN EBL inserted sample. In order to obtain further increased light output power from the UVC LEDs, we applied both SLs as conventional multiple quantum barriers (MQBs) and combinative structure of graded p-AlGaN and p-AlxGa1-xN/AlyGa1-yN SLs as EBL.

Numerical calculation and electrical characterization are being conducted. Detailed will be shown in the conference.

[1] Jinwan Kim, Jaedo Pyeon, Minhwan Jeon, and Okhyun Nam. Jpn. J. Appl. Phys. 54, 081001 (2015)
[2] Comparison of UVC LEDs with polarization doped and conventional EBLs by electroluminescence measurement. (not published)

15:00 *Tu7.5

Interplay of carrier transport and radiative lifetime in vertical III-Nitride laser structures Gregory A. Garrett; U.S. Army Research Laboratory, USA

For wide band gap materials in the ultraviolet, an intrinsically short radiative lifetime benefits efficient, bright spontaneous emission. But for a semiconductor laser, a longer radiative lifetime that is shorter than the nonradiative lifetime could benefit population inversion, induced transparency and gain, and overall device performance. In the wurtzite III-Nitrides system, the radiative lifetime can be increased through reduced wave-function overlap from separated carriers due to polarization fields, and alloy fluctuations in ternary systems. The design of quantum well (QW) active regions can also affect radiative lifetimes with strong confinement giving faster radiative lifetimes, well width fluctuations in very narrow QWs leading to carrier separation, and delocalization from shallow and/or narrow barriers increasing the radiative lifetime. The choice of active region design will also impact carrier injection in devices, most notable in thick vertical emitters. To help understand the interplay of these phenomenon, we present results of carrier dynamics studies, using time-resolved photoluminescence and pump-probe measurements on InGaN based vertical laser structures. The active regions have low Indium content, reducing effects from alloy fluctuations, and are grown on high quality non- and semi-polar bulk GaN to reduce polarization fields and structural defects. Barrier heights and widths are varied to investigate the role of weak versus strong localization.

15:15 Tu6.7

Surface-plasmon-enhanced light emissions extended to Deep-UV spectral regions Koichi Okamoto, Kota Okura, Haruku Nishida, Kazutaka Tateishi, Pangpang Wang, Sou Ryuzaki, and Kaoru Tamada; Institute for Materials Chemistry and Engineering, Kyushu University

In 2004, we reported for the first time that the emission efficiencies of InGaN/GaN quantum wells (QW) were increased by the surface plasmon (SP) resonance with Ag thin films [1]. Next important challenge is to extend this method into deep-UV regions to develop deep-UV LEDs. We obtained the enhancements of deep-UV emissions around 260 nm from AlGaN/AlN QWs with Al films. We also fabricated nanoparticles (NPs) by using Al, In, Ga and Ta, and observed the localized SP resonance peaks at deep-UV regions. We also present the method to tune the local-

ized SP resonance spectra based on the plasmon mode couplings. Quite recently, we observed the peak splitting of extinction spectra when the two-dimensional sheets of silver NPs were placed on a metal substrate [2]. This unique optical phenomenon should be due to the mode coupling between the strong dipole oscillator in NPs and its mirror image, which has the same frequency and opposite phase. By using this structure with Al, very strong and sharp resonance peak was obtained at the wavelength regions shorter than 200 nm by the FDTD simulation. These resonance spectra in the deep-UV regions would be useful to enhance deep UV emissions of super wide bandgap materials such as AlGaN/AlN QWs and also mixed oxide semiconductors.

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[2] K. Okamoto, D. Tanaka, R. Degawa1, X. Li, P. Wang, S. Ryuzaki, and K. Tamada, Sci. Rep., 6, 36165 (2016).

15:30 **Tu8.1

Al-rich AlGaN/AlN based double barrier resonant tunneling diode Shun Washiyama, Pramod Reddy, M. Hayden Brechenridge, Biplab Sarkar, Felix Kaess, Ronny Kirste, Seiji Mita, Ramon Collazo, Zlatko Sitar; North Carolina State University; Adroit Materials

Negative differential resistance (NDR) in Al-rich AlGaN/AlN based double barrier resonant tunneling diode (RTD) at room temperature is reported for the first time. The RTD structure consists of a 350 nm-thick top Si doped AlGaN contact layer, active region, 350 nm-thick bottom Si doped AlGaN contact layer, and AlN/c-sapphire substrate. The active region is composed of a top AlGaN spacer, top AlN barrier, AlGaN well, bottom AlN barrier, and bottom AlGaN spacer. Nominal thickness of each layer in the active region is 1.5/1.0/1.0/1.0/1.5 nm (spacer/barrier/well/barrier/spacer). Al mole fraction in AlGaN layer is fixed at 0.6. Free carrier concentration and Hall mobility in Si doped AlGaN contact layer are 1.5×1018 cm-3 and 62 cm2/Vs, respectively, with a V/Al/Ni/Au metal stack as the Ohmic contact. I-V characteristics of the RTD structure clearly showed NDR with a current peak at around 3.0 V due to quantum resonant tunneling effect through the active region. The peak to valley ratio was approximately 5. In addition, I-V characteristics of the RTD represented asymmetric behavior. NDR was observed only when an external electric field was applied in the positive c-direction. By contrast, no NDR was observed with the applied external electric field in the negative c-direction. Therefore, the observed asymmetric behavior is considered to be a consequence of spontaneous polarization charge at the AlGaN/AlN interfaces.

15:45 Tu8.2

Influence of ambient oxygen on Si incorporation during hydride vapor phase epitaxy of AlN at high temperature Keita Konishi, Reo Yamamoto, Rie Togashi,Toru Nagashima, Rafael Dalmau, Raoul Schlesser, Hisashi Murakami, Ramón Collazo, Bo Monemar, Zlatko Sitar, and Yoshinao Kumagai; Department of Applied Chemistry, Tokyo University of Agriculture and Technology, Japan; Tsukuba Research Laboratories, Tokuyama Corporation, Japan; Institute of Global Innovation Research, Tokyo University of Agriculture and Technology, Japan; HexaTech, Inc., USA; Department of Materials Science and Engineering, North Carolina State University, USA; Department of Physics, Chemistry and Biology (IFM), Linköping University, Sweden

AlN is a promising material for future power devices and deep-UV LEDs. In this work, Si-doping-control in AlN layers during growth on different AlN substrates by hydride vapor phase epitaxy (HVPE) was investigated. The AlN layers were grown on MOVPE-AlN/sapphire templates and PVT-AlN substrates by HVPE at 1450ºC [1]. SiCl4 gas was used for Si doping. Impurity concentrations of O and Si in AlN layers grown on the two kinds of substrates were measured by SIMS. The O impurity incorporated in the AlN layer on the AlN/sapphire template (~2×1019 cm-3) is higher by about one order of magnitude than that on the PVT-AlN substrate. This is attributed to the decomposition of sapphire by the presence of H2 at high temperature. The doping level of Si in AlN on AlN/sapphire templates could be controlled linearly in the range of 2×1019~1×1020 cm-3, but the incorporation ratio of Si decreased below 2×1019 cm-3. On the other hand, the doping level of Si in AlN on PVT-AlN substrates could be controlled in the range of 6×1018~7×1019 cm-3 without decrease of the incorporation ratio. The decrease of Si incorporation ratio into AlN is related to the generation of gaseous SiO molecules by the reaction of Si and ambient oxygen. Thus, the incorporation ratio of Si in AlN becomes the same irrespective of substrates, when the doping level of Si is higher than that of the ambient oxygen.

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[1] Kumagai et al., Appl. Phys. Express 5 (2012) 055504.

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Semiconductor Light Emitting Devices

TUESDAY POSTER ABSTRACTS

11th ISSLED Conference
Tuesday Poster Session
4:00-6:00 PM
Room KC 103/105

TP1

(Student) Performance improvement of near-UV LED by carbon nanotube assisted nanoheteroepitaxy Kun Wang, Xiaohui Feng, and Tongjun Yu; Research Center for Wide-gap Semiconductors, State Key Laboratory for Artificial Microstructures and Mesoscopic Physics, School of Physics, Peking University, China

In previous work, we propose a carbon nanotube (CNT) assisted nanoheteroepitaxy (NHE) method to achieve both TDD reduction and strain release. This is facilely implemented by using a low-cost but unique carbon nanotube (CNT) mask with nano-scale window size and a high fill factor. In this work, the CNT-assisted NHE method was employed to improve the device performance of 400 nm near-UV LED on both conventional and patterned sapphire substrates. By using CNT mask on conventional sapphire substrate (CNT-CSS) and patterned sapphire substrate (CNT-PSS), the threading dislocation densities and residual stress of GaN templates are both significantly reduced. As a result, the performance of LED on CNT-CSS and CNT-PSS is prominently improved in the optical powers and reverse-bias leakage. The optical powers of LEDs at 500 mA are clearly increased from 78.96 mW on CSS and 331.5 mW on PSS to 278.3 mW on CNT-CSS and 475.1 mW on CNT-PSS, respectively. The reverse-bias leakages at -5 V are dramatically diminished from 4.64×10-7 A on CSS and 2.06×10-8A on PSS to 7.32×10-10 A on CNT-CSS and 2.73×10-10 A on CNT-PSS, respectively. Furthermore, resulting from significant reduction in TDDs the efficiency droop in near-UV LEDs on CNT-CSS and CNT-PSS are clearly mitigated. In this way, the device performance of near-UV LED is greatly enhanced in various ways by method of CNT-assisted NHE, which demonstrates great application potential for high-performance short-wavelength LEDs.

TP2

First-principles Investigation of artificial photosynthesis on Ga(In)N surface Xianghua Kong, Zetian Mi, Hong Guo; Department of Physics, McGill University, Canada; Department of Electrical & Computer Engineering, McGill University, Canada

In this talk, we focus on the unknown interaction between a metal nitride surface and CO2 molecule, and peculiar N-terminated wurtzite nonpolar GaN surfaces. Firstly, we studied the preliminary but vital mechanism of photochemical CO2 reduction on GaN (wurtzite) nanowire, and a detailed investigation of CO2 molecules' adsorption and activation on pristine, Mg- and Ge- doped GaN(100) surface is conducted. We found that CO2 molecules can be spontaneously activated on the clean nonpolar surfaces of wurtzite metal-nitrides. And the photocatalytic activity for CO2 reduction can be dramatically enhanced by incorporating a small amount of Mg-dopant. This study reveals the extraordinary potential of III-nitride semiconductor nano-structures in solar-powered reduction of CO2 into hydrocarbon fuels. Secondly, the atomic structures of wurtzite GaN nonpolar m-plane surfaces with different levels of Ga and N surface coverage are investigated and corresponding formation energies are calculated. Such N-terminated surfaces not only passivate the GaN nanowires against attack by air/aqueous electrolytes, but their negative surface charge is also essential for inducing the "reverse" polarization that is crucial for p–GaN to efficiently separate and transport photogenerated charges for high performance in overall water splitting in pure water. Furthermore, these kinds of N-terminated m-plane surfaces of GaN are expected to do good to molecules' adsorption and activation.

TP3

(Student) Lateral epitaxial overgrowth of high quality AlN on patterned h-BN using metal organic chemical vapor deposition Kang Bok Ko, Do Trong Thanh, Beo Deul Ryu, Min Han, Tran Viet Cuong, Chang-Hee Hong; Semiconductor Physic Research Center, School of Semiconductor and Chemical Engineering, Chonbuk National University

It is necessary to improve the crystalline quality and reduce the dislocation density of AlN epitaxial layer in AlGaN based ultraviolet light emitting diodes (UV-LEDs) and photodetectors, which have great potential for applications such as fire detection, water purification, sterilization, decontamination, and thin-film curing. In this context, we performed the lateral epitaxial overgrowth of AlN on patterned stripe h-BN using high temperature metal organic chemical vapor deposition. Herein, the h-BN pattern acts as nucleation sites and a mask layer to partially block the propagation of defects from the substrate. Compared with AlN templates grown on conventional sapphire substrates, the full width half maximum of both the symmetric (0002) and asymmetric (10-12) diffraction curves improve as compared to that of AlN grown on stripe patterned sapphire substrate. Our results suggested that h-BN pattern plays a promising role in the growth of high-crystalline quality AlN.

TP4

(Student) A study on quality variation characteristics of AlN layer according to types of h-BN buffer using MOCVD Min Han, Beo Deul Ryu, Kang Bok Ko, Chang Hee Jo, Yongsu Lim, Kwan Seon Joo, Do Trong Thanh, Tran

Viet Cuong and Chang-Hee Hong; School of Semiconductor and Chemical Engineering, Semiconductor Physics Research Center, Chonbuk National University, Korea
We investigated the characteristics of h-BN buffer layer for the direct growth of --nitride materials using MOCVD. The h-BN has a significant potential for DUV photonic device applications. Additionally, there is a possibility that the high thermal conductivity of h-BN can be applied to improve the heat dissipation of the UV-LED. This application is the same application that graphene inserted in blue LED has heat dissipation effect. In order to realize these applications, it is necessary to directly grow AlN onto the h-BN using MOCVD. In this study, we analyzed the characteristics of h-BN buffer layer for directly grown AlN on h-BN. We prepared three different h-BN buffers to study the h-BN buffer layer that is optimized for AlN layer growth. A variety of measurements were taken to analyze the characteristics of the AlN template and identify the optimized h-BN buffer. We measured the absorption and raman spectroscopy to calculate the optical band gap and check for h-BN existence. XPS was employed to analyze the surface binding configuration of h-BN. In addition, XRD was used to measure crystal quality in the AlN template. Analysis of the XPS B1s spectrum shows that there is a difference between the weak bonding intensity and the strong bonding intensity ratio in each buffer layer. It was confirmed that the change of the buffer layer affects the crystal quality of AlN template.

TP5

Quantum Size Controlled Etching of InGaN Quantum Dots George T. Wang, Benjamin Leung, Xiaoyin Xiao, Arthur J. Fischer, Daniel D. Koleske, Ping Lu, Miao-Chan Tsai, Michael E. Coltrin, Jeffrey Y. Tsao; Sandia National Laboratories; University of New Mexico

III-nitride quantum dots (QDs) have significant potential for single-photon sources or gain media for low threshold and high efficiency visible and UV lasers, among others. “Bottom-up” Stranski- Krastanov growth is widely used, however both the size distribution and densities are difficult to precisely control. Here, we show a top-down fabrication process that can be controlled by the evolving properties of the nanostructures being fabricated. This process, called quantum size controlled photoelectrochemical (QSC-PEC) etching, uses laser excitation at a selected and narrowband wavelength to control the final sizes of the QDs through an etch that self-terminates when the QD band gaps increase due to quantum confinement effects until they exceed the energy of the incident photons. Beginning with epitaxially grown InGaN films, we examine the etch process from large to quantum-scale nanostructures with AFM, TEM, and photoluminescence measurements. Quantitative analysis of size and density of the ensemble are made after image-post processing techniques and deconvolution of the AFM tip and QD. We further investigate the passivation of the QDs through regrowth of AlGaN and GaN capping layers, as well as fabrication of multilayers of QDs from multiple-quantum well structures. These results show the potential for a combination of unprecedented uniformity and density for InGaN QD devices.

