Micro-Light-Emitting Diode ("Micro-LED") arrays: Overview and applications

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www.strath.ac.uk/science/physics/instituteofphotonics/

Talk outline

1. **IOP overview and history**
2. **LED basics:**
    1. p-n diode and electroluminescence
    2. Materials systems
    3. Growth and fabrication
    4. Typical LED characteristics
3. **GaN micro-LEDs:**
    1. Development of micro-LEDs
    2. Addressing schemes and structures
    3. Prospects for full-colour arrays
    4. Integration with CMOS backplanes
4. **Applications:**
    1. Displays
    2. Visible light communications
    3. Navigation via. “Structured Light”
    4. Fluorescence lifetime measurements
    5. Mask-free photolithography & opto-electronic tweezing
    6. Optogenetics
5. **Summary and future prospects**

Institute of Photonics

INSTITUTE OF PHOTONICS

Established 1995

UNIVERSITY of STRATHCLYDE
TECHNOLOGY & INNOVATION CENTRE

Cumulatively in excess of £20M of funding as principal investigators from EPSRC alone

Over 100 contracts with industrial partners

Central role in the formation of the UK's first Fraunhofer Centre, mLED Ltd, CST Ltd and Photonix Limited

Three Royal Academy of Engineering Research Fellows and a Fraunhofer/RAEng Chair in Advanced Laser Engineering

60 staff and students with a principal investigator complement of 10

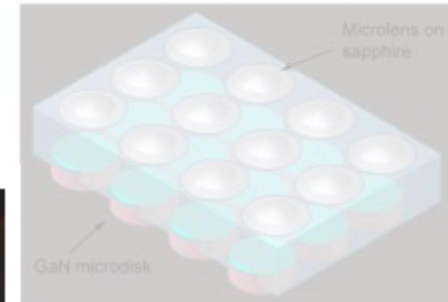
Graduated over 70 PhD-level students, many of whom now work for local industry

12 photonics laboratories and a clean room microfabrication facility (totalling over 1000m^2) in the University's flagship Technology & Innovation Centre

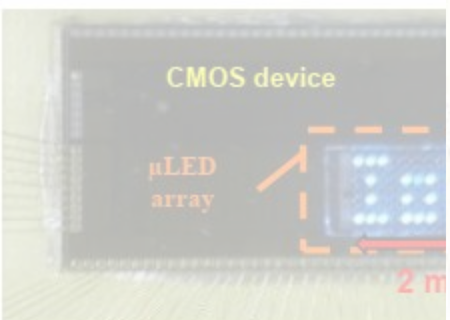
Some micro-LED milestones in the group

- Started our own fabrication of these devices in **2001**

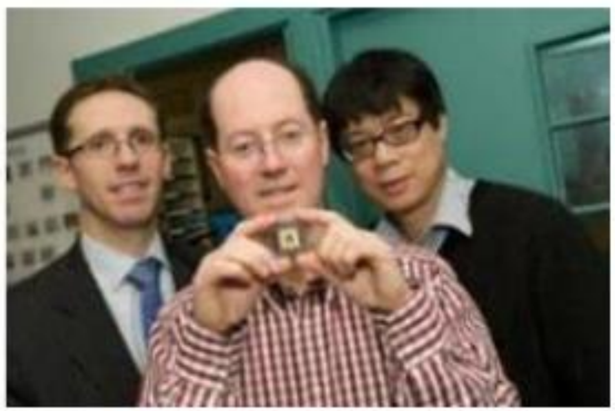
128 x 96 monochrome matrix addressed arrays (12 x 12μm^2 pixels) , plus integrated microlenses by **2004**

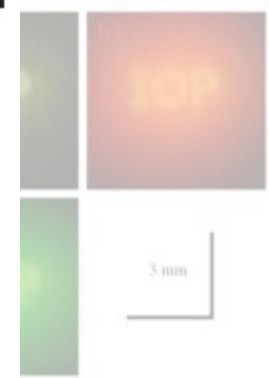


First CMOS driven devices … ır conversion in **2007/8**

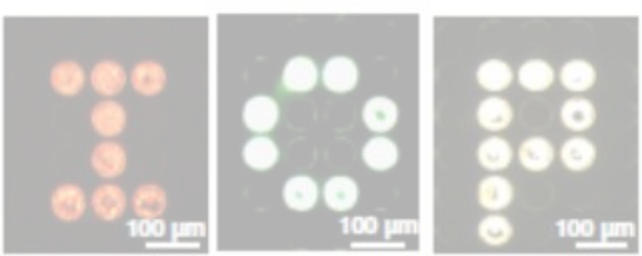


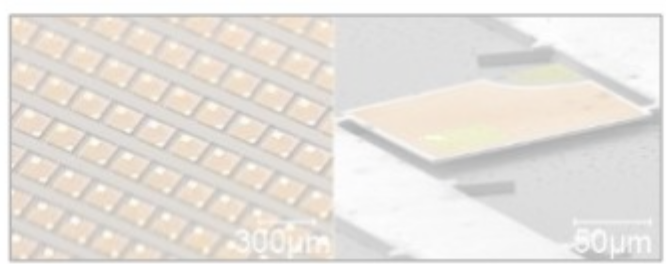
Est. 2009
Sold 2016

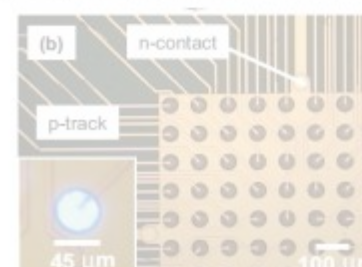




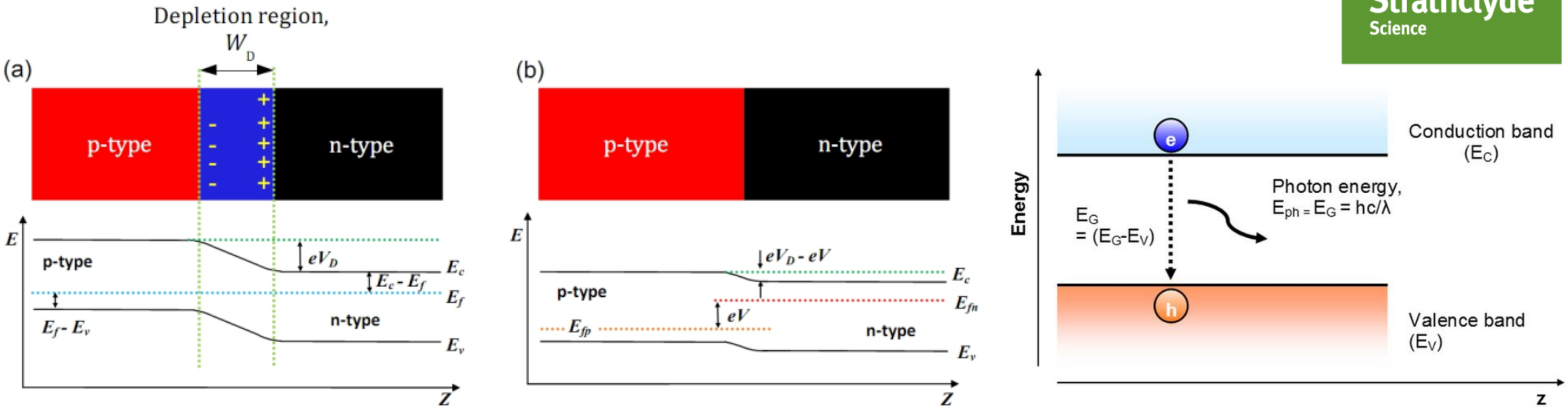
Current density dependent colour/bandwidth **2012**, transfer printing **2013**, GaN/Si micro-LEDs **2013/14**