TP6

Microstructure of In0.20Ga0.80N nanowires on Si (111) substrate evaluated by aberration-corrected scanning transmission electron microscopy Masataka Imura, R. G. Banal, Y. Koide, Y. Nakayama, M. Takeguchi, S. Mizutani, T. Tabata, S. Nakagawa, Y. Honda2, M. Yamaguchi, and H. Amano; NIMS; Nagoya University; Akasaki Research Center

InGaN nanowires are promising materials for high-brightness light emitting device owing to the unique emitting properties and crystal shapes. The development of the device crucially depends on the evaluation of the polar directions and formation mechanism of crystalline defects. For InGaN nanowire, the evaluation of polarity is difficult by commonly-used convergent-beam electron diffraction and ion scattering spectroscopy owing to the alloy crystal structure of GaN and InN and its nano structure. To discuss the formation mechanism of defects, the atomic resolution microscopy is required. However, these evaluations have not yet been investigated well. In this study, scanning transmission electron microscopy (STEM) with Cs-corrected system revealed the atomic column structure of In0.2Ga0.8N nanowires. The polarity, crystalline defects, and inhomogeneity of In composition were clearly evaluated using this atomic structure. The In0.2Ga0.8N nanowires possessed the group-III (+C) polarity. The dislocations were not observed in the nanowire. Rather the stacking faults (SFs) with type I1(ABABCBCB), which is the smallest formation energy, were observed in the nanowires parallel to c-plane. The inhomogeneous In composition, especially high In incorporation, was partially observed at the interface of SFs in some places. Hence we could assume that the high In incorporation was one of the reasons for the formation of SFs.

TP7

Selective area growth of III-nitride core–shell nanorod array on quartz substrates by combined epitaxy of MBE and MOCVD Si-Young Bae, Jung-Wook Min, Hyeong-Yong Hwang, Kaddour Lekhal, Ho-Jun Lee, Young-Dahl Jho, Dong-Seon Lee, Yong-Tak Lee, Nobuyuki Ikarashi, Yoshio Honda1 & Hiroshi Amano; Institute of Materials and Systems for Sustainability (IMaSS), Nagoya University, Japan; School of Electrical Engineering and Computer Science, Gwangju Institute of Science and Technology (GIST), Korea; Department of Electrical Engineering and Computer Science, Nagoya University, Japan; Akasaki Research Center (ARC), Nagoya University, Japan

Recent progress of buffer layer deposition has provided a new means to control the preferential orientation of GaN on amorphous substrates. In the epitaxial view, these substrates are quite challenging to induce a single crystal domain due to the lack of lattice relation. Nevertheless, selective area growth (SAG) gives rise to enabling a local epitaxy irrespective of the kinds of substrates, thereby forming three-dimensional (3D) building blocks with geometrically controlled manner. Above the superior crystal properties, the axial GaN nanostructures, i.e., nanorods are able to provide several merits for optoelectronic applications: suppression of the quantum-confined Stark effect, enhanced indium incorporation, tuneable emission spectrum by adjusting the diameter and/or external bias and large emission area. Recently, we have fabricated near-vertically elongated GaN nanorods on quartz substrates. To obtain flat surface of buffer layer on amorphous substrates, plasma-assisted molecular beam epitaxy (PA-MBE) was employed, thereby achieving ordered coalesced columnar GaN structures and preferred orientation along the surface normal direction. After forming dielectric mask hole array, GaN nanorod was elongated with selective manner owing to applying pulsed-mode metal–organic chemical vapor deposition (MOCVD). For the potential optoelectonic device applications, the microstructural and optical properties of InGaN/GaN core–shell nanorods were also investigated in this study.

TP8

Hybrid White Inorganic/Organic LEDs using Organic Colour Converters Jochen Bruckbauer, E. Taylor-Shaw, N. J. Findlay, C. Brasser, E. Angioni, B. Breig, S. Arumugam, A. R. Inigo, P. R. Edwards, D. J. Wallis, P. J. Skabara and R. W. Martin; Department of Physics, SUPA, University of Strathclyde, United Kingdom; Department of Pure and Applied Chemistry, WestCHEM, University of Strathclyde, United Kingdom; Department of Materials Science and Metallurgy, University of Cambridge, United Kingdom

In this work, we present an alternative approach for producing white light-emitting diodes (LEDs) by combining a highly-efficient inorganic blue LED with individually-designed and versatile organic colour converters. Advantages include relatively straightforward synthesis of these organic molecules, the ability to fine-tune photophysical properties by molecular design, fast switching times and facile processing. Each organic converter consists of a blue absorbing component and a yellow emissive component. For deposition on the blue LED, the organic material was embedded into a transparent matrix. The first compound is based on the BODIPY chemical unit. White light was achieved but the colour rendering capabilities were poor due to the limited emission in the green spectral range. To correct this, the emissive and absorbing units were replaced to include more green spectral components as well as to increase the overlap between the absorption band of the organic molecule and the blue LED emission. This led to an improvement in colour rendering as well as a threefold increase in blue-to-white efficacy (ratio of white luminous flux and blue radiant flux). The LEDs were also investigated for their ability to produce warm and cool white light, angular emission dependence and their lifetime. Overall, our results demonstrate the flexibility of organic colour converters to produce hybrid white LEDs with good colour conversion capabilities and great potential for solid-state lighting.

TP9

(Student) Enhanced light output from Eu-doped GaN red LED by a microcavity Tomohiro Inaba, Keishi Shiomi, Takanori Kojima, and Yasufumi Fujiwara; Division of Materials and Manufacturing Science, Graduate School of Engineering, Osaka University

Realization of GaN-based red light-emitting diodes (LEDs) is a key issue towards nitride-based monolithic full-color LED displays. We have obtained red emission from Eu-doped GaN (GaN:Eu) LED. However, it is not sufficient for practical use yet. In this contribution, we investigated the effect of a microcavity on the electroluminescence (EL) from the GaN:Eu LED to improve the extraction efficiency. Samples were grown by OMVPE on (0001) sapphire substrates. The growth was initiated with an undoped GaN buffer, followed by a 28 pairs Si-doped AlInN/GaN distributed Bragg reflector (DBR), a 200 nmGaN:Eu,O and a 50 nm Mg-doped GaN. A 15-pairs ZrO2/SiO2 DBR was then deposited on the surface to form a microcavity. The sample without the microcavity was also prepared for comparison. The transmittance of the microcavity exhibited a peak around 627 nm with a FWHM of 7.3 nm. The integrated EL intensity of the sample with the microcavity was enhanced by 4.6 times, compared with the sample without the microcavity. The EL lifetime of the sample with the microcavity was 1.03 times larger than the sample without the microcavity. Thus, the main contribution to the overall enhancement of the EL intensity is the improvement of the light extraction efficiency. These results indicate that the Eu emission is affected by the modulation of optical modes in the microcavity and suggest that the microcavity structure is effective for enhancing the light extraction from the GaN:Eu LED.

TP10

(Student) Color tunablility of Eu-doped GaN LEDs achieved through a re-excitation driven up-conversion process Wanxin Zhu, W. Ruo, B. Mitchell, Y. Fujiwara, V. Dierolf; Osaka University; Lehigh University; West Chester University

Europium doped GaN (GaN:Eu) is a promising material for the active layer in nitride-based red light-emitting diodes

(LEDs). The output power of these LEDs has reached the sub-mW level, but further improvement is strongly desired for practical application. The behavior of Eu ions doped into GaN was investigated under intense excitation conditions to explore the excitation energy transfer characteristics in the presence of large carrier densities. Under such conditions, strong emission from the higher excited 5D1 and 5D2 states of the Eu ions was observed in highly efficient AlGaN/ Eu-doped GaN multiple quantum wells (GaN:Eu MQW) grown by organometallic vapor phase epitaxy (OMVPE). This behavior was studied using a variety of excitation sources and conditions. Most notable, it is found that under fs-pulse excitation, the excitation into the higher energy states only occurs when a second excitation pulse comes within the lifetime of the excited 5D0 state. To explain this observation, we propose an up-conversion process in which an already excited Eu ion is further excited from its 5D0 excited state into the 5D1 and 5D2 states. Therefore, by controlling the number of injected carriers into the GaN:Eu MQW LED, its color was changed from red to yellow.

TP11

(Student) Point defect reduction via supersaturation based chemical potential control in high Al-content AlGaN grown by metalorganic chemical vapor deposition Shun Washiyama, Pramod Reddy, Qiang Guo, Andrew Klump, Biplab Sarkar, Ronny Kirste, Seiji Mita, Ramon Collazo, Zlatko Sitar; North Carolina State University; Adroit Materials

A reduction of point defects in high Al-content AlGaN layer is required for high efficiency deep UV emitters such as LEDs and LDs. In this study, chemical potential control through vapor supersaturation is applied to reduce point defects in AlGaN grown by MOCVD. Si doped Al0.7Ga0.3N layers were grown on an AlN template on top of c-plane sapphire by MOCVD. NH3 flow rate was used as a variable parameter to control the vapor supersaturation of Al and Ga during deposition. SiH4 flow rate was varied from 1.3 nmol/min to 18 nmol/min. Hall measurements revealed that there were two regimes for the electronic properties of AlGaN in the low doping regime: 1) mobility collapse regime (4.5 nmol/min). In the mass transport regime, carrier concentration was nearly proportional to SiH4 flow rate. As SiH4 flow rate was lowered from 4.5 nmol/min to 1.3 nmol/min, carrier concentration abruptly dropped from 3×1018 cm-3 to 9×1016 cm-3 due to the presence of acceptor type compensating point defects. Supersaturation based chemical potential control was employed to reduce the compensating point defect density. Vapor supersaturation was increased by increasing NH3 flow rate to produce a more N-rich growth environment. The reduction in compensating impurities resulted in a significant increase in both carrier concentration and electron mobility from 9×1016 cm-3 to 3×1017 cm-3 and from 55 cm2/Vs to 68 cm2/Vs.

TP12

(Student) Enhanced light output power of AlGaN-based deep ultraviolet light-emitting diodes with nano-patterned AlN/sapphire substrates Donghyun Lee, Seungmin Lee, Jeonghwan Jang, Jongmyeong Kim, Giwoong Kim, Jehong Oh, Daeyoung Moon, Yongjo Park and Euijoon Yoon; Seoul National University; Advanced Institutes of Convergence Technology

AlGaN-based deep ultraviolet (DUV) light-emitting diodes (LEDs) have attracted much attention due to their applications such as water purification and sterilization. However, the external quantum efficiency (EQE) of DUV LEDs is still much lower than that of InGaN-based visible LEDs, limiting the expansion of the applications and the market. The low EQE of DUV LEDs is attributed to poor crystal quality of the AlGaN layer, leading to low internal quantum efficiency (IQE), and low light extraction efficiency (LEE).

We have investigated 280 nm AlGaN-based DUV LEDs with periodic air-voids-incorporated nanoscale patterns enabled by nanosphere lithography and epitaxial lateral overgrowth (ELO). Nanoscale ELO on the nano-patterned substrate (NPS) improved the crystal quality of overgrown layers at relatively low growth temperature of 1050 oC and at small coalescence thickness less than 2 um. Full-width at half-maximum values of x-ray rocking curves for (002) and (102) planes of AlN were found to decrease from 235 arcsec to 186 arcsec and from 457 arcsec to 432 arcsec, respectively. In addition, the periodically embedded air-void nanostructure enhanced the LEE of DUV LEDs by breaking the total internal reflection. The light output power (LOP) of DUV LEDs on NPS was enhanced by 67% at a current of 20 mA compared to the reference DUV LEDs. We attribute such a significant enhancement of LOP to simultaneous improvements in the crystal quality of AlGaN epitaxial layer, i.e., IQE and LEE.

TP13

(Student) High Reflectivity Ultraviolet AlGaN-Metal Hybrid Distributed Bragg Reflectors Karan Mehta, Theeradetch Detchprohm, Young Jae Park, Yuh-Shiuan Liu, Oliver Moreno, Shuo Wang, Hongen Xie, Shyh-Chiang Shen, Fernando A. Ponce, Russell D. Dupuis, Paul D. Yoder; Georgia Institute of Technology; Arizona State University

AlGaN based distributed Bragg reflectors (DBRs) in the UV spectrum are known to have very low reflectivities due to the low refractive index contrast and limitations imposed by the critical thickness of AlGaN alloys (tensile strain of ~2.41% for AlN on GaN). Near-bandedge excitonic resonances influence the real part of AlGaN's dielectric function which can be exploited to sharply increase the high index material's refractive index, hence allowing us to achieve higher reflectivities by judiciously choosing the materials of the DBR. This has been demonstrated by our group both

experimentally and by simulations for wavelengths ranging from 240-370 nm.

Silver has a very low refractive index (99% with the combination of only 20-30 epitaxial DBR pairs and silver coating, as opposed to over 50 pairs needed to achieve the same reflectivity without silver. Also, using only 20-30 epitaxial DBR pairs with a silver coating underneath leads to a reduced thermal resistance between the active region and the heat sink. Additionally, this process makes the cavity's resonances independent of the CMP precision, since the cavity length is set by the epitaxial DBR which can be precisely controlled.

TP14

(Student) AlN/h-BN Nanowire Heterostructures for Deep Ultraviolet Photonics David Arto Laleyan, Songrui Zhao, Hong Nhung Tran, Huy Binh Le, Zetian Mi; University of Michigan; McGill University

Al-rich AlGaN and AlN are ideal choices for achieving solid-state deep ultraviolet (DUV) light sources. To date, however, the realization of high efficiency DUV optoelectronic devices has been limited by the presence of dislocations and the inefficient p-type conduction in conventional planar AlGaN structures. In this work, AlN/h-BN nanowire heterostructures were grown on silicon substrate by plasma-assisted molecular beam epitaxy under nitrogen rich conditions. Following the growth of AlN nanowires, a h-BN thin layer was subsequently deposited using an in situ electron beam source. The AlN/h-BN nanowire heterostructures exhibit stronger photoluminescence emission at 210 nm compared to the AlN nanowires without the h-BN capping layer, attributed to the reduced surface recombination. We have further demonstrated, for the first time, a functional AlN/h-BN nanowire light emitting diode that operates at 210 nm. The underlying AlN segment is doped n-type using Si. By exploiting the acceptor-like boron vacancy formation, we have discovered that h-BN can function as a highly conductive, DUV-transparent p-type electrode. As a consequence, the AlN/h-BN device shows excellent current-voltage characteristics, with a turn-on voltage < 6 V. Moreover, the electroluminescence intensity of such an AlN/h-BN nanowire LED device is more than one order of magnitude stronger than AlN p-i-n LEDs without a BN layer, which is attributed to the enhanced hole injection and reduced electron overflow.