Basic *p-n* diode

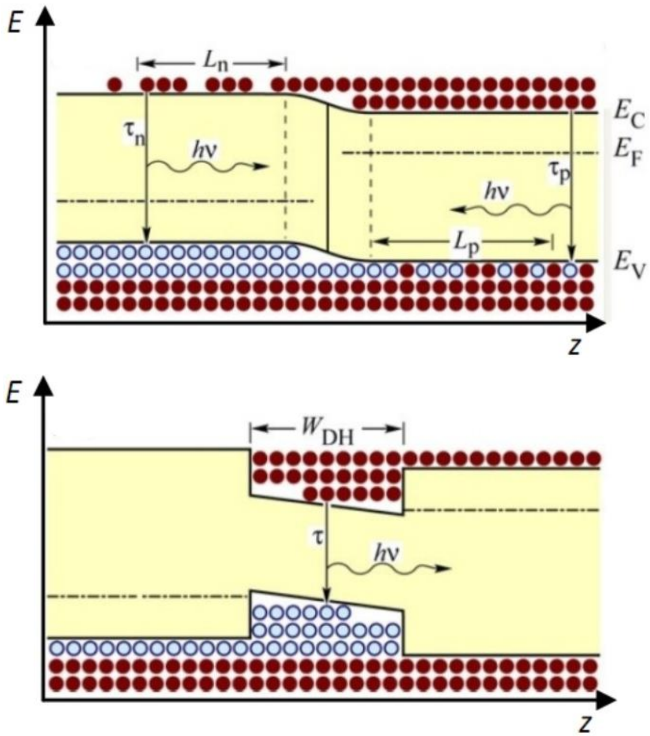


LED under (a) zero and (b) forward bias. (c) electroluminescence

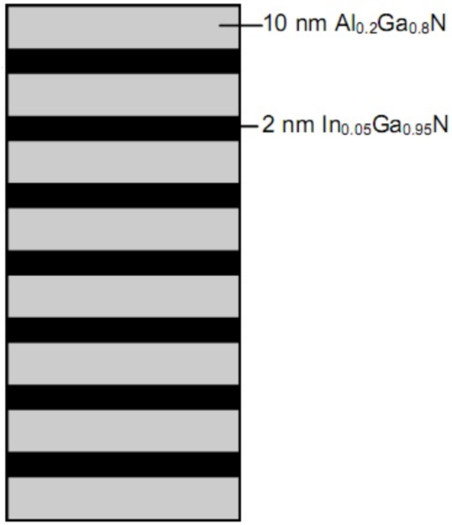
- Simplest form of diode – Holes(electrons) diffuse from the p-type(n-type) material into the adjacent n-type(p-type)
- Creates a depletion region that prevents current flow, figure (a)
- Forward biasing the diode (+ve voltage from p to n) counteracts the depletion region, figure (b). Current can flow if the forward bias is high enough.
- Current only flows in one direction!
- Electrons from the conduction band combine with holes in the valence band (c).
- Energy lost (E_G) during this transition is (ideally) released as a photon

Quantum well structures

(a)



(b)

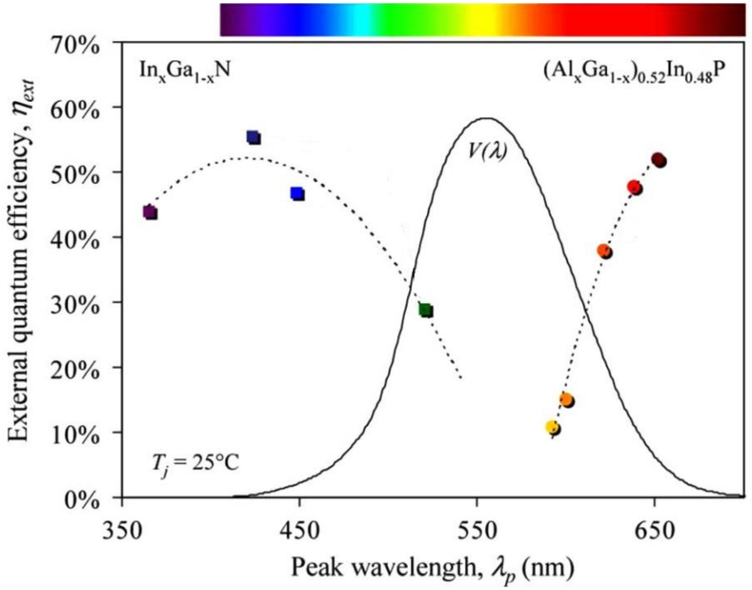


(c)
$$E_G = \frac{n^2 h^2}{8mL^2}$$

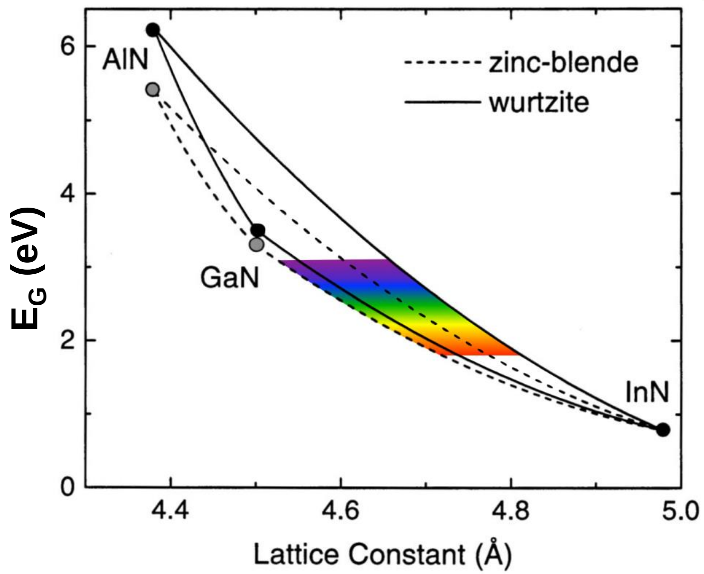
n = integer
h = Planck's constant
m = particle effective mass
L = well width

- Practical LEDs rarely use simple p-n structures. Low carrier density (*N*) leads to a low radiative recombination rate (*R*), and thus inefficient recombination:
    - ($R = BN$), where B is the radiative recombination rate
- LEDs use multiple "quantum wells" (b) to confine carriers in a narrow length for efficient recombination.
- Careful engineering of QW thickness also allows tuning of E_G (c)

Materials systems



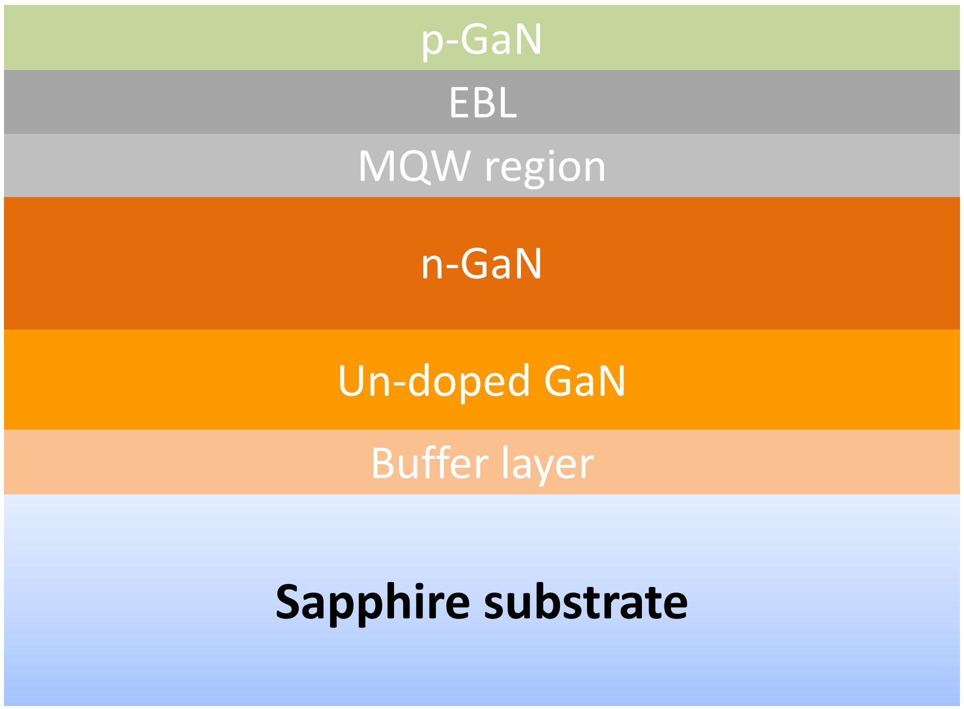
M. Crawford, IEEE Journal of Sel. Topics in Quantum Electronics, Vol 15, p1028 (2009)



Vurgaftman & Meyer, *JAP*, **94**, 3675 (2003)

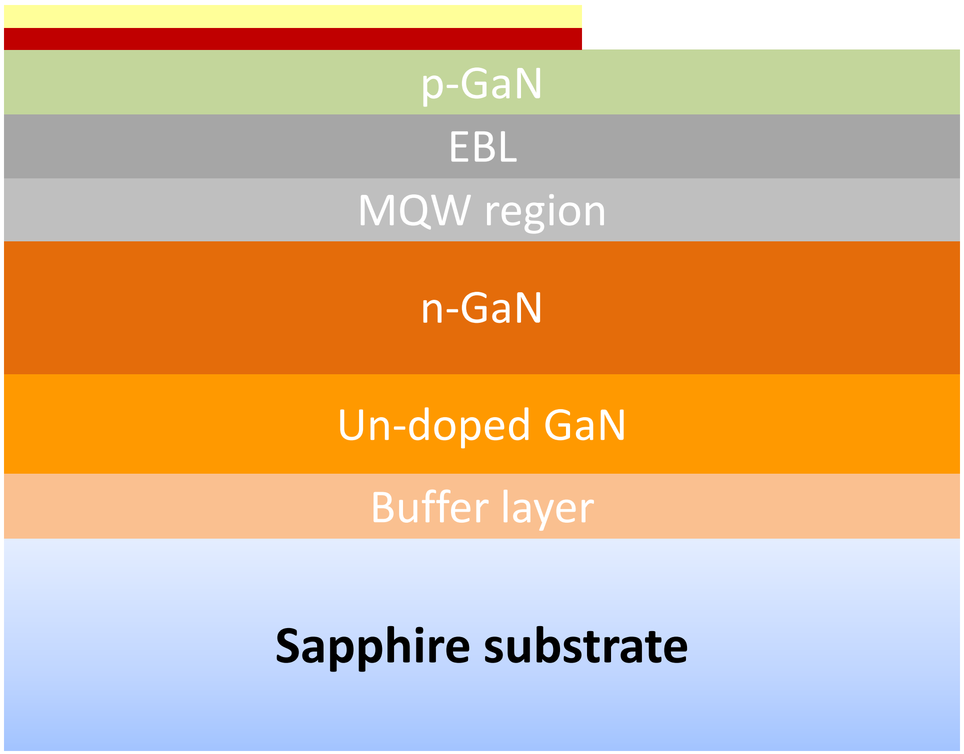
- E_G can be engineered by growing LED structures from different semiconductor alloys, adjusting the alloy composition, and adjusting the thickness of Quantum Well active regions.
- Different alloy systems can cover different parts of the spectrum
    - "Green-yellow" gap still exists where there is a lack of efficient green/yellow emitters

Typical structure and process flow



1. Begins with lattice-matched growth substrate, e.g. sapphire or Si *(300 μm thickness)*
2. Thin "buffer layer" of unintentionally-doped GaN by MOCVD (*25 nm*)
3. Thicker layer of un-doped GaN (*2-3 μm*)
4. Layer of doped n-type GaN (*1-2 μm*)
5. Multi-quantum well (MQW) active region (*100 nm*)
6. Electron-blocking layer (*100 nm*)
7. Layer of doped p-type GaN (*200-300 nm*)

LED basics – growth and fabrication



1. Pattern the p-GaN surface using photolithography
2. Dry-etch (RIE or ICP) down to the n-GaN
3. Deposit metal contacts and current-spreading layers (Ni/Au, Pd, *100 nm*)
4. Deposit SiO_2 passivation layer
5. Package and bond LED die

GaN-based LED – structure and growth process varies in different materials systems!

Growth substrates (GaN)

Sapphire	• Low cost & plentiful • Large area (2”) • Acceptable performance • Optically transparent	• Electrically insulating • Large lattice mismatch (13%) • Poor thermal conductivity
Si	• Potentially very cheap • Very large areas (6”) • Electrically conductive • Improved thermal conductivity	• Challenging growth • Coeff. of thermal expansion (CTE) mismatch • Large lattice mismatch (16.9%) • Opaque
Metallic substrates (e.g. Cu)	• Small lattice mismatch • Excellent thermal conductivity • Electrically conductive	• Large thermal expansion mismatch • Unstable at high growth temps.
Free-standing GaN	• Matched lattice constant and CTE • Electrically conductive	• Very high cost • Large areas not available

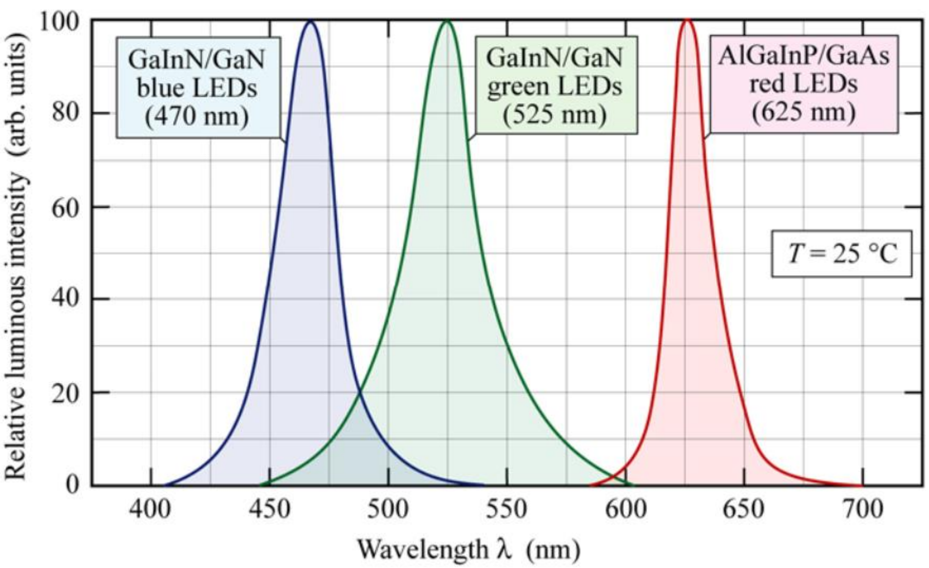
- Choice of epitaxial growth substrate vitally important
- Sapphire is currently the most commonly used for GaN LEDs

G. Li *et al.*, Reports in Progress in Physics, Vol 79 (2016)

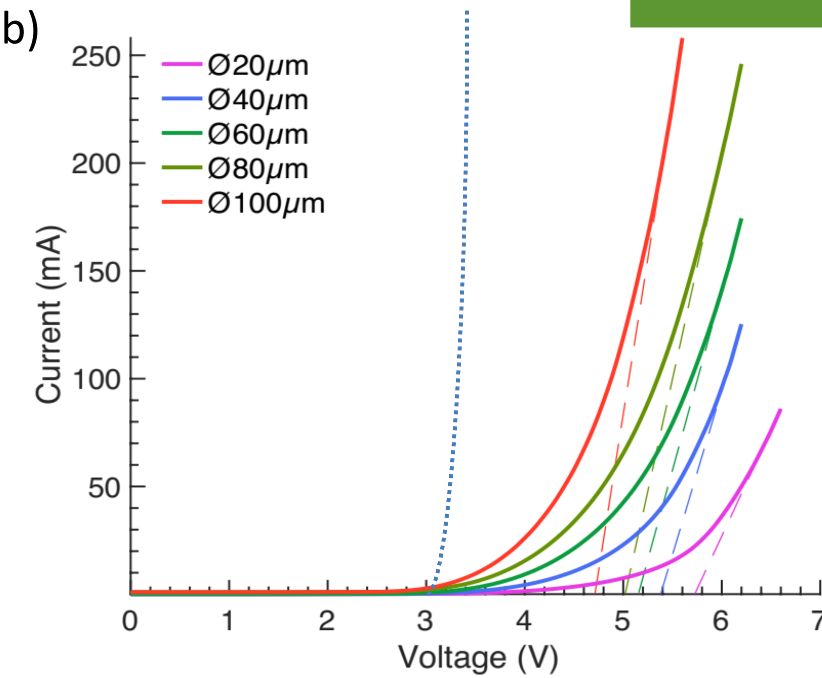
Typical characteristics: I-V

Schubert, *Light-Emitting Diodes*, 2nd edition, Cambridge Uni. Press, 2006

(a)