TP15

(Student) Deep Ultraviolet AlGaN Nanowire Light Emitting Diodes by Selective Area Epitaxial Growth Xianhe Liu, B. H. Le, S. Zhao, H. Kim, and Z. Mi; Department of Electrical & Computer Engineering, McGill University, Canada; Department of Electrical Engineering and Computer Science, University of Michigan, USA

To date, the external quantum efficiency (EQE) is limited to ~10%, or less for deep ultraviolet (DUV) light emitting diodes (LEDs), which is attributed to the poor material quality, inefficient Mg-dopant incorporation, and low light extraction efficiency in the conventional planar structures. To address these issues, nanowires have been demonstrated to exhibit superior quality, enhanced Mg-dopant incorporation, and improved light extraction. In this regard, we have studied the selective area growth (SAG) of AlGaN nanowires over the entire Al compositional range and have further demonstrated AlGaN nanowire LEDs operating at 279 nm. Electron beam lithography was used to define nanoscale aperture arrays in the Ti mask deposited on a GaN-on-sapphire template, and the growth of nanowires occurred selectively only in the aperture arrays. The resultant nanowires exhibited extremely high uniformity and crystalline quality as revealed by detailed structural characterization. The internal quantum efficiency was estimated to be 45% at room-temperature. AlGaN nanowire LEDs also exhibit excellent electrical and optical performance, including a low turn-on voltage of 3.7 V and an output power ~3.5W/cm2 at a current density of 500 A/cm2. More studies will be performed to enhance the light extraction efficiency by utilizing photonic crystal structures to achieve high power operation.

TP16

(Student) Flexibly and Repeatedly Modulating Lasing Wavelengths in Single Core-Shell Semiconductor Microrod Hua Zong, Yue Yang, Tiantian Wei, Xiaodong Hu; State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University

Modulating lasing wavelength flexibly and repeatedly in a single rod is essential to the practical applications of micro/nanorod lasers. In this paper, a structure that decouples the gain medium and optical cavity is proposed, where the corresponding mechanism for the lasing wavelength shift is explained. Based on the above structure, one kind of wavelength-continuously-variable lasers is achieved in a single GaN/InGaN core-shell microrod without modifying the geometry of resonant cavity or cutting the microrod. By using this method, lasing wavelength can be modulated from 372nm to 408nm flexibly and repeatedly in a 10um facilely synthesized microrod. This new approach demonstrates great application potential in numerous fields consisting of optical telecommunication and environmental monitoring.

TP17

(Student) Light extraction efficiency enhancement of InGaN nanowire light-emitting diodes on flexible substrates Mohsen Asad, Renjie Wang, Yong-Ho Ra, Zetian Mi, and William S. Wong; Department of Electrical and Computer Engineering, University of Waterloo, Canada; Waterloo Institute of Nanotechnology, University of Waterloo, Canada; Department of Electrical and Computer En-

gineering, McGill University, Canada; Department of Electrical and Computer Engineering, University of Michigan, USA

The heterogeneous integration of disparate materials allows opportunities to create functionally enhanced microsystems. By combining nanowire (NW) light-emitting diodes with flexible substrate, mechanical bending of the substrate would result in the motion of the LED structure within a NW array network. This motion alters the spacing between adjacent NWs and may be used to dynamically change the optical emission characteristics of the LEDs. InGaN NW LEDs on sapphire were transferred onto flexible substrates using a laser-liftoff process. A double-transfer process, employing an intermediate substrate, allowed recovery of the original orientation of the devices on the flexible platform. SEM and AFM characterizations showed no measurable degradation due to the double-transfer process. A 2.5 V turn-on and a forward current of 0.4 mA at 4 V remained constant after transfer and during mechanical bending, suggesting a strain-free NW LED active region during flexing. The measured EL intensity increased by 11% as a function of decreasing radii of curvature (38 mm to 32 mm) due to an effective change in the NW spacing during bending. A three-dimensional FDTD simulation will illustrate the dependence of the emission intensity with the effective electromagnetic coupling of the active NW regions at the tip of the NW. From the FDTD simulation and observed EL under bending, we concluded that a very small change in the NW distance and rotation angles enhance the light-extraction efficiency.

TP18

(Student) Characterization of InGaN/GaN ultra-fine nanopillars fabricated by hydrogen-assisted thermal decomposition etching Yusuke Namae, Shun Ishijima, Akihiro Matsuoka, Kohei Ogawa, Tomoya Mizutani, and Akihiko Kikuchi; Sophia University; Sophia Nanotechnology Research Center

Size and position controlled ultra-fine InGaN/GaN nanopillars with InGaN single quantum disks were successfully fabricated by a novel etching technique based on hydrogen-assisted thermal decomposition. The smallest InGaN/GaN nanopillar arrays with diameter about 10 nm showed clear PL emission at room temperature without any post etching treatment. We call this low-damage etching technique as hydrogen environment anisotropic thermal etching (HEATE). The HEATE was carried out for a GaN(25 nm)/InGaN(3 nm)/GaN(60 nm) single quantum well wafer at 900 oC for 20min under 100 Pa of hydrogen pressure using SiO2 etching mask. The nanopillar array showed remarkable size-dependent wavelength shift in low-temperature (4K) photoluminescence. The typical PL peak wave length of a 150 um square mesa was 450 nm, and that of nanopillar arrays with average diameters of 80, 60 and 9.8 nm were 440, 430 and 416 nm, respectively. A steep blueshift occurred below the diameter 80 nm. Temperature dependency of PL peak wavelength were also evaluated. For the case of nanopillars with the average diameter of 80 nm, the wavelength showed well-known S-shaped PL shift due to In compositional inhomogeneity. For the case of nanopillars with the average diameter of 15 nm, the peak wavelength was monotonically reduced with increasing temperature from 418.4 nm at 4 K to 423.4 nm at 300 K. These results possibly suggest that the ultra-fine InGaN quantum disk relieved from In compositional inhomogeneity.

TP19

(Student) Molecular Beam Epitaxial Growth and Characterization of n-GaN/Al/p-AlGaN Tunnel Junction Nanowire Heterostructure Sharif Md. Sadaf, Songrui Zhao, Yong-Ho Ra, Ishiang Shih and Zetian Mi; Department of Electrical and Computer Engineering, McGill University, Canada; Department of Electrical Engineering and Computer Science, University of Michigan, USA

III-nitride backward diodes (conduct more current at a reverse bias) are in demand for a broad range of electronic and optoelectronic applications including visible/ultraviolet light-emitting diodes (LEDs), laser diodes (LDs), and multi junction solar cells. We have demonstrated a monolithic n++-GaN/Al/p++-Al(Ga)N nanowire backward diode, wherein an epitaxial Al layer serves as the tunnel junction. Such an Al(Ga)N based n-p-n nanowire backward diode exhibits record low resistivity (<1.5×10-4 Ω.cm2). The device turn-on voltage is ~2.6 V. The excellent device performance is directly related to the much-reduced dopant formation energy in the near surface region of low dimensional nanowires grown by molecular beam epitaxy (MBE). Moreover, the epitaxial Al layer forms an ohmic contact with the n and p-AlGaN layers. In addition, structural properties of Al/Al(Ga)N nanowire heterostructures were thoroughly studied by X-ray diffraction (XRD), scanning electron microscopy (SEM), and high-resolution transmission electron microscopy (HRTEM). It was found that nearly defect-free Al metal layer can be grown on GaN. Moreover, crystalline Al(Ga)N can also be grown on the Al metal layer, despite the large lattice mismatch (~11%). The use of such high-quality GaN/Al/AlGaN tunnel junction to realize high-efficiency UV LEDs will also be presented.

TP20

Performance improvement of contacts to optoelectronic devices grown on single crystal AlN substrate Biplab Sarkar, Pramod Reddy, Brian B. Haidet, Andrew Klump, Seiji Mita, Erhard Kohn, Ronny Kirste, Ramon Collazo and Zlatko Sitar; Department of Materials Science and Engineering, North Carolina State University, USA; Adroit Materials

In this work, contacts to Al-rich n-AlGaN and p-GaN grown on single crystal AlN substrates are investigated. Both n-AlGaN and p-GaN epitaxial films grown on AlN substrate shows orders of magnitude higher free carrier concentration than films grown on sapphire substrate. However, ohmic contacts to Al-rich n-AlGaN grown on AlN substrate are highly non-linear due to the absence of crystalline defects, resulting in a higher contact resistance at low bias compared to n-AlGaN grown on sapphire substrate. Techniques such as reduction of barrier height at the free surface have been developed to lower the contact resistance by ~4 orders of magnitude. On the other hand, Ni/Au metallization is observed to form alloyed contact on p-GaN with a semiconductor spreading resistance inversely proportional to the free carrier concentration. Consequently, an order of magnitude lower contact resistance is achieved in p-GaN grown on AlN substrate compared to sapphire substrate. Contact models for both type of contacts has been developed, and corresponding pathways for performance improvement will be discussed. In conclusion, this work presents an in-depth contact analysis, challenges and corresponding solutions which will lead to more efficient UV and deep-UV optoelectronic devices.

TP21

(Student) Annealing and sputtering of AlN films on sapphire for deep-ultraviolet LED Yuta Yamaki, S. Iwayama, H. Miyake, K. Hiramatsu; Department of Electronic Engineering, Mie University, Japan;Graduate School of Regional i Innovation Studies. Mie University, Japan

Sputtering is a suitable method for the fabrication of AlN templates on sapphire because of its high uniformity of film thickness and low cost [1]. Recently, we have successfully obtained high-quality AlN on sapphire by high-temperature annealing with the face-to-face method [2]. However, there are few reports on optimum deposition conditions and the mechanism behind AlN film formation for templates of deep-ultraviolet LEDs. In this study, we investigated the annealing and sputtering of AlN films on sapphire, and we discuss the mechanism of AlN film with thickness of 5 to 300 nm deposition by RF sputtering. The X-ray rocking curve (XRC) for AlN (0002) in the AlN film only exhibits a sharp peak when the thickness of the AlN film is 10 nm. When the deposited AlN film has a thickness of 20 nm or above 20 nm, a broad peak appears with the sharp peak. This means the AlN films with a thickness of less than 10 nm or below 10 nm are well oriented, and the mosaic AlN nanorods increased with the AlN thickness above 20 nm. After annealing the sputtered AlN film with a thickness of 200 nm, the full widths at half maximum (FWHMs) of the XRCs for AlN (0002) and (10-12) became 60 and 240 arcsec, respectively. It was found that an AlN film exhibiting a sharp peak in the AlN (0002) XRC is important in improving the crystalline quality by annealing.

[1] Z. Vashaei et al. : J. Cryst. Growth 311 (2009) 459.
[2] H. Miyake et al., J. Crystal growth 456 (2016) 155.

TP22

(Student) Characterization of threading dislocations in HVPE-grown AlN substrates by wet chemical etching Taro Mitsui, Mari Higuchi, Toru Nagashima, Toru Kinoshita, Reo Yamamoto, Galia Pozina, Rafael Dalmau, Raoul Schlesser, Ramón Collazo, Bo Monemar, Zlatko Sitar, and Yoshinao Kumagai; Department of Applied Chemistry, Tokyo University of Agriculture and Technology, Japan; Tsukuba Research Laboratories, Tokuyama Corporation, Japan; Department of Physics, Chemistry and Biology (IFM), Linköping University, Sweden; HexaTech, Inc., USA; Department of Materials Science and Engineering, North Carolina State University, USA; Institute of Global Innovation Research, Tokyo University of Agriculture and Technology, Japan

Recently, high quality AlN substrates with deep-UV transparency have been developed by hydride vapor phase epitaxy (HVPE) of thick AlN layers on bulk AlN substrates prepared by physical vapor transport. In this study, threading dislocations (TDs) in the HVPE-grown AlN substrates are characterized by wet chemical etching and transmission electron microscope (TEM) observations. The HVPE-AlN substrates (190-μm-thick) and metalorganic vapor phase epitaxy (MOVPE)-grown AlN(1.5-μm-thick)/sapphire templates for comparison were dipped into a molten KOH-NaOH eutectic at 450 oC to form etch pits on their surfaces. The etch pits were observed and counted by scanning electron microscope (SEM) and Nomarski differential interference contrast (NDIC) microscope. Cross-section TEM observations were also performed on specimens prepared with the aid of focused-ion beam etching. The surfaces of MOVPE-grown AlN/sapphire templates showed three kinds of etch pits: small shallow pits, middle-sized hexagonal truncated pits, and large-sized hexagonal truncated pits, which were correlated to edge, mixed, and mixed+screw dislocations, respectively. On the other hand, the surfaces of HVPE-AlN substrates showed only hexagonal truncated pits. TEM observations revealed that the pits originated from edge dislocations, and the density of the pits was

TP23

Control of Bowing in Free-standing GaN Substrate by Using Selective Etching Hoki Son, Jinho Kim, Youngjin Lee, Jonghee Hwang, Jin-Woo Ju, Dae-Woo Jeon; Optic & Display Materials Center, Korea Institute of Ceramic Engineering & Technology, Korea; Photonic ICT & Energy Research Center, Korea; Photonics Technology Institute, Korea

GaN-based nitride semiconductor materials that cover whole range of visible and ultra-visible light are applied to high-intensity light emission diodes (LEDs) and laser diodes

(LDs).The hydride vapor phase epitaxy (HVPE) technique is one of the promising approaches to obtain high-quality and large-area bulk-like substrates for homo-epitaxy. However, the difference in the lattice parameter and thermal expansion coefficient between the GaN layer and the underlying substrate leads to severe bowing. In this paper, we report that selective etching on N-polar face by EC(electro-chemical)-etching effect on the reduction of bowing and strain of FS(free-standing)-GaN substrates. We applied the EC-etching to concave and convex type of FS-GaN substrates. After the EC-etching for FS-GaN, nano porous structure was formed on N-polar face of concave and convex type of FS-GaN. Consequently, the bowing in the convex type of FS-GaN substrate was decreased but the bowing in the concave type of FS-GaN substrate was increased. Furthermore, the FWHM (full width at half maximum) of (1 0 2) reflection for the convex type of FS-GaN was significantly decreased from 601 to 259 arcsec. In the case, we confirmed that the EC-etching method was very effective to reduce the bowing in the convex type of FS-GaN and the compressive stress in N-polar face of convex type of FS-GaN was fully released by Raman measurement.

TP24

Characterization of AlN layer on 4 inch Sapphire substrate by High Temperature Annealing in Nitrogen Atmosphere Akira Mishima, Yuji Tomita, Yoshiki Yano, Toshiya Tabuchi, Koh Matsumoto, Hideto Miyake; Taiyo Nippon Sanso Corporation, Japan; Graduate School of Regional Innovation Studies, Mie University, Japan

To realize high-performance, low-cost deep ultraviolet LEDs , high-quality AlN with a large diameter substrate is required for the underlying layers. Recently, an improvement in the crystallinity of an AlN buffer layer was achieved via high-temperature annealing under a N2 gas atmosphere [1]. In this study, we developed an annealing furnace for 4 inch wafers and used it to anneal AlN on a 4 inch c-plane sapphire substrate at a high temperature. The AlN layer was grown to a thickness of 300 nm on a 4 inch sapphire substrate using metalorganic chemical vapor deposition (SR4000HT, TNSC). The substrate was then annealed at 1700 °C for 3 h in N2 atmosphere by using the annealing furnace (STA1800, TNSC). Before and after annealing, the AlN surface morphology was observed using an optical microscope, and its crystal quality was evaluated by the full-width at half-maximum (FWHM) of the X-ray rocking curve (XRC). In the optical microscopic images, no significant changes were observed after annealing. By the annealing, the FWHM of the XRC of the (002) plane was decreased from 85.7 arcsec to 51.6 arcsec, and that of the (102) plane was drastically decreased from 1100.0 arcsec to 274.3 arcsec at the center of the wafer. In addition, decreases in the FWHMs of the AlN XRCs were confirmed over the whole surface of the 4 inch wafer. By the annealing, it was not confirmed great change at bowing of wafer. Its bowing was less than 10 μm.

[1] H. Miyake et al., J. Crystal Growth 456, 155 (2016)

TP25

Improvement of AlN crystalline quality by combination of high temperature annealing and MOCVD growth Mingxing Wang, Fujun Xu, Zhixin Qin, Lisheng Zhang, Na Xie, Xinqiang Wang, and Bo Shen; State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, China

High quality AlN templates have a crucial influence on performance of deep ultraviolet (DUV) devices, andit is essential to obtain AlN template with flat surface and low threading dislocation density. In this study, we have investigated the microstructural evolution of AlN films by introducing high temperature annealing under nitrogen atmosphere, which is proven effective in improving AlN crystalline quality. AlN films with different thickness were grown on c-plane sapphire substrates by metal-organnic chemical vapor deposition (MOCVD). Then the AlN films were annealed at 1550-1750 - in N2 atmosphere. After high temperature (HT) annealing, the crystalline quality of AlN was greatly improved. Particularly, the crystalline quality of the 540-nm thick AlN film after annealing at 1700 - for 1h shows the best results. The X-ray diffraction -scan full width at half maximum FWHM values for (002) and (102) reflections are 88 and 319 arcsec, respectively. Cross-sectional transmission electron microscope (TEM) observation for the annealing AlN films confirms that the reduction of TDD involves a movement of the threading dislocations (TD) which probably originates from glide and climb processes at high temperature.

TP26

Enhanced optical properties by two-dimensional photonic quasicrystal layers on a Y2O3:Eu3+ thin-film phosphors Hyojun Kim, Ki-Young Ko and Jinho Ahn; Department of Materials Science and Engineering, Hanyang University,Korea; Institute of Nano Science and Technology, Hanyang University, Korea; Korea Invention Promotion Association, Korea

Recently there has been growing interest in the use of thin-film phosphors in flat panel displays (FPD) such as field-emission displays (FED) and plasma display panels (PDP). Even though thin film phosphor shows superiority over the powder phosphors in many aspects, it shows limited light extraction efficiency of ~7% (Eu3+-doped Y2O3, Y2O3:Eu3+) due to total internal reflection (TIR) and waveguide effect. In order to resolve this drawback, two-dimensional (2D) photonic crystal layers (PCLs) have been applied to various light emitting devices incorporating luminescent film materials. However, this 2D PCLs show im-

provement of extraction efficiency only at specific angles, and this causes a light dazzling optical effect produced by Bragg diffraction. In this study, we fabricated various 2D photonic quasicrystal (PQC: non-periodic but ordered) layers using nano-sphere lithography (NSL) and their optical effects have been evaluated. Quasicrystals were formed by NSL using mixture of two different size polystyrene (PS) spheres of 1um/420nm or 600nm/150nm. We examined the optical effects of 2D PQC layers on the photoluminescence property of annealed Y2O3:Eu3+ TFPs fabricated by sol-gel method. The 2D PQC layer improves the light extraction efficiency by 8.7 times compared to the conventional Y2O3:Eu3+ TFPs with uniform emission distribution along the angle.

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WEDNESDAY ORAL PRESENTATIONS

*Invited talk, **Student talk

8:30 *PL3

Invention of high efficient blue LED and future solid state lighting Shuji Nakamura; Materials and ECE Department, University of California Santa Barbara, USA

Maruska and Tietjen did the first GaN growth by using hydride vapor phase epitaxy in 1969. Since their first GaN growth, a lot of breakthroughs have been achieved for the crystal growth of GaN and InGaN, conductivity control of p-type GaN, and the device structures of LED and laser diodes. Then finally, first high efficient blue LEDs were invented in 1993 by Nakamura et al. The first white LED was also developed using the blue LED and YAG phosphor by Nichia Chemical Ind., in 1996. Since the first high efficient blue LEDs on sapphire were invented in 1993, these blue and white LEDs have been used for all kinds of applications, such as back light of LCD display, general lighting and others. I name these LEDs grown on sapphire and SiC substrate as 1st generation LEDs. In spite of lot of efforts, the wall-plug efficiency (WPE) of the 1st generation LEDs is still around 40% at the current density of 35Acm-2. Recently, high efficient violet LEDs were developed using GaN substrates by Soraa Inc. It is called GaN on GaN LED. These high efficient violet LEDs grown on GaN substrates are called as 2nd generation LEDs which has a higher WPE of 75% at a current density of 35Acm-2. The high efficient blue LEDs on sapphire with the WPE of more than 50% (EQE>70%) at a current density of 35Acm-2 were developed by UCSB group using the tunnel-junction (TJ) recently. I like to talk about the latest results of the TJ blue LEDs and laser diodes.

9:15 W2.1

Effects of Electron Retarding Electrodes on Semiconductor Light-Emitting Devices Dong-Sing Wuu, Ching-Ho Tien, Sin-Liang Ou; National Chung Hsing University, Taiwan; Da-Yeh University, Taiwan

In the semiconductor light-emitting devices (LEDs), the electron mobility is much higher than the hole mobility. Therefore, moderate the structure to match the hole and electron mobility is important. Recently, many reports have been conducted on dilute magnetic semiconductors (DMSs) based on ZnO doped with transition metals, such as Ni, Co, and Mn. In this study, the cobalt-doped ZnO (CZO) dilute magnetic films were deposited by pulsed laser deposition as an electron retarding electrode and then applied for LEDs. In comparison to the conventional 450 nm blue (lateral-type) and 530 nm green (lateral-type and vertical-type) LEDs, there were 15.9%, 17.7%, and 8.5% enhancements in the output power (@350 mA) after fabricating the CZO n-electron retarding electrode on the n-GaN layer. By incorporating the CZO n-electron retarding electrode into the LEDs, the electrons would be scattered because of the collisions between the magnetic atoms and the electrons as the device is driven, leading to the reduction of the electron mobility. Therefore, the excessively large mobility difference between electron and hole carriers occurred in the conventional LEDs can be efficiently decreased after preparing the CZO n-electron retarding electrode on the n-GaN layer, resulting in the increment of carrier recombination rate and the improvement of light output power. Details of the feasibility of electron retarding electrodes applied for yellow and ultraviolet LEDs will also be discussed.

9:15 W3.1

AlGaN Nanowire Tunnel Junction Light Emitting Diodes and Lasers in the UV-C Band Songrui Zhao, S. Sadaf, X. Liu, and Z. Mi; Department of Electrical and Computer Engineering, McGill University, Canada; Department of Electrical Engineering and Computer Science, Center for Photonics and Multiscale Nanomaterials, University of Michigan, USA

To date, it has remained challenging to realize high performance AlGaN quantum well LEDs and electrically pumped lasers operating in the UV-C band, due to the presence of large densities of dislocations and inefficient p-type doping. In this context, we have investigated the molecular beam epitaxial growth and characterization of nearly dislocation-free Al-rich AlGaN nanowire heterostructures on Si. We have conceived the concept of Al-tunnel junction nanowire LEDs. We show that, with the incorporation of n+-GaN/Al/p+-AlGaN tunnel junction, the resistance of AlGaN nanowire LEDs operating in the UV-C band is reduced by nearly a factor of ten and the output power is enhanced by two orders of magnitude. An output power ~9 mW has been measured from 275 nm AlGaN nanowire LEDs fabricated on Si substrate, the highest power ever reported for UV-C LEDs on Si. We have further discovered the formation of quantum dot-like nanostructures in nearly defect-free AlGaN nanowires, which leads to significantly reduced transparency carrier density compared to conventional quantum well structures. We have demonstrated, for the first time, electrically pumped semiconductor lasers operating in the UV-C band. For AlGaN nanowire lasers operating at 239 nm, a very small threshold current of 0.35 mA is measured at room temperature. Work is currently in progress to demonstrate high power laser diodes in the UV-C band by incorporating Al-tunnel junction and optimizing the design and fabrication process.

9:30 **W2.2

Very thin ITO/metal mesh hybrid films for a high-performance transparent electrode in GaN-based LEDs

Jung-Hong Min, Hoe-Min Kwak, Seung-Hyun Mun, Woo-Lim Jeong, Dong-Seon Lee; Gwangju Institute of Science and Technology; Research Institute for Solar and Sustainable Energies

We have introduced very thin ITO layers (5 nm, 10 nm, and 15 nm) hybridized with metal mesh to produce high-performance transparent conductive layers (TCLs) in near-ultraviolet light-emitting diodes (NUV LEDs). Using UV-Vis-IR spectrometry, Hall measurement, and atomic force microscopy, we found that 10 nm was the optimum thickness for the very thin ITO layers to obtain outstanding transmittance and sheet resistance values, and stable contact properties. The 10 nm-thick ITO layer hybridized with the metal mesh TCLs showed a value of 4.56 Ω/- for sheet resistance and a value of 89.1% for transmittance. Moreover, the NUV LEDs fabricated with the hybrid TCLs had ~ 140% enhanced light output power compared to that of 150 nm-thick ITO layers. Finally, to verify the practical usage of the TCLs in industry, we packaged the NUV LED chips using lead frames, wire bonding, and silicone and obtained improved values of turn-on voltage (3.48 V) and light output power (~ 116%) even after the packaging.

9:30 **W3.2

AlGaN/GaN Nanocolumn UV-A Light Emitting Diodes Grown on Graphene/Silica Glass

Andreas Liudi Mulyo, I. M. Høiaas, D. C. Kim, B.O. Fimland, H. Weman and K. Kishino; Department of Electronic Systems, Norwegian University of Science and Technology (NTNU), Norway; Department of Engineering and Applied Sciences, Sophia University, Japan

One major hindrance in achieving high efficiency deep ultraviolet (DUV) AlGaN light emitting diodes (LEDs) is the lack of a transparent electrode. Due to this, DUV LEDs are made flip-chip with the emission through a sapphire or AlN substrate. However, these substrates are also absorbing a large part of the emitted light. In this work, a combined epitaxial substrate and transparent electrode consisting of CVD grown graphene transferred onto a fused silica glass substrate support is proposed in order to circumvent the mentioned limitations. Apart from having a small lattice mismatch with III-nitrides, graphene provides excellent optical transparency even in DUV, and is envisaged to improve the efficiency of DUV LEDs. Utilizing the advantages provided by the use of graphene on fused silica, we have grown self-assembled GaN/AlGaN nanocolumn (NC) p-i-n structures emitting in the near UV (UVA) as a first proof-of-principle demonstration. The NCs are grown using plasma-assisted molecular beam epitaxy and have a high degree of size and height uniformity. Vertical and uncoalesced n-GaN NCs are achieved using an n-AlN buffer layer. The NCs have a 10 nm un-doped GaN quantum well as the active emitter, sandwiched between n- and p-AlGaN. The LED device fabrication uses standard photolithography to make the top p-GaN and bottom graphene contacts, employing Ni/Au and Au, respectively. Prototype LED devices indicate UVA emission through the graphene/silica substrate side.

9:45 W2.3

Mesa-free flat-surface III-nitride light-emitting diodes

Jaehee Cho; School of Semiconductor and Chemical Engineering, Chonbuk National University, Korea

III-nitride light-emitting diode (LED) devices are the driving force behind solid-state lighting with its explosive growth in illumination applications. One of the characteristics of standard III-nitride LEDs grown on a sapphire substrate is that the anode and cathode contact electrodes are located on the same surface because the sapphire substrate is electrically inert. In order to make a cathode contact (n-electrode), it is mandatory to etch out part of the p-type semiconductor to form mesas and expose the n-type semiconductor underneath. As the result, the LED wafer has an undulated surface topography, which can deteriorate the quality of device during a series of follow-up fabrication steps. In this presentation, a mesa-free flat-surface GaInN LED is demonstrated by employment of ion-implantation technology and without employment of a dry-etch mesa-formation process. For the areas in which cathode contacts are formed, the LED epitaxial wafer's p-type surface layer was converted from p-type to n-type conductivity by implantation of a high Si donor concentration. We investigated the metal ohmic contact properties of the type-converted n-type GaN and fabricated mesa-free LEDs that have cathode and anode contacts at the same surface height. The resulting mesa-free flat-surface LED showed very comparable characteristics in terms of the specific contact resistance on the type-converted n-type layer and the light-output power, compared to those obtained by a reference LEDs.

9:45 W3.3

Hybrid top-down/bottom up fabrication of regular arrays of AlN/AlGaN core-shell nanorods for UV emission

Pierre-Marie Coulon, E.D. Le Boulbar, C. Bryce, P.R. Edwards, R.W. Martin, D. W. E. Allsopp, P.A. Shields; Dept. Electrical & Electronic Engineering, University of Bath, UK; Department of Physics, SUPA, University of Strathclyde, UK

Core-shell III-nitride structures offer great promise for UV light emitters due to their lower defect density, reduced quantum confined Stark effect, high-quality lateral non-polar growth and improved extraction efficiency, all known problems of current planar UV devices. This paper reports

on the fabrication and characterization of AlN/AlGaN core-shell nanorods emitters by a hybrid top-down/bottom-up approach. Displacement Talbot lithography has been used to fabricate a 1.5 µm pitch hexagonal array of 200 nm thick Ni metal dots via lift-off to act as a hard etch mask. An AlN nanorod scaffold was then created by inductive coupled plasma dry etching of an AlN template with a Cl2/Ar-based chemistry. The impact of etching parameters on the nanorod etch rate, tapering profile and mask selectivity in order to achieve straight nanorod arrays with high aspect ratios will be presented. The influence of Metal Organic Vapor Phase Epitaxy (MOVPE) regrowth conditions on the AlN facet recovery morphology, growth rate and regrowth uniformity will be described and systematically monitored by scanning electron microscopy. Finally, AlxGa1-xN shells regrowth by MOVPE with various compositions will be presented along with optical characterisation via hyperspectral cathodoluminescence imaging to assess their emission wavelength range and spatial homogeneity. The reported hybrid top-down/bottom-up approach is promising and opens new perspectives for UV LEDs based on core-shell nanostructures.

10:30 W4.1

Identification of Compensating Defects in AlN and AlGaN Douglas L. Irving, Joshua S. Harris, Kelsey J. Mirrielees, Jonathon N. Baker, Brian D. Behrhorst, Dorian Alden, Ronny Kirste, James Tweedie, Ramón Collazo, Zlatko Sitar; Department of Materials Science and Engineering at North Carolina State University, USA; Adroit Materials

Due to the wide range of available direct bandgaps and their mutual solubility, III-N materials (III=In,Ga,Al) have been critical to many technologically relevant optoelectronic applications. While significant strides have been made in the production of high quality bulk materials which, in turn, have enabled the creation of low defect density heterostructures, controlled doping in III-N materials remains a significant obstacle. This has been attributed to the wide band gaps and the depth of the valence bands in these materials. Practically, the presence of unintentional defects can lead to the compensation of intentional dopants, as well as the onset of undesirable below band gap absorption which hinders optical efficiency. In an effort to develop a mechanistic understanding of dopant compensation in this class of materials, we have implemented first principles density functional theory calculations with screened hybrid exchange-correlation functionals to determine the properties of individual defects in AlN and AlGaN. The formation energies of each defect are used within a grand canonical equilibrium model to identify the predominant defects as a function of growth conditions. Results from these methods are compared with complementary experimental data that includes below band gap optical absorption and photoluminescence, electrical measurements, and available SIMS measurements.