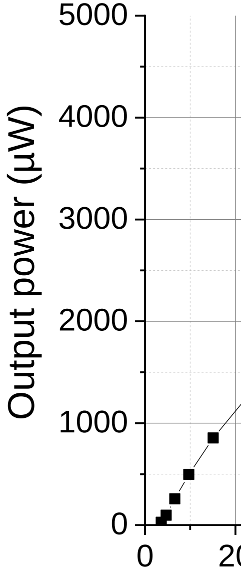


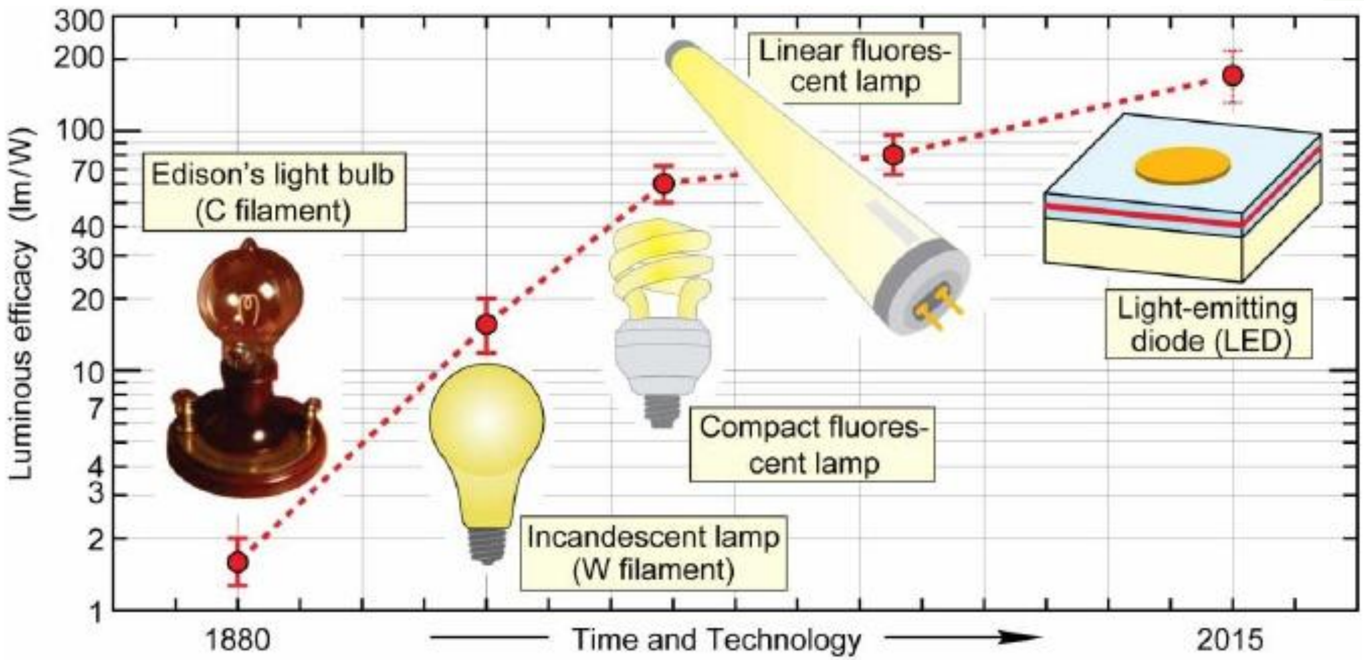
(b)

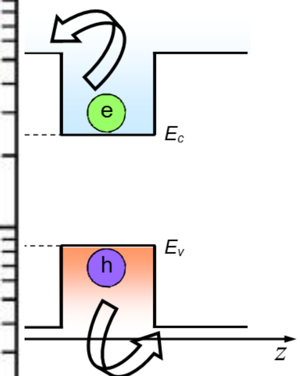


- Typical emission spectra (a) – peak wavelength largely determined by E_G
  - Peak wavelength will vary due to heating effects, variations across the wafer…
  - Distribution of carriers and states gives the emission spectra their shape
  - FWHM typically on the order of 20 nm. Still perceived as monochromatic by eye
- Real LED I-V behaviour deviates from "ideal diode"
  - Parasitic effects, e.g. series and shunt resistances
  - Depend on material properties and device structure

Typical characteristics: L-I and efficacy

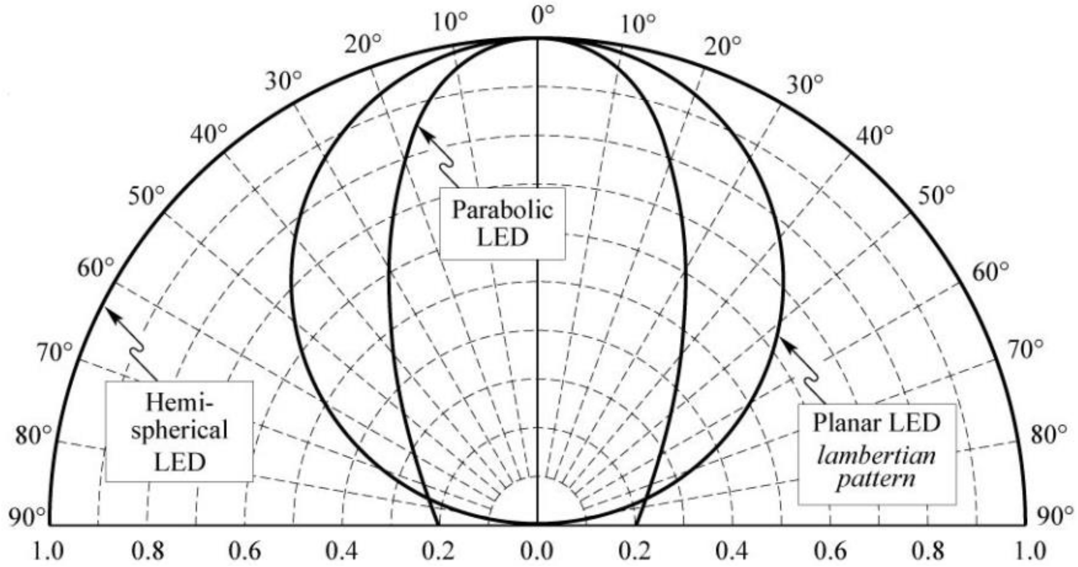




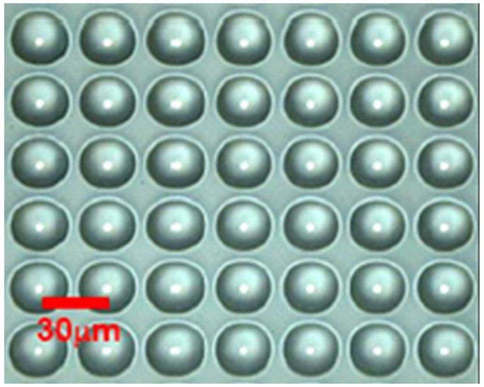


- At low currents the LED output increases approximately linearly with increasing current
- At higher currents the output "rolls over" as non-radiative recombination effects begin to dominate:
  - (a) Shockly-Read Hall, (b) Auger recombination, (c) carrier-overflow
  - Non-linearity and drop in efficiency need to be considered for application
- Nevertheless, LED efficacies still significantly exceed conventional light sources

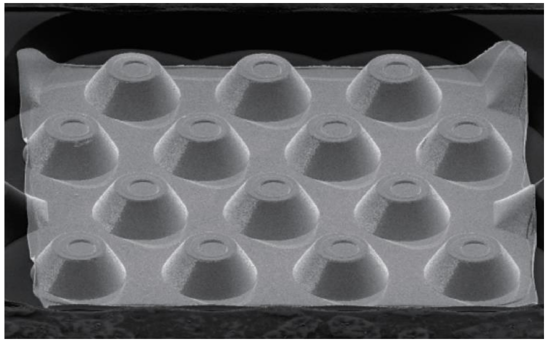
Typical characteristics: emission pattern



- Planar LED emission intensity follows a Lambertian pattern:
    - Reduces to 50% at 60° from the normal
    - Defined by total internal reflection
- Profile can be changed by shaping die (parabolic LEDs) or optics such as micro-lens arrays



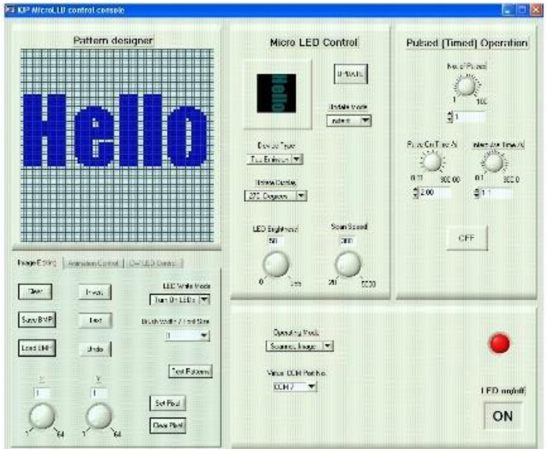
A. Mackintosh *et al.*, J. Phys. D, Vol 41 (2009)



40 µm

P. Maaskant, Aplied Physics Express, Vol 6, p022102 (2013)

GaN micro-LED arrays



- Typical off-the-shelf LED dies on the order of a few hundred µm to a mm per side
- “Mini-LEDs” (50 to 200 µm) or “micro-LEDs” (< 50 µm) are far smaller
    - *In a similar area micro-LED arrays have hundreds or thousands of individual pixels*
- Typically fabricated on standard MQW GaN LED wafers on *c*-plane sapphire
    - GaN-on-Si substrates have also been used
- Photolithography defines elements. Dimensions typically 1-100 µm per pixel
- Typical emission ranges from **near-UV** (370 nm) to **green** (520 nm)
- mW-range output power per pixel is typical
- Individually-addressable or matrix-addressable

Addressing schemes: Matrix

Matrix-addressing scheme

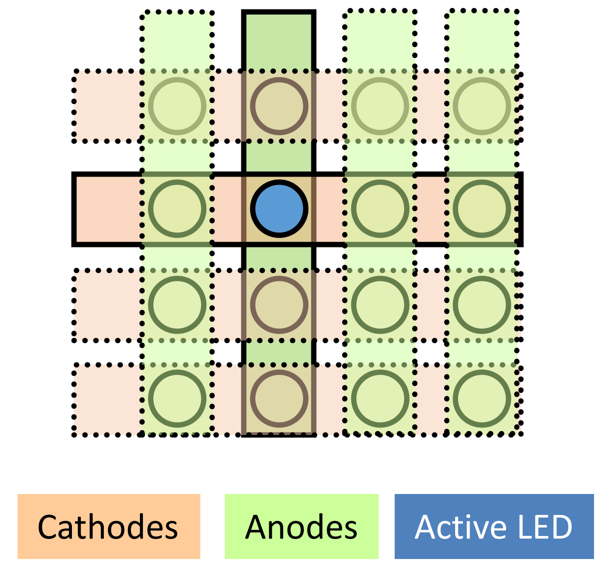
- Pixels in each column/row share a common anode/cathode
- Individual pixels are addressed by biasing the appropriate row & column
  - Passive Matrix – pixels only active when directly biased. Raster scanning required.
  - Active Matrix – transistor/capacitor holds the ON state of each pixel

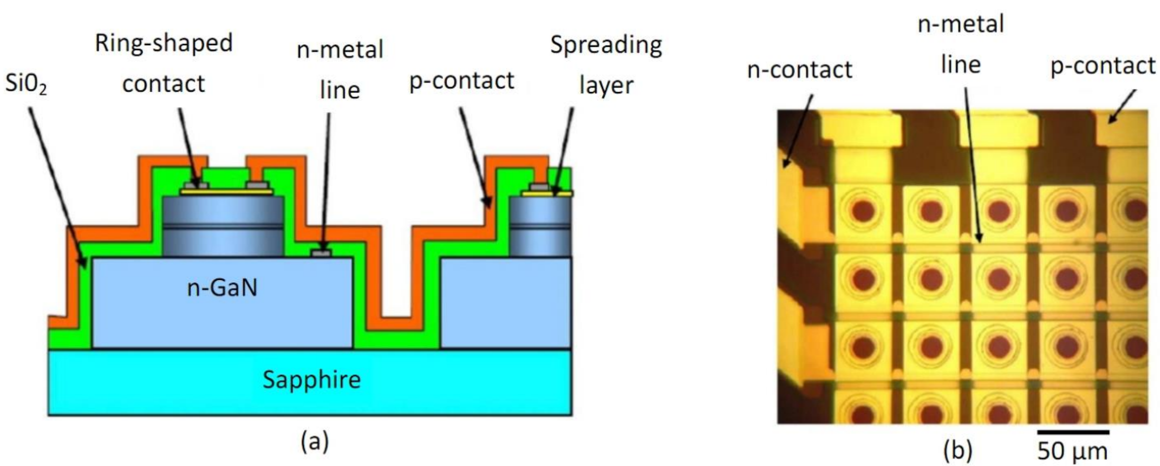
Advantages

- Simpler bond-out:
  - $m + n$ connections to drive $m \times n$ pixels

Disadvantages

- Requires deep-etch into n-GaN to isolate cathodes
- Addressing scheme may not be suitable for very high frame rates or brightness





(a) (b)

Addressing schemes: Individual

Individual-addressing scheme

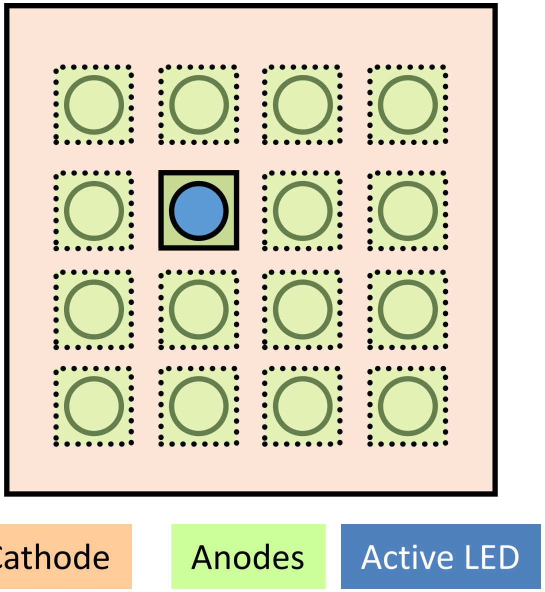
- Shared cathode (n-GaN), individual anodes (p-GaN)
- Individual pixels addressed by individual column

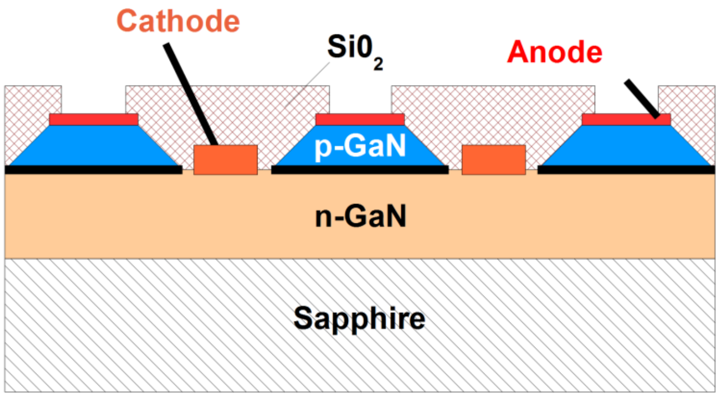
Advantages

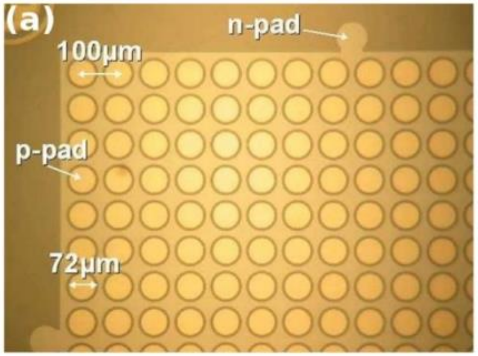
- Individual control over each pixel
- Fastest frame rates – update each pixel in parallel
- Simpler fabrication (no deep etch)