10:30 *W5.1

Hexagonal boron nitride epilayers for deep UV photonics Hongxing Jiang, Jingyu Lin; Department of Electrical and Computer Engineering; Texas Tech University, USA

Hexagonal boron nitride (h-BN) possesses extraordinary physical properties including wide bandgap (~6.5 eV) and layered-structure. In this talk, a brief overview on synthesis of wafer-scale h-BN epilayers by MOCVD will be presented. Band-edge and impurity related emission properties will be discussed. It was shown that the unique 2D structure of h-BN induces exceptionally high density of states and large exciton binding energy (~740 meV), which results in high optical absorption and emission intensity. By growing h-BN under varying ammonia flow rates, the impurities involved in the donor-acceptor pair and acceptor bound exciton transitions have been identified to be nitrogen vacancy shallow donors and deep level acceptors associated with carbon impurities occupying the nitrogen sites. Nitrogen vacancy related defects can be minimized and epilayers exhibiting pure free exciton emission have been obtained by growing h-BN under high ammonia flow rates. P-type conduction and diode behaviors in p-n structures consisting of p-type h-BN/n-Al0.62Ga0.38N have been demonstrated. The attainment of p-type h-BN could potentially overcome the intrinsic problem of low p-type conductivity in Al-rich AlGaN for deep UV photonic devices. As deep UV photodetectors, h-BN detectors exhibit a peak responsivity at 217 nm with virtually no responses for below bandgap excitation as well as a very low dark current density.

10:45 W4.2

High-quality, laterally grown Ge films on Si utilizing a new relaxation mechanism Nathaniel Quitoriano, Weizhen Wang; Department of Mining and Materials Engineering, McGill University, Canada

We have recently grown Ge thin films on Si using a metal-catalyzed, lateral growth technique at 380 -. There are two surprising results from this work; first, the films are fully relaxed, despite the low growth temperature and, second, the cross sectional transmission electron micrographs suggest high-quality (low threading dislocation density) films. Standard planar growth of Ge on Si involves the nucleation and glide of dislocations to relax the 4% lattice mismatch between the two materials; the nucleation of dislocations implies highly defective films, which is why the high-quality state of the lateral films is surprising. Dislocation glide is a thermally activated process and so, at these low temperatures, it would be greatly impeded and should result in a strained film, which is why the fully relaxed nature of our laterally grown Ge on Si is surprising. Given these surprising results we propose a new relaxation mechanism which enables the high-quality growth of large lattice-mismatched materials. We hypothesis that the strain induced by the lattice mismatch can be relaxed by extending the preexist-

ing misfit dislocations and that lateral growth can "build in" dislocations as it grows. This technique could be applied to other materials systems like GaN on Si or InP on Si, providing a pathway to fabricate high-performance device on low-cost, lattice-mismatched substrate.

11:00 *W4.3

Point defect control in III-nitrides by chemical potential and defect quasi Fermi level control Ramon Collazo, Pramod Reddy, Shun Washiyama, Felix Kaess, Ronny Kirste, Seiji Mita, James Tweedie, Michael Gerhold, and Zlatko Sitar; Department of Materials Science and Engineering, North Carolina State University, USA; Adroit Materials, Inc., USA; Engineering Science Directorate, Army Research Office, USA.

Defect incorporation is dependent on the defect formation energy and hence on associated chemical potentials and the Fermi level. Here, we demonstrate systematic point defect control by using the defect formation energy as tool by: chemical potential control and Fermi level control. Chemical potential control with a case study of C in MOCVD GaN is reported. We derive a relationship between growth parameters, metal supersaturation and chemical potentials of III/N and impurity atoms demonstrating successful quantitative predictions of C incorporation as a function of growth conditions. Hence growth environment necessary for minimal C incorporation within any specified constraints may be determined with control from >1E19cm-3 to ~1E15 cm-3. Fermi level control is demonstrated by modifying the Fermi level describing the probability of the defect level being occupied/unoccupied i.e. defect quasi Fermi level (DQFL). The DQFL is modified by introducing excess minority carriers (by above bandgap illumination). A predictable reduction in compensating point defects in (Si, Mg) doped Al/GaN measured by electrical measurements, photoluminescence and secondary ion mass spectroscopy (SIMS) provides experimental corroboration. Further, experiments with varying steady state minority carrier densities at constant illumination prove the role of minority carriers and DQFL in defect reduction over other influences of illumination that are kept constant.

11:30 W.4.4

Nano Patterned Sapphire Substrates for improved GaN growth and LED performance Younghoon Sung and Heon Lee; Korea University

Sapphire substrates are mainly used for fabricating nitride-based Light Emitting Diode (LED) devices, for reasons such as chemical stability and thermal stability of sapphire. Patterned Sapphire Substrates (PSS) is one of the most influential factors in improving the efficiency of LED devices. The advantage of the PSS is that it can enhance the Internal Quantum Efficiency by improving the GaN crystal quality through decreasing GaN dislocation, and also it can improve the light extraction efficiency by the pattern it has in. Currently, in most industries, LEDs are manufactured using 2-inch or 4-inch sapphire substrates. This is due to the bowing phenomenon caused by the difference in thermal expansion coefficient between GaN and sapphire substrate. The bowing due to the difference in thermal expansion coefficient can be minimized when the GaN thickness is become thin. For this purpose, it is necessary to reduce the pattern height and size. In order to solve this bowing problem, the nano pattern was formed on the sapphire substrate through the Nano Imprint Lithography (NIL), Lift off and the dry etching process. After GaN layer growth, crystal quality of flat substrate, PSS and Nano-PSS (NPSS) was confirmed by PL analysis. As a result, the PL value was measured in the order of PSS, NPSS, and flat substrate. Based on this result, it is possible to fabricate a high efficiency and low cost LED device when the NPSS is optimized to the MOCVD growth conditions.

11:00 W5.2

Picometer precise measurement of AlGaN surfaces and quantum wells with scanning transmission electron microscopy James M. LeBeau, J. Houston Dycus, Seiji Mita, Ronny Kirste, Shun Washiyama, Alexander Franke, Kelsey J. Mirrieless, Everett D. Grimley, Douglas L. Irving, Ramon Collazo, Zlatko Sitar; Department of Materials Science & Engineering, North Carolina State University, USA

Unit-cell level structural distortions, occurring due to local chemical fluctuations or at surfaces, play a major role in determining material properties. Measurements of these distortions, however, are often either indirect or are limited by a number of factors. While scanning transmission electron microscopy can provide direct imaging of atomic structure, accuracy and precision of structural measurements have been traditionally hampered by sample drift and other scan distortion. This limitation has obscured the capabilities to directly correlate local structure in bulk or at surfaces with chemistry. In this talk, I will introduce revolving scanning transmission electron microscopy (RevSTEM). The method achieves sub-0.1% accuracy and picometer level precision. For example, I will show how picometer level precision enables the study of AlGaN/AlN strain relaxation in quantum wells to directly probe composition and the origins of compositional pulling. Turning to surfaces, I will also show how STEM can serve as a powerful tool for surface science of III-nitrides, enabled by a new sample preparation approach we developed to minimize surface contamination. Using this method, I will show our work directly imaging, I will also present recent STEM results exploring the formation of native crystalline oxides on III-nitride surfaces.

11:15 W5.3

Optical and structural properties of semipolar (11-22) AlGaN epilayers with high AlN content Jochen Bruckbauer, G. Naresh-Kumar, Z. Li, L. Jiu, P. R. Edwards, J. Bai, T. Wang, C. Trager-Cowan, and R. W. Martin; Department of Physics, SUPA, University of Strathclyde, United Kingdom; Department of Electronic and Electrical Engineering, University of Sheffield, United Kingdom

Despite significant progress in the development of deep-UV c-plane AlGaN LEDs, the quantum efficiencies and output powers remain low and are limited by high densities of extended defects, the quantum-confined Stark effect (QCSE) and the availability of suitable, cost-efficient substrates. In order to address these issues, AlGaN layers were grown on (11-22) GaN overgrown on GaN microrod arrays on m-sapphire; this not only decreases the defect density and avoids cracking but also reduces the electric fields and the strength of the QCSE. Thick (11-22) AlGaN layers with AlN contents of 38-56% were grown using MOCVD. With increasing AlN content the emission blueshifts as far as 271 nm and the occurrence of chevrons on the sample surface (features present in overgrown semipolar structures) also increases. Cathodoluminescence (CL) hyperspectral imaging revealed two dominant emissions; the shorter wavelength peak is predominant in the majority of the sample surface, whereas the more intense longer wavelength peak emanates only from around the chevrons. The presence of chevrons seems to influence the growth conditions leading to a different rate of AlN incorporation on the facets. CL images at both wavelengths exhibit dark and bright stripes perpendicular to the direction of the chevrons. The darker stripes contain a higher density of extended defects (stacking faults/dislocations), as revealed by electron channelling contrast imaging, which lead to nonradiative recombination.

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8:30 *PL4

Progress of AlGaN UVC LED and challenge to GaN THz-QCL Hideki Hirayama; RIKEN

AlGaN deep ultraviolet light-emitting diodes (DUV-LEDs) are attracting a great deal of attention, since they have the potential to be used in a wide variety of applications, such as for sterilization, water purification, UV curing, and in the medical and biochemistry fields. However, the efficiency of AlGaN DUV LED is still as low as several percent. The first target for the efficiency of AlGaN DUV-LEDs is to go beyond an efficiency of 20%, which would make them comparable to mercury lamps. Clearly, improving the light-extraction efficiency (LEE) is a major topic. In this work, we demonstrate an external quantum efficiency (EQE) of over 20% in an AlGaN DUV-LED by improving LEE. Our simulations show that LEEs of more than 60 % can be expected for AlGaN DUV-LEDs by using a combination of transparent contact layers and photonic light extraction structures. Also attracting a great deal of attention are terahertz quantum cascade lasers (THz-QCLs), which are compact, high-power, narrow line-width THz laser light sources that have the potential to be useful in a variety of applications such as in medical imaging, security screening, wireless communications, etc. We are studying THz-QCLs using III-nitride semiconductors, with which there is the potential to realize QCLs with wide frequency ranges. We fabricated GaN/AlGaN THz-QCL structures and demonstrated stimulated emission by current injection at the frequency range from 5.4 to 7 THz.

9:15 Th2.1

AlGaInP-based flip chip micro LED fabrication and performance study Ray Hua Horng, Wei-Yu Tseng , Ken-Yen Chen, Yu-Ting Tsai, and Huan-Yu Chien; Institute of Electronics Engineering, National Chiao Tung University, Taiwan; Department of Process Engineering, Epileds Technology, Taiwan; Graduate Institute of Precision Engineering, National Chung Hsing University, Taiwan

In this study, the thickness of epilayer is reduced to 3.2μm from 7μm. The dimension of flip-chip LED is 5mil x 8mil flip-chip LED and the photoelectric effect of each LED device are also analyzed after the devices are formed. ITO layer is deposited on P-GaP layer by E-Gun, then sapphire layer is glued on ITO layer, and the main structure is formed. GaAs substrate is completely removed by chemical etching. After wet etching process, the n+GaAs layer is exposed and N-metal is deposited on surface of exposed n+GaAs layer. The structure which is without protective is etched by ICP RIE before the photoresist is removed. After N-electrode and P-electrode regions are defined, Ti/Al/Ti/Au is deposited by E-Gun to raise the height of P-electrode. And then SiO2 is deposited by PECVD. Etching SiO2 to define N-electrode and P-electrode area and then Ti/Au is deposited on electrode area by E-Gun. Performance of these two LED devices is measured. The driving voltage is about 1.8 V. Output power is not decayed caused by reducing epilayer. Visible emission wavelength of two devices, thick and thin epistructure, are 627 nm, and 632 nm, respectively. The result of each device is almost the same. Flip chip red LED device with thinner epi-layer can be produced and the photoelectric effect is as good as the traditional red LED. This study result will be applied to integrate high resolution functional full-color display with green, and blue LEDs.

9:15 *Th3.1

Vacuum-fluorescent-display devices emitting polarized deep-ultraviolet and visible lights using m-plane Al1-xInxN epitaxial nanostructures Shigefusa F. Chichibu, Kazunobu Kojima, Akira Uedono, and Yoshitaka Sato; IMRAM-Tohoku Univ.; Univ. of Tsukuba; Futaba Corp.

In the active layer of blue LEDs, InGaN QWs are exclusively used, since InGaN alloys of low InN mole fractions exhibit bright emissions with internal quantum efficiency higher than 80% in spite of high threading dislocation density (108 to 109 cm-2). This property is markedly different from the conventional (Al,In,Ga)(As,P) semiconductors or AlGaN alloys. For realizing compact, low power-consumption light sources for high CRI LED-lighting and for sterilization and disinfection purposes, near- to deep-ultraviolet LEDs are indispensable, and are under development using AlGaN. Whereas, as the growth of high-quality crystal is difficult, AlInN alloys have rarely been considered as light-emitting media, although their bandgap energies cover from UV-C to infrared wavelengths. In this presentation, we demonstrate planar vacuum-fluorescent-display devices emitting polarized UV-C, blue, and green lights using m-plane AlInN bulk epilayers. The materials are revealed by positron annihilation and time-resolved photoluminescence measurements to contain a large number of nonradiative recombination centers consisting of Al vacancies higher than 1019 cm-3. Such defective materials may not emit light owing to one-sided nonradiative recombination of excited carriers. However, the films emit the light with the photoluminescence lifetime of 22-32 ps at 300 K. Such defect-resistant radiative performance suggests supernormal localized characteristics of electron-hole pairs in AlInN.

9:30 Th2.2

Efficient InGaN based LEDs within the "Green Gap" grown on Silicon Substrate JL Zhang, Jiang FY, Liu JL, Xu LQ, Wang GX, Ding J, Mo CL, Wang XL, Quan ZJ, Zheng CD, Wu XM, Pan S, Fang F; National Institute of LED on Silicon Substrate; Nanchang University; Nanchang Yellow and Green Lighting Ltd

The "green gap" of LED has been lasting for a long time, neither InGaN nor AlGaInP system performed well in the green-yellow emission range. Efforts were made to explore the potential of InGaN in green-yellow emission, and breakthrough on the "green gap" has been made after we improve the quantum well quality by material growth optimization and reduce the strain by proper structural design. Efficient InGaN based LEDs with various wavelengths ranging from 520-nm-green to 585-nm-orange were successfully developed on silicon substrate. The devices were in size of 1×1 mm2, and measured under CW mode at 200 mA (20 A/cm2). The wall-plug efficiency of the InGaN LEDs is 40% at 520 nm, 21.7% at 565 nm and 11.6% at 585 nm, which decreases approximately 0.45% per nanometer with increasing wavelength. White LEDs made up by mixing InGaN based blue, cyan, green and yellow LEDs on silicon substrate, together with commercialized AlGaInP red LEDs, was demonstrated with CRI as high as 94.8 and luminous efficacy above 100 lm/W at a color temperature of 3262 K. The efficiency of CM-LEDs is comparable with those PC-LEDs with same color temperature and CRI.