Disadvantages

- More bonds required
- Individual driver required for each LED

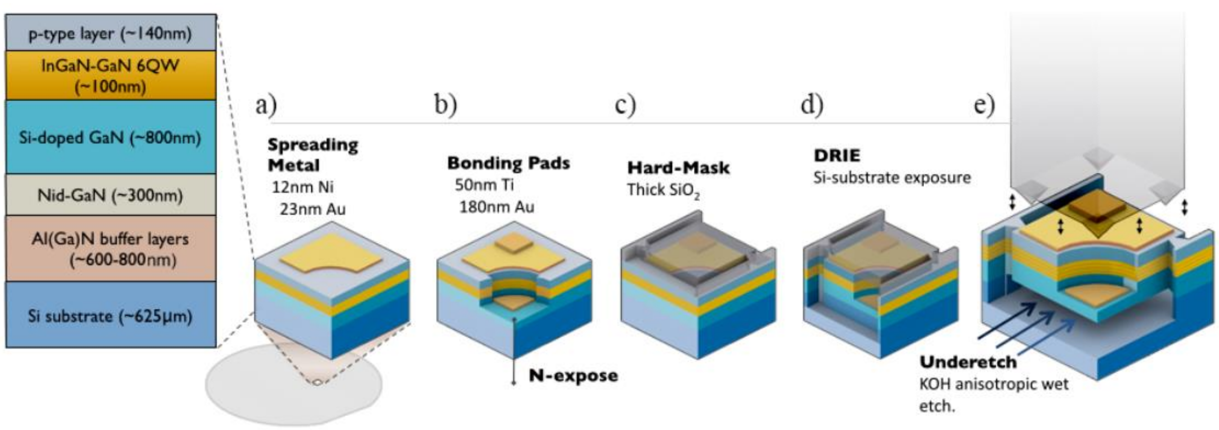


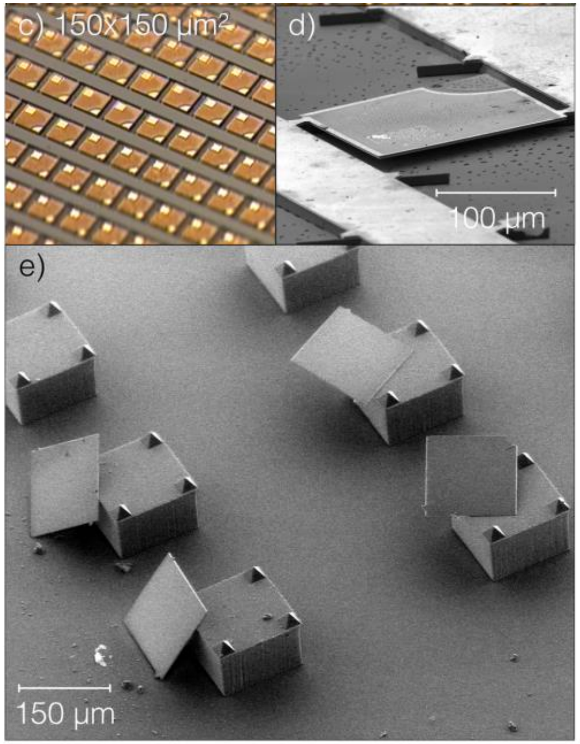




Multi-colour micro-LEDs

- A micro-LED array fabricated from a “normal” single wafer will be monochrome – every pixel emits the same colour
- How do we fabricate a multi-colour display? Broadly speaking, there are three approaches:
    - **Mechanical assembly from multiple wafers**
    - Colour-conversion
    - Monolithic growth

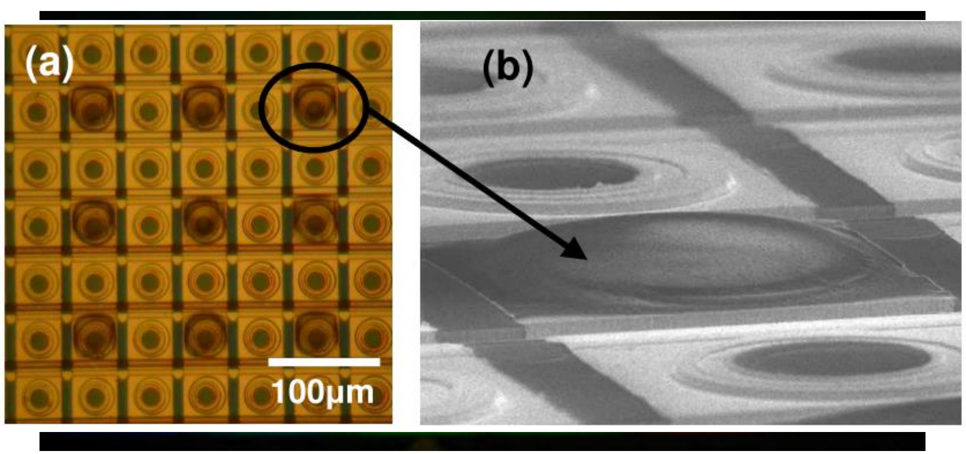




A. Trindade, *PhD thesis*, U. of Strathclyde (2015)

Multi-colour micro-LEDs (2)

- A micro-LED array fabricated from a “normal” single wafer will be monochrome – every pixel emits the same colour
- How do we fabricate a multi-colour display? Broadly speaking, there are three approaches:
  - Mechanical assembly from multiple wafers
  - **Colour-conversion**
  - Monolithic growth



M. Wu *et al.*, Optics Express, Vol 17, p 16436 (2009)

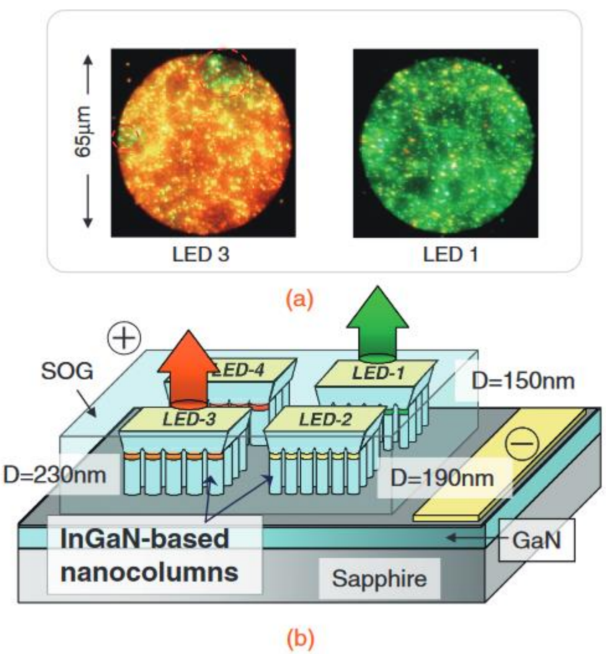
Decreasing QD diameter.

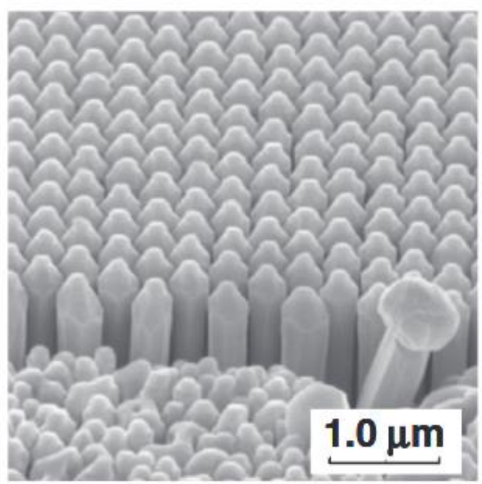
Image from www.sigmaaldrich.com

- Solution-processable materials such as Quantum Dots or Light-Emitting Polymers
- Deposition onto selected pixels by e.g. ink-jet printing
- Short-wavelength Micro-LED emission is down-converted to longer wavelengths
- This approach is typically used in white-emitting LED lightbulbs

Multi-colour micro-LEDs (3)

- A micro-LED array fabricated from a “normal” single wafer will be monochrome – every pixel emits the same colour
- How do we fabricate a multi-colour display? Broadly speaking, there are three approaches:
    - Mechanical assembly from multiple wafers
    - Colour-conversion
    - **Monolithic growth**

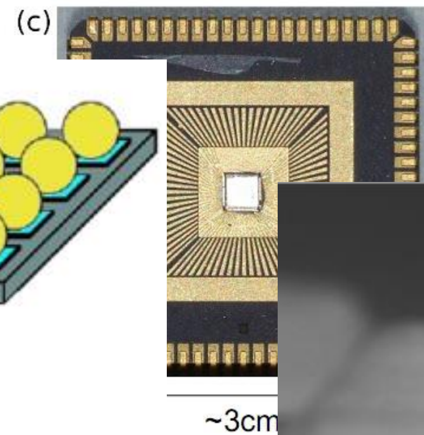


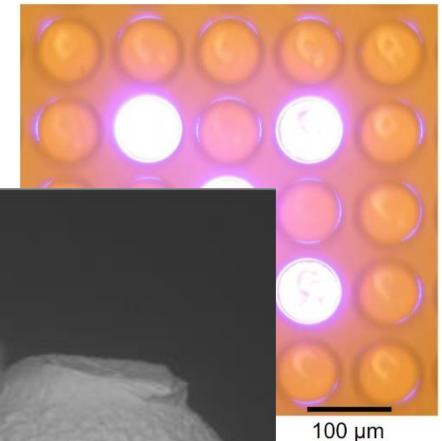


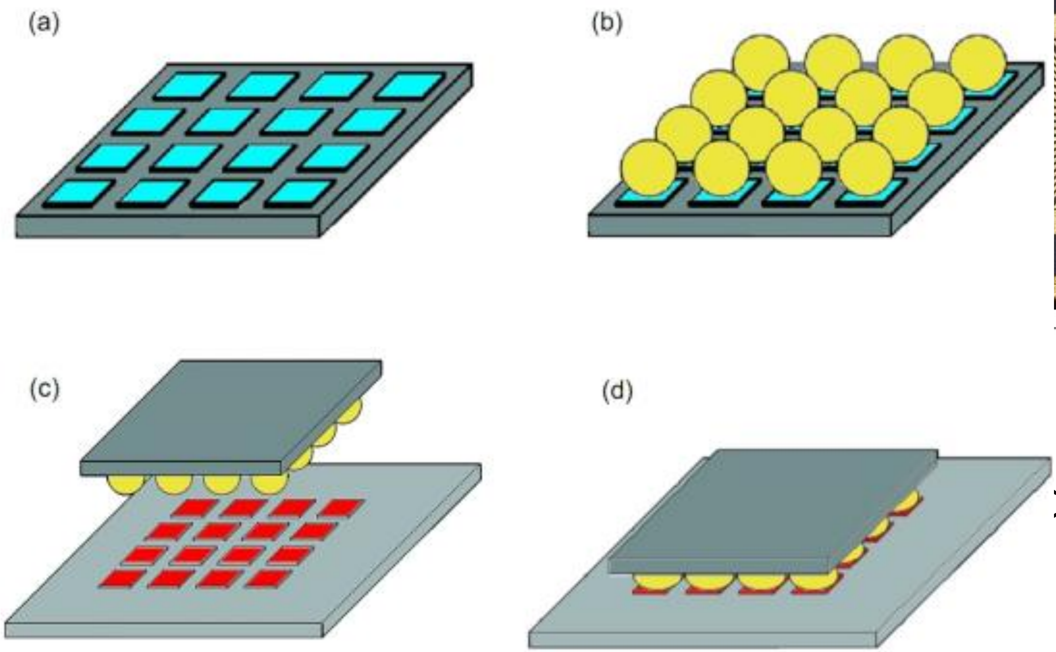
- Novel epitaxial material aims to allow multi-colour/white LED material using “exotic” approaches such as:
    - Nano-columns
    - Doping with rare-earth materials

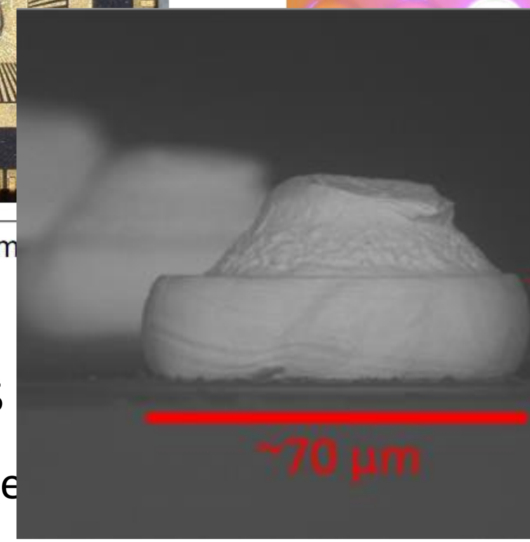
K. Kishino *et al.*, Applied Physics Express, Vol 6 (2013)

µLED/CMOS integration







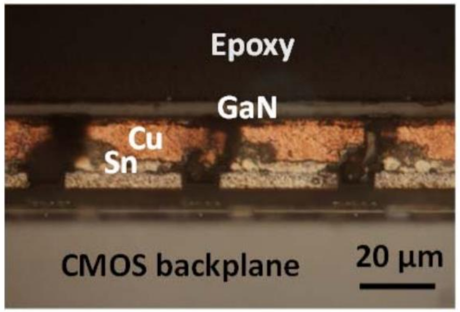


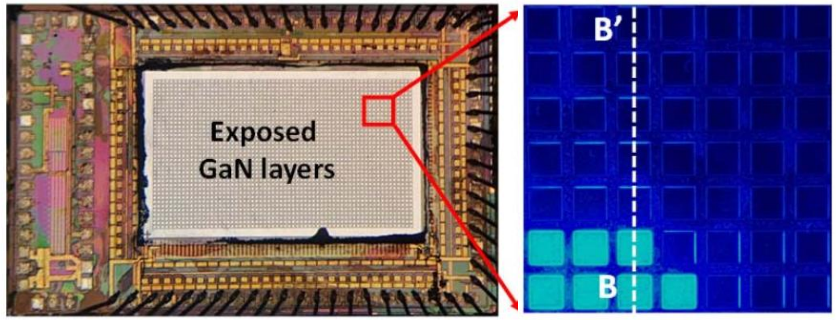
MOS

Unive

- Fabricated using standard low-voltage 0.35 µm CMOS process
- Optimised for generation of intense (high peak current) ns optical pulses
- Individual µLEDs bump-bonded to individually-controllable CMOS drivers
- Computer control of µLED array pixel and pattern outputs

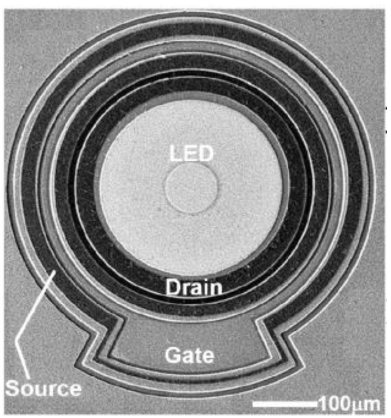
µLED/CMOS integration (2)

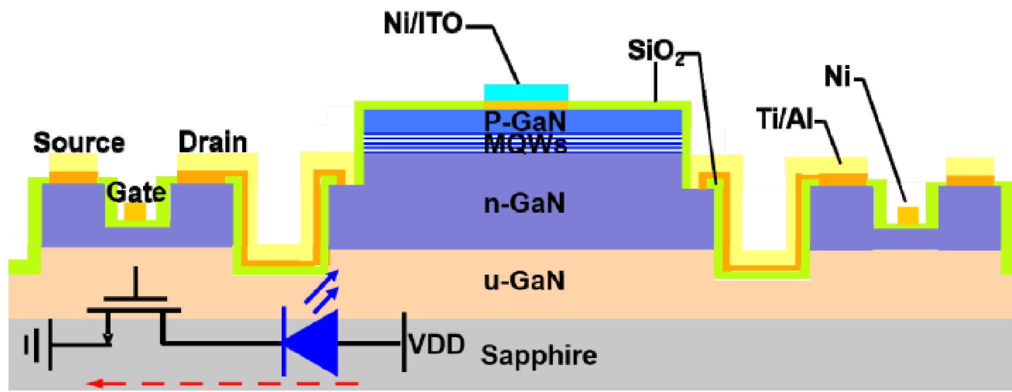




Flip-chip bonding of GaN-on-Si micro-LEDs to CMOS

- Zhang *et al.*, IEEE Phot. Tech. Letters, **31**, p865 (2019)





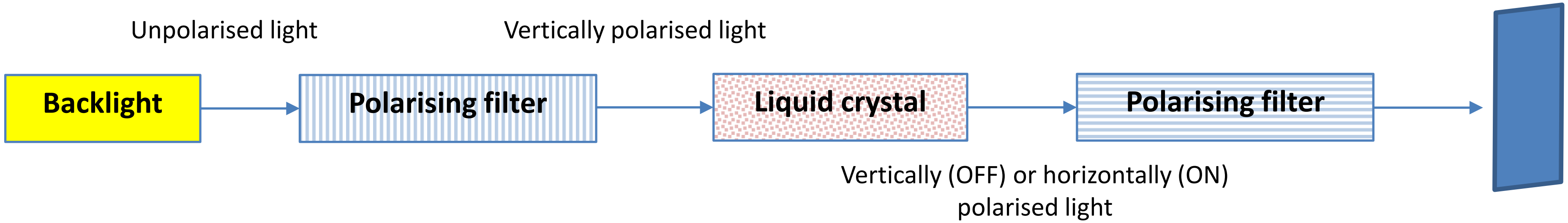
Monolithic integration of GaN micro-LEDs and MOSFET driver