9:45 Th2.3

High efficacy direct green InGaN LEDs Adam Bauer, J.P. Ahl, A. Walter, T. Chen, B. Galler, J. Off, T. Filz, B. Hahn; OSRAM Opto Semiconductors GmbH

Increasing efficacies of directly green emitting LEDs in the 530 nm range has proven a most challenging task for decades. Unlike 450 nm devices and despite significant research efforts from both industrial as well as academic side, maximum "green" efficacies at current densities around 45 A/cm² have been stagnating at values only slightly above 100 lm/W for conversion-free direct emitters. Mainly by consequently refining the approach of optimizing carrier transport in high indium containing InGaN epitaxial multi quantum well regions, we recently achieved significantly higher efficacies up to 140 lm/W at 45 A/cm² and at dominant wavelengths around 530 nm. Since at the same time compatibility to standard chip production processing is maintained, market roll-out of numerous products based on the entire UX:3- lineup has already started, thus making record-breaking green efficacies commercially available.

9:45 Th3.2

Small Size InGaN Pyramidal Quantum Dots to Reduce the Effects of Internal Fields M. O. Eriksson, C. W. Hsu, K. F. Karlsson, J. P. Bergman, and Per Olof Holtz; IFM, Linköping University, Sweden

While the nitride based quantum dots (QDs) have an immense potential for light emitting applications, an essential limiting factor for their optical performance, e.g. efficiency and response, is the prevailing internal fields causing the Quantum Confined Stark Effect (QCSE). By employing QDs with a diminutive length in at least one dimension, we have demonstrated that the effect of these internal fields can be minimized. For this purpose, selectively grown pyramidal InGaN QDs, both symmetrical and elongated pyramidal dots, have been developed. In both cases, the luminescence is linearly polarized, but in the latter case, the direction of the polarization of the generated excitonic emission can be controlled. In addition, a high degree of polarization, up to 85%, can be achieved. The small size of the dots is evidenced by the insignificant energy shift of the emission with increasing excitation power, and the short lifetimes of the neutral and charged excitons, 320 ps and 130 ps, respectively, which remain essentially unchanged with increasing power, i.e. consistent with a weak QCSE. The monitored ratio of >2 between the lifetimes of these excitons imply a QD size close to the exciton Bohr radius. By means of a comparison between the experimental results and the theoretical calculations, a length down to 1.4 nm has been estimated for the shortest dimension of the InGaN QD, i.e. smaller than its free exciton Bohr radius.

10:30 Th4.1

Thick InGaN layer with the indium solid composition over 10% using tri-halide vapor phase epitaxy H. Murakami, K. Ema, N. Matsumoto, M. Meguro, H. Murakami, Y. Kumagai, and A. Koukitu; Tokyo University of Agriculture and Technology

InGaN ternary alloys have been regarded as promising materials for light-emitting devices and photovoltaic cells. However, poor crystalline quality of In-rich InGaN epitaxial layers is critical issue for realizing high efficiency optical devices with longer wavelengths due to the lack of initial substrates for InGaN epitaxy. Therefore, thick, high crystalline quality InGaN layers with high indium composition are desired for use as an initial substrate for longer wavelength light emitters. InGaN thick epitaxial layers were grown by tri-halide vapor phase epitaxy (THVPE) using InCl3 and GaCl3, and NH3 as precursors. N2 was used as the carrier gas. Growth temperature was varied from 850ºC to 900ºC. The input ratio of InCl3 in group-III precursors was adjusted to control the solid composition. Input partial pressure of NH3 was fixed at 4.0x10-2 atm. By comparing the InGaN layers grown with various temperatures, mirror-like surface could be obtained at 870ºC while the surface degradation occurred for the InGaN layer grown at 900ºC due to the thermal decomposition. Subsequently, we tried to grow thick In0.10Ga0.90N layer at 870ºC by prolonging the growth time. In0.10Ga0.90N layer with the thickness of approximately 5 μm was successfully prepared after 6h growth. The FWHM of X-ray rocking curves were 555 arcsec for (000-2) and 494 arcsec for (10-1-1) reflections. At the symposium, the experimental results of high indium composition of 15% InGaN will be presented.

10:30 *Th5.1

Nitride light emitters - from superluminescent diodes to semiconductor optical amplifiers Nitride light emitters - from superluminescent diodes to semiconductor optical amplifiers Piotr Perlin, Szymon Stanczyk, Anna Kafar; Institute of High Pressure Physics, "Unipress" TopGaN Ltd.

Nitride semiconductors- based light emitters are not only light emitting diodes but also: laser diodes, optical semiconductor amplifiers (OSA) and superluminescent diodes (SLD). The two latter type of devices complete somehow the set of tools needed for the full development of the visible optoelectronics.

Optical semiconductor amplifiers are needed for all application demanding high optical power, single mode, Gaussian beam emission. We can mention here visible light telecommunication, second harmonic generation, optical atomic clocks etc. In case of superluminescent diodes, these devices should help in building ultra-high-resolution optical tomography systems, micro-projectors etc… Within this work we will present the progress in the development of broad spectral emission (linewidth>15 nm) SLDs, fabricated using a lateral composition gradient method. We shall also discuss the development of nitride optical amplifiers. Our OSAs are fabricated as tapered amplifiers or bent waveguide amplifiers. They reach the gain of 10-20 dB depending on the input power. However, optical amplifiers being broad area devices, pose challenging, thermal problems in case of nitride materials. Accordingly, the maximum gain is usually limited by the temperature increase due to the self-heating. Thus, to reach the maximum optical power you must fulfill many conditions: efficient suppression of self-lasing, securing low active-area temperature operation and avoid fast gain saturation.

10:45 **Th4.2

Synchrotron X-ray study of InGaN layer grown on relaxed InGaN substrate A. Even, C. Richter, M.-I. Richard, Y.M. Vaillant, P. Ferret, O. Ledoux, D. Sotta, E. Guiot, T. Schulli, and A. Dussaigne; CEA, LETI, MINATEC Campus, France; ID01/ European Synchrotron Radiation Facility (ESRF), France; Aix-Marseille Université, France; Nelumbo Digital SAS, France; Soitec S.A., France

To achieve long wavelength emission with InGaN-based LEDs, large indium contents are needed in the active layer. Yet, a limitation to the incorporation of indium exists because of the strain induced by the lattice mismatch between InGaN active layer and the GaN substrate, a phenomenon known as the compositional pulling effect. We recently proposed to tackle this issue by growing a full InGaN structure on a relaxed InGaN substrate. An easier In incorporation is expected owing to a reduction of strain. The InGaN substrate called InGaNOS is manufactured by Soitec using their Smart CutTM technology. Three nuances of InGaNOS with lattice parameters of 3.190, 3.200 and 3.205 Å are available. InGaN/InGaN quantum wells grown on InGaN buffer on InGaNOS showed strong redshift with increased InGaNOS lattice parameter allowing emission from green to amber range. Still, more characterizations of the structure, and especially the evaluation of strain in the InGaN buffer layer, are needed. To deeper understand the relation between the substrate and grown InGaN layer, an X-ray diffraction study was lead at European Synchrotron. Sample consisted of a 200 nm thick InGaN layer grown on InGaNOS with a lattice parameter of 3.190 Å was measured. A mapping of real (2D) and reciprocal (3D) space on symmetric and asymmetrical Bragg reflections was performed at a resolution of 270 nm. A detailed data analysis reveals the full strain/tilt pattern in the buffer layer that is imposed by the substrate.

11:00 *Th4.3

InGaN monlayer: MBE growth and microstructure analysis Xinqiang Wang, Zhaoyin Chen, Xiantong Zheng, Ping Wang, X. Rong, Bo Shen, Tobias Schulz, Martin Albrecht; State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, China; Leibniz-Institute for Crystal Growth, Berlin, Germany

InGaN, with a tunable bandgap energy from 3.4-0.64 eV, nearly perfectly matches the solar spectrum, is a good candidate for high efficiency solar cell. However, high quality InGaN, in particular with high In content, is difficult to realize. To solve this problem, Yoshikawa et al proposed to use (InN)m/(GaN)n digital alloys instead of random InGaN alloys making the InGaN in long range ordering [1]. This approach attracted great interest due to its potential application in devices such as solar cells. Unfortunately, the growth is difficult as well since it needs the atomic level control at either InN or GaN layer [2]. In this talk, we will first report the growth of InGaN monolayer by molecular beam epitaxy, where it was confirmed that the monolayer is InGaN but not pure InN though we only deposit InN. Then, we will focus on the microstructure of this InGaN monolayer, where a periodic arrangement of In and Ga atom was observed. Finally a possible mechanism of that ordered structure of InGaN will be reported.

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11:00 *Th5.2

Novel light emission engineering using III-V dielectric metasurfaces Sheng Liu, Aleksandr Vaskin, Sadhvikas Addamane, Yuanmu Yang, Michael B. Sinclair, Gordon A. Keeler, Benjamin Leung, Miao Tsai, George Wang, Ganesh Balarishnan, Isabelle Staude, Igal Brener; Sandia National Laboratories, Friedrich-Schiller-Universität Jena

All-dielectric metamaterials consist of arrays of high-index, subwavelength-size Mie resonators have been attracting much attentions recently because they strongly interact with both electric and magnetic fields and therefore enable manipulation of the electromagnetic permittivity and permeability. Great success has been achieved in nonlinear optical processes, ultrathin optical components and advanced wavefront engineering using dielectric metamaterials. However, most of the work has been done using silicon, which is not an efficient light emitter. To overcome this, our group recently demonstrated III–V semiconductors based dielectric metamaterials using monolithic fabrication technique that allow for full integration with optoelectronic functionality. In this talk, I will show that we engineer the photoluminescence of light emitters that are epitaxially grown inside the dielectric metamaterials. We design and fabricate two different kinds of structures: symmetry-broken Fano resonator arrays and regular nano-cylinder resonator arrays. With both designs, we observe large enhancement of the photoluminescence intensities, wide spectral tuning as well as significant modification of far-field emission patterns. Our demonstration of active dielectric metasurfaces with enhanced and tunable PL paves the road for new ways to study light matter interaction and for using metasurfaces for tailoring the spectrum and beam shape of quantum emitters.

11:30 Th4.4

Optical Characterization of Ordered InGaN Ternary Alloys Based on (InN)1/(GaN)n Short-period Superlattices Grown by Dynamic Atomic Layer Epitaxy (D-ALEp) Daichi Imai, Kazuhide Kusakabe, Akihiko Yoshikawa; Department of Materials Science and Engineering, Meijo University; Center for SMART Green Innovation Research, Chiba University

Ordered InGaN ternary alloys based on (InN)1/(GaN)n short-period superlattices (SPSs) have attracted much attention for their application to advanced photonic and electronic devices, because these alloys can be potentially free from their immiscibility problems. Recently, we fabricated coherent structure (InN)1/(GaN)n SPSs consisting of 1-ML InN QWs and 4-ML GaN barriers [1, 2]. In this paper, we investigated on the band engineering behaviors with paying special attention on the role of the volume ratio of InN and GaN in the SPSs. (InN)1/(GaN)n SPSs with n = 4-9 were grown at 650 oC on MOVPE-grown GaN/Al2O3 templates by PA-MBE based D-ALEp. SPS-structures were characterized by TEM and HR-XRD. The effective bandgap energy (Eg) was studied by PL and PLE analyses. It was found that Eg of (InN)1/(GaN)n SPSs with n - 7 MLs located around the Eg of discrete 1-ML-InN QW (~3.2 eV). On the other hand, it shifted to lower energies than that of 1-ML-InN QW when n decreased to 4 MLs. Theoretically simulated electron and hole wave functions overlapping in each 1-ML-InN layer in SPSs drastically increased when n < 6 MLs. Thus, we concluded that (InN)1/(GaN)n SPSs behaved as an ordered InGaN ternary alloy when n = 4 MLs. Effect of incomplete InN coverage in the SPSs on Eg will be also discussed in this paper.

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11:30 *Th5.3

Progress in single photon emittes based on GaN quantum dots Yasuhiko Arakawa, Mark Holmes and Munetaka Arita; Institute for Nano Quantum Information Electronics, University of Tokyo; Institute of Industrial Science, University of Tokyo

III-Nitride quantum dots are promising nanostructures for room temperature quantum information technologies, since excitons can be sustained at higher temperature. In 2002, we demonstaretd high-quality GaN/AlN quantum dots with the Stanski-Krastnanov growth mode using MOCVD [1]. The quantum dots exhibited a large biexciton binding-energy (-32 meV), realizing a single photon emission at 200 K in 2006 [2].

Recently, we have acheived the single photon emission at or above room temperature via a position controlled GaN/AlGaN nanowire quantum dot. The structure was grown by selective area MOCVD. A large binding energy of biexciton (> 60meV) realized in the quantum dot enabled single photon emissions at room temperature in 2014 and at 350 K (77-) in 2016, respectively[3,4]. We also succeeded in the formation of interface-fluctuation GaN quantum dots in a thin GaN/AlxGa1-xN (x < 0.25) quantum well. The high temperature growth process led to a striking suppression of spectral diffusion and narrow emission linewidths as low as ~90 micro-eV. A high purity single photon emission from this interface fluctuation quantum dot was achieved of g(2)(0) value smaller than 0.1 at 10 K[5].

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11:45 Th4.5

Origin of green emission in InGaN-based MQWs G.Tamulaitis, J.Mickevičius, D.Dobrovolskas, M.Kolenda, A.Kadys, T.Grinys; Institute of Applied Research and Semiconductor Physics Department, Vilnius University, Lithuania

Shifting the emission wavelength of InGaN-based laser diodes to the green region far enough for applications in picoprojectors encounters substantial problems. We report on the study of capabilities of pulsed metalorganic chemical vapor deposition (MOCVD) to solve this problem by optimizing the timing parameters and growth temperature and by introducing short-period superlattices (SPSL) as buffer layers.

The structural characterization of the structures was performed using TEM and XRD techniques. Photoluminescence of the samples was studied under steady- and quasi-steady-state conditions in a wide range of excitation power densities from 4 W/cm2 to 10 MW/cm2. The carrier lifetimes were estimated using time-resolved photoluminescence spectroscopy based on a streak camera. A distinct feature of the study is that the effective band gap was estimated using the time-resolved differential transmission spectroscopy.

A considerable shift of the photoluminescence band peak down to ~2 eV at low carrier densities is achieved by decreasing the growth temperatures for both SPSL and quantum wells down to 800 °C. However, an increase in the carrier density resulted in a considerable blue shift of the band and strong droop effect in green emitting MQWs. The comparison of the data on PL and differential optical transmittance revealed that the large red shift in the PL band position is predominantly caused by a long tail of localized states rather than by introduction of higher In content.

13:30 **Th6.1

High Efficiency, Ultrasmall InGaN micro-LEDs for Displays and Solid State Lighting David Hwang, Asad Mugha, Christopher D. Pynn, Shuji Nakamura, Steven P. DenBaars; Materials Department, University of California, Santa Barbara, USA; Department of Electrical and Computer Engineering, University of California, Santa Barbara, USA

III-nitride μLED based displays are poised to outperform incumbent technologies, such as liquid crystal displays and organic light-emitting diode displays, with regards to efficiencies. InGaN μLEDs are promising due to high brightness, high luminous efficacies, and long lifetimes. However, as the dimensions of μLEDs decrease, surface recombination effects may limit the efficiencies. External quantum efficiencies (EQEs) of red AlGaInP μLEDs have been shown to drop sharply with size. We present findings that ultrasmall InGaN μLEDs can sustain high EQEs as areas are shrinked from 0.01 mm^2 to 10^-4 mm^2. The peak EQEs of the smallest and largest μLEDs were 40.2% and 48.6%, respectively. The difference in EQE was from nonradiative recombination from etch damage. The efficiency droop at 900 A/cm^2 of the smallest μLED was 45.7% compared with 56.0% for the largest and was lower because of improved current spreading. Optical micrographs show that smaller μLEDs have more uniform emission than the larger ones. The forward voltage of the μLEDs also dropped with size, since there is less volume of resistive layers, such as indium tin oxide and p-GaN. These results showed ultrasmall μLEDs may be fabricated without a significant loss in optical or electrical performance. Similar trends for green μLEDs as well as new epitaxial and chip designs to decrease electrical and optical losses will also be presented.

This work is supported by the King Abdulaziz City for Science and Technology.

13:30 *Th7.1

Intersubband transitons in GaN nanowires: towards the nanowire QWIP A. Ajay, J. Lähnemann, M. den Hertog, D. A. Browne, C. B. Lim, and E. Monroy; CEA-Grenoble, France

Nanowire (NW) heterostructures constitute an interesting approach for intersubband (ISB) photodetectors due to their small electrical cross-section, which comes without degradation of light absorption. In the case of GaN/AlN, the large conduction band offset makes it apt for devices in the telecommunication range around 1.5 μm. Such devices require n-type doping to populate the first electronic level, and their operation wavelength and bandwidth are very sensitive to the carrier density. Here, we first report an assessment of ISB transitions around 1.55 μm in GaN/AlN NW heterostructures using Ge and Si dopants. We present systematic studies of the impact of doping on ISB transitions. To discriminate between doping and geometry effects, we compare the results with similar structures in planar geometry (with both dopants). Then, single-NW quantum-well infrared photodetectors (QWIPs) are fabricated using GaN NWs that incorporate a 40-period GaN/AlN superlattice absorbing at 1.5 μm. Under illumination with IR lasers, a photocurrent is observed, which we attribute to transitions between excited states of the conduction band in the GaN insertions. The spectral dependence of the photocurrent shows a maximum in the range of 1.3–1.5 μm. The IR photocurrent scales linearly with increasing laser power, which confirms that it is rather independent of surface-related phenomena, in agreement with theoretical calculations, and in contrast to the UV band-to-band photocurrent in the same NW.

13:45 Th6.2

Enhanced fluorescence from structurally engineered colloidal quantum dots and its application to phosphor-capped white LEDs Kyungtaek Min, Jongho Lee, Kyung-Sang Cho, Yeonsang Park, Heonsu Jeon; Ajou University; Seoul National University; Samsung Advanced Institute of Technology

The role of phosphors for color conversion has become extremely important for the white LEDs and solid-state lighting applications. Conventional phosphor developments have been heavily materials-oriented to address higher internal quantum efficiency or modified absorption/emission bands. Here we propose and demonstrate a new approach to improve the color conversion efficiency by structurally engineering phosphor materials. For the proof-of-the-concept, we shape densely-packed colloidal quantum dots (CQDs) into a planar photonic crystal (PhC) structure such that the interaction between CQD nanophosphors and excitation photons is boosted up via the photonic band-edge effect. Our CQD-PhC phosphor consists of a lateral one-dimensional PhC Si3N4 backbone layer on quartz substrate and CdSe-CdS-ZnS core-shell-shell CQDs spin-coated atop. When the CQD-PhC phosphor was optically excited at the PhC band-edge energy, we observed CQD fluorescence 5 times higher than that from the reference phosphor. We also incorporated red and green CQD-PhC phosphors with a GaN-based blue LED chip to demonstrate that trichromatic white light can be generated with a high efficiency. We achieved the chromaticity coordinates (0.33, 0.34) and correlated color temperature 5500 K, yet with a substantially less amount of CQDs than the reference LED.

14:00 *Th6.3

Routes to ultra-efficient III-nitride emitters for solid-state lighting J. J. Wierer, Jr., X. Wei, S. A. Al Muyeed, W. Sun, R. Song, and N. Tansu; Lehigh University

This presentation will cover potential routes to ultra-high efficiency in III-nitride light-emitters for solid-state lighting (SSL). First, methods to overcome efficiency droop and parasitic Auger recombination in violet-blue emitters will be discussed. This includes a theoretical analysis of laser diodes (LDs) as the light source instead of light-emitting diodes (LEDs), and also using quantum dots in place of quantum wells in both LEDs or LDs. QD-based active regions are of great interest because QD-based LDs can achieve gain and thresholds at lower carrier densities before Auger recombination becomes appreciable, and QD-based LEDs can achieve higher efficiencies at higher currents because of higher spontaneous emission rates and reduced Auger recombination. Second, we experimentally explore AlGaN interlayers within InGaN based multiple quantum wells (MQWs) in order to improve light emission efficiency from the green though the red. These AlGaN interlayers help with increasing indium incorporation in the InGaN alloy, improving heterointerface abruptness, and reduce defect formation. Additionally, this AlGaN interlayer acts as a strain compensation layer, and forces pseudomorphic growth of the entire MQW stack in order to limit defect formation and retain high radiative efficiency. The sum of these improvements in III-nitride light emitters across the entire visible spectrum will lead to more efficient SSL sources.

14:00 Th7.2

Core-Shell GaN Nanowire LEDs for Optically Active Scanned Probe Tips Matt D. Brubaker, Joel C. Weber, Paul T. Blanchard, Bryan T. Spann, Alexana Roshko, Todd E. Harvey, Norman A. Sanford, and Kris A. Bertness; Physical Measurement Laboratory, National Institute of Standards and Technology, USA

GaN nanowire (NW) LEDs hold great promise as nanoscale light sources for a broad range of microelectronics, materials, and biological measurement applications. To realize a practical measurement platform, we are developing a scanned-probe-based device that uses a single GaN NW LED as the tip. Isolated and single NW LEDs have been grown on silicon substrates compatible with cantilever microfabrication and use a selective area growth (SAG) process that utilizes polarity-controlled buffer layers to produce N-polar NWs with arbitrarily large pitch spacing. The NW LEDs are p-n homojunction devices and have a radial structure. By contacting the n-type core through the conductive buffer layer and the p-type shell by a metal contact layer, these single NW devices produce electroluminescence at ~380 nm, likely through donor-acceptor-pair recombination in the p-type shell. Interestingly, these devices remain operative at 5 K, suggesting that carrier freeze-out does not preclude low-temperature operation and further suggests degenerate Mg doping in the p-type shell. The high p-doping level in these NWs is likely attributed to N-rich growth conditions, which encourages Mg incorporation on the Ga site, and to the low growth temperature used for the shell (relative to the core). Low-temperature shell growth is made possible by the isolated nature of the NWs, where otherwise growth by molecular beam epitaxy would lead to self-shadowing effects and a non-uniform shell layer.

14:15 **Th7.3

Phosphor-Free III-Nitride Nanowire Light-Emitting Diodes on Flexible Substrates M. R. Philip, D. D. Choudhary, M. Djavid, M. N. Bhuyian, D. Misra, and H. P. T. Nguyen; Department of Electrical and Computer Engineering, New Jersey Institute of Technology, USA

III-nitride nanowire (NW) light-emitting diodes (LEDs) have recently been explored as an exciting topic to the photonic community. Such NW structures are normally grown on Si, which may largely absorb photon emitted from LED active

region, severely limiting light output power. Additionally, Si has lower electrical conductivity and thermal expansion coefficients compared to metal. In this study, we report on the achievement of high performance NW LEDs on metal substrates (copper) via substrate-transfer process. Nanowire LEDs were first grown on silicon-on-insulating substrate by molecular beam epitaxy. Subsequently, NWs were removed from original substrate then transferred onto copper by combining dry/wet etching processes. The LED on copper was characterized and showed stronger photoluminescence, electroluminescence intensities and better current-voltage characteristic compared to NW LED on Si. Our simulation results further confirm the improved device performance of LED on copper. The light extraction efficiency of NW LED on copper shows 9 times higher than that of LED on Si at the same NW radius of 55nm. Moreover, by engineering the device active region, we achieved high brightness phosphor-free LEDs on copper with highly stable white light and high CRI of >95, showing their promising applications in general lighting, flexible displays and wearable electronic applications. The achievement of NW LEDs on polymer substrate is currently in progress and will also be presented.

14:30 Th6.4

High power LEDs for Outdoor Luminaire Applications Yong Seok Choi, John Cesaratto, Oleg Shchekin, Werner Goetz; Lumileds, LLC (United States)

High power LEDs have served as a key component in light engines for outdoor luminaire applications for more than 10 years. They have enabled highest efficacy, luminous flux and have proven lumen maintenance capability. High power LED light engines illuminate an ever increasing portion of roads, stadiums, and industrial spaces improving lighting quality over conventional luminaires while saving electricity. New trends include the integration of LEDs with controls and driver components for connected lighting. In this paper, we will discuss the development of next generation high power LEDs at Lumileds. Development objectives are exceptional performance over a wide operational range, superior beam quality and highest luminance from a compact light emitting surface. The development entails high power LED architecture engineering for luminous flux, thermal management, and radiation pattern with improved color uniformity. Furthermore, we will show case studies on system-level optical performance.

14:30 *Th7.4

III-Nitride Nanowire Monolithic Diode Lasers and Photonic Integrated Circuit on (001)Silicon Pallab Bhattacharya, A. Hazari, F.C. Hsiao, J. Dallesasse; EECS Department, University of Michigan, USA; ECE Department, University of Illinois at Urbana-Champaign, USA

GaN-based nanowires and nanowire heterostructures can be grown on (001) Si substrates by molecular beam epitaxy. The polarization field and density of extended defects in the nanowires are smaller than in planar heterostructures. These nananostructures therefore enable a new III-nitride based technology which allows the realization of light sources that have emission in the green gap and beyond. Single nanowire heterostructures and arrays have been used to demonstrate novel light sources. We have demonstrated green- and red-emitting LEDs and edge-emitting diode lasers made with nanowire arrays in which the light-emitting active region consists of multiple InGaN disks surrounded by GaN barriers. The structural and optical properties of these nanowire heterostructures and the LEDs and lasers will be described. The lasers have Jth ~ 1-2A/cm2 and small signal modulation bandwidths ~ 4-6 GHz have been measured. By increasing the In content in the InxGa1-xN disks, up to x = 1 (InN), we have realized edge-emitting lasers with peak emission at 1.3µm. The InN/InGaN/GaN nanowires have been characterized and modeled to understand their electronic and optical behavior. Finally, we will describe the characteristics of monolithic 1.3µm photonic integrated circuits on (001) Si consisting of a nanowire laser and detector, made with the same nanowire array, and a coupling dielectric waveguide in between.

14:45 **Th6.5

High-power and directional laser-based white lighting using computational design and thermally stable phosphor morphologies Clayton Cozzan, Guillaume Lheureux, Michael J. Brady, Nicholas O'Dea, Claude Weisbuch, Shuji Nakamura, Steven P. DenBaars, Ram Seshadri; Solid State Lighting & Energy Electronics Center University of California Santa Barbara, USA; Materials Department University of California Santa Barbara, USA

For high power and directional white lighting applications, laser diodes (LDs) show promise due to directional emission and more light output for a given chip area without droop. Central to solid-state white lighting are phosphors that convert solid-state radiation from the device to other colors that mix and render white light. High power emitters in potential applications such as smart headlamps and high lumen lighting pose new design challenges for phosphors, as typical phosphor encapsulants cannot withstand the heat generated at LD fluency levels. In the current work, stable and efficient inorganic phosphor morphologies for laser-based lighting systems were developed, and property-processing relationships for multiple examples ceramic phosphors will be discussed. Computational modeling of fundamental phosphor properties using measured physical parameters and Monte Carlo ray tracing techniques informed our laser-based lighting device design and prototyping. Thermal modeling was employed to understand the heating of the light source and the phosphor, and to

explore heat-sinking strategies. The results of simulated devices and lab-built lighting devices using both single crystal and ceramic phosphors both outperform comparable LED-based technologies while having tunability of the angular divergence and color rendering, high light output, and smaller chip area. Live demos of our devices were successfully presented at the ARPA-E Summit 2017 (Washington DC), and will be shown.

15:00 *Th6.6

Understanding and mitigating Auger recombination in nitride LEDs Emmanouil Kioupakis, Christina Jones, Logan Williams, Nocona Sanders, Dylan Bayerl, Andrew McAllister, Guangsha Shi, Chu-Hsiang Teng, Qimin Yan, Pei-Cheng Ku; University of Michigan, USA

InGaN LEDs suffer from reduced efficiency at high power and longer wavelengths, attributed to Auger recombination and its interplay with polarization fields. We employ theoretical calculations to understand and mitigate Auger recombination in nitride LEDs. Our findings demonstrate that carrier localization due to InGaN random composition fluctuations increases the Auger recombination rate more than the radiative, and has a detrimental effect to the internal quantum efficiency. We also studied radiative and Auger rates for degenerate carries in InN. Auger recombination remains strong for densities at which radiative recombination is suppressed by phase-space filling, which is detrimental to the internal quantum efficiency. On the other hand, our calculations demonstrate that extreme quantum confinement in atomically thin GaN wells enables light emission in the deep UV range, as well as the formation of stable excitons at room temperature with shorter radiative lifetimes than free carriers. We further explore BInGaN as an alternative alloy to InGaN. By engineering the B:In ratio we designed BInGaN alloys that are lattice-matched to GaN with band gaps spanning the entire visible range. Our results highlight the promise of BInGaN alloys for high-power high-efficiency LEDs. This work was supported by the NSF ECCS-CDS&E (1607796), DMREF (1534221), and DMR-CAREER (1254314) programs. Computational resources were provided by the DOE NERSC facility (DE-AC02-05CH11231).

15:00 Th7.5

Conversion efficiency enhancement in polarization-induced InGaN/GaN nano-photoelectrodes for hydrogen generation Bin Liu; Tao Tao; Ting Zhi; Wenjun Luo; Zili Xie; Dunjun Chen; Zhaosheng Li; Rong Zhang, Youdou Zheng; Key Laboratory of Advanced Photonic and Electronic Materials, School of Electronic Science and Engineering, Nanjing University, China; Ecomaterials and Renewable Energy Research Center (ERERC), School of Physics, Nanjing University, China.

Photo-electrochemical water splitting for hydrogen generation is considered as a promising new energy technology due to the environmental friendly property and free resources on the earth. Although III-nitride semiconductor materials have been demonstrated as favorable photoelectrodes(PEs), high energy conversion efficiency and self-driven working are highly desirable for practical applications. In this study, owing to the high quality of InGaN/GaN multiple quantum wells grown on patterned sapphire substrates, the ordered nanostructured PEs effectively have been fabricated by nano-imprint lithography technique. The nanostructured PEs exhibit the incident photon conversion efficiency(IPCE) ~ 42% at the wavelength from 400nm to 450nm. More significantly, the device can work without any external driving voltage, which is due to the polarization-induced effect after fabrication into nanorods. Furthermore, SiO2/Si3N4 dielectric distributed Bragg reflectors are employed to improve the IPCE up to 60 % further, which is close to our theoretical estimation. These achievements could pave a way for the practical applications of GaN-based PEs.

15:15 Th7.6

InN Nanopillar Photodetector with Enhanced Infrared Response Using Indium-Tin Oxide Nanorods Lung-Hsing Hsu; Institute of Lighting and Energy Photonics, National Chiao Tung University, Taiwan; Research Center for Applied Sciences, Academia Sinica, Taiwan

An enhanced infrared photoresponse is observed in InN/ITO rods fabricated by LP-MOCVD and oblique-angle electron beam evaporation. The higher growth temperature and more V/III could trend toward hexagonal InN pillars epitaxy. The peak energy blue-shift phenomenon due to higher Fermi-level to acceptor emission was investigated by temperature dependent photoluminescence (PL) measurements. ITO nanorods enhanced the broadband and angle-independent anti-reflection in the range between 400 nm and 2000 nm. The novel photodetection device in InN pillars/ITO rods materials exhibits the enhanced IR response owing to ITO nanorods contributing to antireflection in the visible to near infrared wavelength range. The high quality InN pillars and ITO nanorods can be available to integrate into real devices and the portion photocurrent (610 nm long pass) of InN detection as high as 24.5% measured via AM1.5G solar simulated spectra.

16:00 Th8.1

Nanorod array shaping and formation through nano-mold process Je Won Kim; Department of Information and Communication Engineering, Namseoul University Cheonan, Korea

The purpose of this study is to produce the three-dimensional structure with the application of nano-structure mold

process. The three-dimensional structure and growth will provide more friendly ways through nano manufacturing process using mask patterning and etching process. This study will show multiple wavelength of light emitting diodes different from the single wavelength of existing ones through formation of nano-mold with uniformity and reproducibility. This study will show the characteristics of various wavelengths beyond blue and green through newly developed nano-mold and its nanorod array. This research will also prove the feasibility of the white light emitting diode without phosphor as multiple wavelength in a single chip can be realized. This kind of study about the light emitting diode with nano structure is actively being conducted to develop the next generation technology for AVR and wearable display. This study is aimed at forming new nano-mold applied with semiconductor's manufacturing process, suggesting the new characteristics of nano structure by the way of realizing the light emitting diode of three-dimensional structure by this mold.

16:00 *Th9.1

Highly spatially resolved investigation luminescence of III-nitrides nanostructures using STEM-CL Jürgen Christen, Frank Bertram; Otto-von-Guericke-University Magdeburg, Experimental Physics, Germany

The combination of luminescence spectroscopy - in particular at liquid He temperatures - with the high spatial resolution of a scanning transmission electron microscopy (STEM) (Delta_x < 1 nm at RT, Delta_x < 5 nm at 10 K), as realized by the technique of low temperature scanning transmission electron microscopy cathodoluminescence microscopy (STEM-CL), provides a unique, extremely powerful tool for the optical nano-characterization. Typical results, which will be presented, include the nm-scale analysis of 3 dimensional GaN based nanostructures visualizing the enormous capability of STEM-CL characterization: We present a unique approach to analyze the free-carrier concentration within Si-doped GaN cores of a microrod LED and the related impact on the luminescence properties of the coaxial shell layers by nanocathodoluminescence and µ-Raman spectroscopy.

CL microscopy is utilized to investigate the correlation of structural and optical properties as well as defect density, strain distribution, locally resolved stoichiometry and impurity incorporation on a sub-micrometer scale for nanorords grown in a bottom-up as well as top down approach. The last example will deal with quantum structures embedded in nanorods and their spatially resolved characterization.

16:15 Th8.2

Stress Modulation of GaN Epilayer on Sapphire with Graphene Interlayer B. Wang, Y. L. Fang, J. Y. Yin , Z. R. Zhang , Y. M. Guo , J. Li, W. L. Lu, Z. H. Feng; National Key Laboratory of ASIC, China

Graphene is a monolayer with a two-dimensional hexagonal lattice of carbon atoms. Instead of strong chemical bonds between GaN and sapphire, the GaN and graphene are bound by the weak van der Waals interactions, therefore the graphene interlayer is predicted to modulate the stress of GaN epilayer. In this study, GaN epilayer is grown on sapphire substrate with (sample 1) and without (sample 2) graphene interlayer by MOCVD respectively and the stress performance of the two samples is analyzed. Graphene interlayer is deposited by CVD.

The E2(high) Raman peak of the GaN is located at 577.66 cm-1 and 566.75 cm-1 respectively for sample 1 and sample 2. The blue shift occurred obviously with graphene interlayer. Calculated by the shift of GaN E2(high) peak, the residual stress of GaN are 2.36 GPa (sample 1, compressive stress) and 0.17GPa (sample 1, tensile stress), respectively. The GaN of sample 2 is almost completely relaxed. The curvature shows that the two samples are both convex with a bow value of 21.74um(sample 1) and 1.39um(sample 2) respectively. The sample 2 is more flat with a smaller bow value.

Due to the weak van der Waals force between graphene and GaN, the interactions between sapphire substrate and GaN epilayer is relaxed. During the high temperature growth and cooling process, the lattice and thermal expansion mismatch between sapphire substrate and GaN epilayer will be buffered by elastic graphene interlayer, and the residual stress of GaN is modulated.

16:30 Th8.3

GaN growth on Al template by MBE for the fabrication of micro displays T. Honda, Y. Hoshokawa, K. Uehara, T. Onuma and T. Yamaguchi; Kogakuin University

GaN-based micro-size light-emitting diodes (µ-LEDs) have much attention for the application to micro displays with LED pixels. In this case, small LEDs less than 50 µm in diameter are required for their fabrication. Now we suppose the discrete LED chips with a micro-cup array, the backside of LED wafers should be polished off for their cleaving. Thus, the liftoff process of the LEDs is interesting in view of the fabrication of µ-LEDs. GaN growth on a metal template is a candidate for the liftoff process, because the GaN layers and substrates can be separated using chemical liftoff techniques. In this paper, GaN growth on an aluminum (Al) template is reported. We also discuss the reduction of Al surface segregation. Here, the introduction of low temperature (LT) buffer is effective for the reduction and atomically flat Al surface is a key to realize the improvement. The GaN layers were grown on Al templates, which were grown on (0001)sapphire substrates, by molecular beam epitaxy with RF-excited N2 gas (RF-MBE). The Al layers were grown at RT or 250°C. After their nitridation, LT-GaN buffers were grown on them. The GaN layers were grown

on the LT-GaN layers at 650°C. It was found that the Al layers were not a "simple" face-centered crystal (fcc) but they had a natural supper-lattice structure along the growth direction. A relationship between the Al segregation on the GaN surface and surface morphologies of Al templates will be discussed in the session.

16:30 *Th9.2

High-Resolution Transmission Electron Microscopy and Energy Loss Spectroscopy Applications to Semiconductor Nanostructures Gianluigi A. Botton; McMaster University

Transmission electron microscopy (TEM) is an essential characterization technique for the study of semiconducting nanostructures. Coupled with electron energy loss spectroscopy (EELS), TEM becomes a very powerful toolkit to investigate both the structure of defects and the electronic structure of materials with both high spatial resolution (down to the atomic level) and high energy resolution (even below 0.1eV). In this communication, state-of-the-art advances in TEM will be shown, with particular emphasis on the investigation of the growth of semiconducting compounds and the structure of interfaces and nanowires. First, the powerful chemical analysis capabilities of atomic-resolved chemical imaging will be shown and examples of this technique, related to the study of ordering in GaN compounds[1], will be discussed. Second, examples of quantitative measurements of strain in semiconductor nanostructures will be given[2]. This work highlights the potential of the microscopy characterization "arsenal" to investigate the relationship between structure, composition and properties. Further examples will be related to the investigation of the plasmonic response of materials and will show how EELS can provide spectroscopic information necessary to understand the properties of devices.

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[2] Woo, SY; et al., (2015), NANOTECHNOLOGY, 26(34), 344002.

16:45 Th8.4

Growth of GaN single crystal by LPE-Na flux method adding nitrogen-doped addtives Z. L. Liu, G. Q. Ren, X. J. Su, J. F. Wang and K. Xu; Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, China; Suzhou Nanowin Science and Technology Co., Ltd., China

It has been found that homoepitaxial device layers grown on freestanding GaN substrates are essential to the improvement of the performance of devices. Therefore, further development of high quality, low cost and large scale GaN substrates is needed. The Na flux method which is one of the major methods has many advantages to grow bulk GaN single crystals. However, it is difficult to grow large-size GaN crystals with a moderate growth rate because of the difficulty in controlling the spontaneously nucleation process. Moreover, the surface of GaN seed will be redissolved in the solution before the solution becomes saturated with nitrogen. This will cause the quality of the overgrowth GaN to reduce. To overcome such drawbacks, there are several attempts have being used. In our study, by comparing the effect of different carbon additive types, including carbon nanotubes, active carbon, graphene, graphite, and ordered mesoporous carbon, on the suppression of polycrystal generation and growth rate of LPE-GaN, it shows that the carbon sources with graphitic N in the majority can more effectively suppress the polycrystals and achieve a higher growth rate of LPE GaN single crystals, while it is benefit for growth of large size GaN single crystal. Moreover, the GaN seed redissolution is effectively suppressed by adding the nitrogen-doped carbon additives. The growth mechanism of GaN by Na flux method adding nitrogen-doped carbon additives has been studied.

17:00 Th8.5

Low-dislocation Density and 6 Inch GaN Substrates Grown by Hydride Vapor Phase Epitaxy Jianfeng Wang, Guoqiang Ren, Yu Xu, Demin Cai, Mingyue Wang, Yuming Zhang, Xiaojian Hu, and Ke Xu; Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, China; Suzhou Nanowin Science and Technology Co. Ltd., China

Further reduction of dislocation density and enlargement of wafer size are two important issues for homo-epitaxial technology based on GaN substrates, which is leading the next wave nitride semiconductor development. This paper reports our recent progress of HVPE-grown GaN substrates. By employing a new developed HVPE system, bulk GaN crystal can be grown up more than 10mm in thickness with the diameter of 2 inch. After slicing, it is found that the dislocation density is declining sharply from 108cm-2 to 104cm-2 when the thickness is increasing from several micrometers to several millimeters. By the enlargement and optimization of HVPE reactor, 4 inch and 6 inch crack-free GaN layers with the thickness about 300μm is successfully grown on the Sapphire substrate. With our home-made laser-lift-off equipment, 4 inch and 6 inch GaN layers are separated from Sapphire, with the typical dislocation density about 106 cm-2. For the un-doped GaN substrate, the back carrier concentration is as low as 1~5*1016cm-3. For the N-type GaN substrate, the behavior of Ge-doping and Si-doping is carefully compared. For the semi-insulating GaN substrate, the relationship between the resistivity and the concentration of Fe and Si is discussed.

Finally, the performance of some typical devices based on our GaN substrates is also demonstrated under the cooperation with other research groups, such as blue and green

LDs, SBDs with the breakdown voltage of 1200V,and inter-subband absorption structures.

17:00 Th9.3

Optical properties in InGaN/AlGaN quantum wells on GaN nanocolumns fabricated by selective area growth

Takao Oto, Tatsuya Kano, Rin Miyagawa, Fumito Tachibana, and Katsumi Kishino; Department of Engineering and Applied Sciences, Sophia University; Sophia Nanotechnology Research Center, Sophia University

Nanocolumns (NCs) have attracted great attention due to the low dislocation density, high light extraction, and low strain energy. We have investigated the structural and optical properties in the InGaN-based NCs by Ti-mask selective area growth (SAG). By replacing a GaN barrier with an AlGaN for the InGaN-based quantum wells (QWs), a strain-compensated QW was fabricated on GaN, resulting in the high radiative recombination probability [1]. A self-assembled InGaN/AlGaN dot-in-NC was reported [2], but the size and shape are inhomogeneous. In this study, using the SAG, we investigated the optical properties in the InGaN/GaN and InGaN/AlGaN QWs on the GaN NCs changing systematically the GaN column diameters D. From the temperature and excitation power dependences of the photoluminescence (PL) peak-energy, it was found that the in-plane potential fluctuation decreased in the InGaN/AlGaN QWs compared to the InGaN/GaN QWs probably because of the strain compensation [3]. PL lifetimes at 300 K in the InGaN/AlGaN QWs were longer than those in the InGaN/GaN QWs for the range of D=80–200 nm, exhibiting the decreased nonradiative recombination. And the internal quantum efficiency was enhanced in the InGaN/AlGaN QW. Thus, the use of AlGaN barriers contributes to the improved emission properties in the InGaN-based NCs. [1] H. Zhao et al., IEEE J. Quant. Electron. 45, 66 (2009). [2] H. P. T. Nguyen et al., Sci. Rep. 5, 7744 (2014). [3] M. E. Aumer et al., Appl. Phys. Lett. 80, 3099 (2002).

17:15 Th9.4

Sub-µm Correlation of Optoelectronic and Photoelectric Performance of GaN/InGaN Nanorod LEDs

Wolf Quitsch, Sebastian Beuel, Moritz Loewenich, Tilman Schimpke, Adrian Avramescu, Martin Strassburg, Gerd Bacher; Werkstoffe der Elektrotechnik and CENIDE, Universität Duisburg-Essen, Germany; OSRAM Opto Semiconductors GmbH, Germany

GaN/InGaN based nanorods are promising candidates for the next generation of light emitting diodes (LEDs). Due to the high surface to volume ratio, higher luminance at the same current density is expected as compared to layered LEDs. Furthermore, the unique geometry enhances photon outcoupling efficiency and polarization free crystal facets become accessible, enabling new device concepts such as high frequency LEDs. In order to compete with established device concepts, a high homogeneity of the quantum well emission, combined with efficient current injection is mandatory. In order to access these three-dimensional structures, advanced measurement techniques with high spatial resolution in all dimensions become important. Here, we present an approach to study the correlation of electroluminescence (EL) with photoluminescence (PL) and photocurrent (PC) under quasi-resonant optical pumping with sub-µm spatial resolution. Mapping the EL of a single nanorod, the majority of the emission is found close to the tip. In contrast, the PL intensity decreases from the bottom to the tip, coming along with a red shift of the luminescence, which we attribute to a gradient of the In concentration and/or the thickness along the wire. Interestingly, the simultaneously mapped photocurrent shows a rise towards the tip. This indicates an efficiency loss via carrier escape from the active layer to be responsible for the optoelectronic and photoelectric device performance.

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