- Low fill-factor
- Lee *et al.*, Optics Express, **22**, pA1589 (2019)

Applications

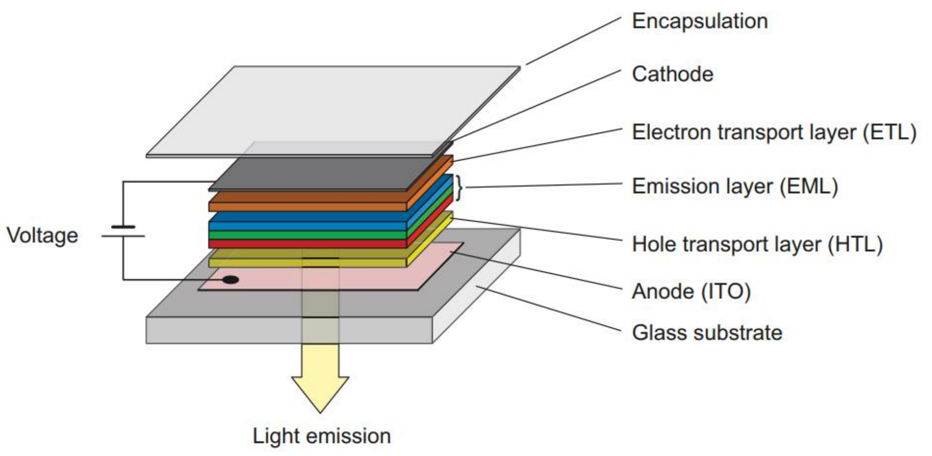
- Displays
- Visible light communications:
  - “Li-Fi”
  - Low light level communications
- Structured illumination
  - Navigation using light patterns
  - Camera-based communications
- Fluorescence sensing
- Optogenetics
- Opto-electronic trapping and mask-free photolithography

Displays – LCD



- Mature display technology
- Advantages:
  - Efficient and compact displays compared to old CRT technology
  - Scalable technology
  - No “burn-in”
- Disadvantages:
  - Inefficient
  - Narrower viewing angle
  - Low brightness and contrast
  - Slow response time of LQ (10s of ms)

Displays – OLED



https://pulsenews.co.kr/view.php?year=2017&no=852666

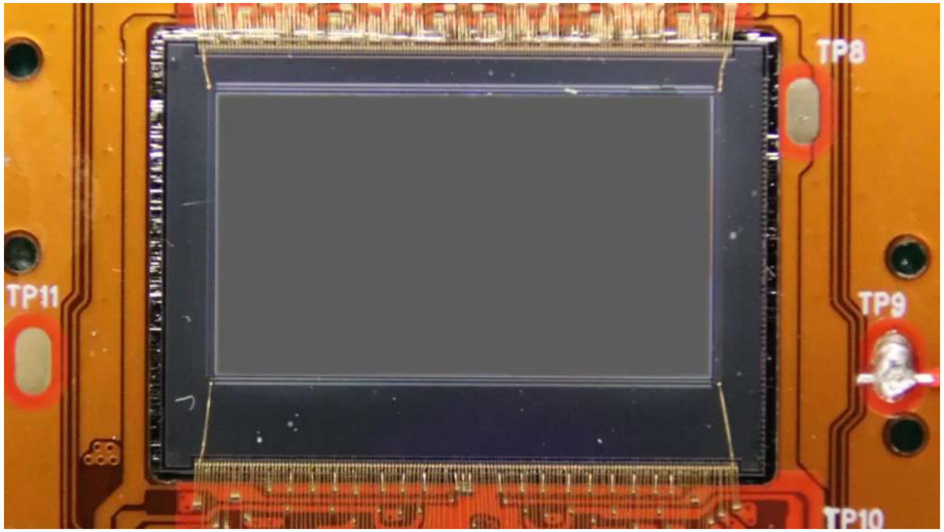
- Light-emitting polymers/molecules
- Advantages:
  - High contrast
  - Fast pixel response (< 0.1 ms)
  - Higher efficiency
  - Flat & thin (< 1 μm)
  - Compatible with flexible and arbitrarily-shaped surfaces
- Disadvantages:
  - Pixel degradation
  - Limited brightness
  - Risk of “burn-in”

Displays – Micro-LED

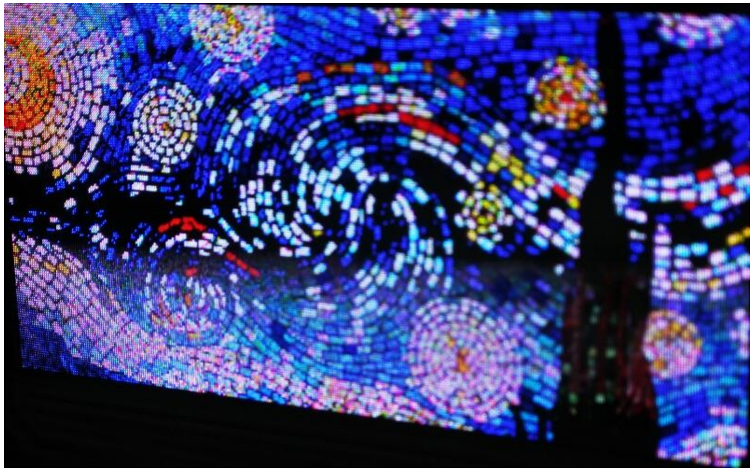
University of Strathclyde Science

- Samsung revealed Micro-LED displays at 2019 CES
- 75” 4k resolution display and 219” “The Wall” display built with micro-LED modules
- Advantages:
  - Ideal contrast (directly emissive pixels)
  - High brightness and efficiency
  - Long lifetime (>100k hours) with no degradation or “burn-in”
- Disadvantages:
  - Very high cost compared to incumbent technologies
  - More challenging fabrication

Micro-LED micro-displays



http://www.plesseysemiconductors.com



https://x-celeprint.com/news

Inorganic Micro-LEDs can address shortcomings of existing VR/AR technology:

- Size & weight
- Power consumption
- Resolution
- Brightness & contrast

Plessey Semiconductors

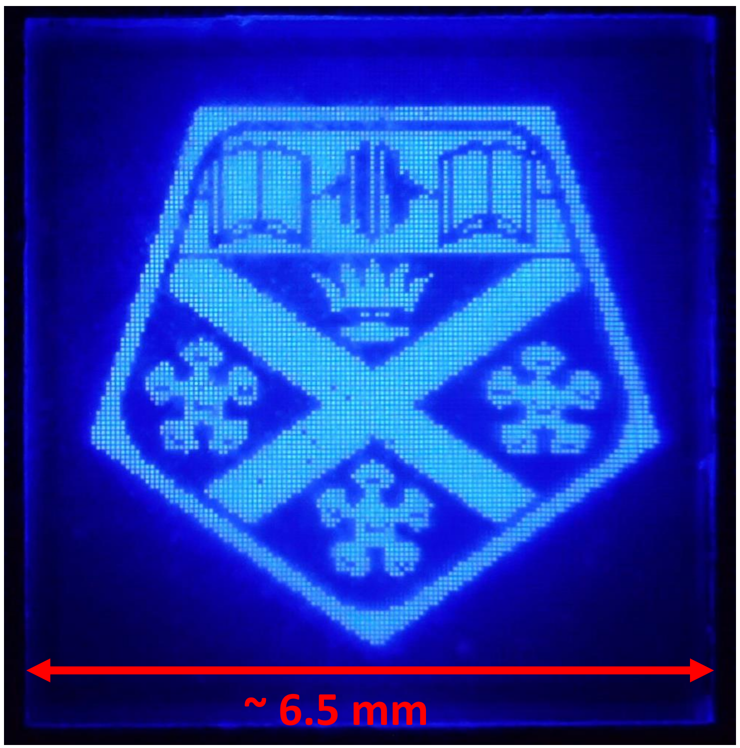
- GaN-on-Si micro-LED array bonded to CMOS display driver
- 1920×1080 monochrome display, 8 µm pixels, 0.7” diagonal display

X-Celeprint

- Transfer-printed full-colour display
- 5.1”, 70 ppi

High-frame rate micro-LED display

"MegaProjector"



Resolution

- 128×128 resolution
- Pixel area: 30×30 μm^2
- Pixel pitch: 50 μm

Output

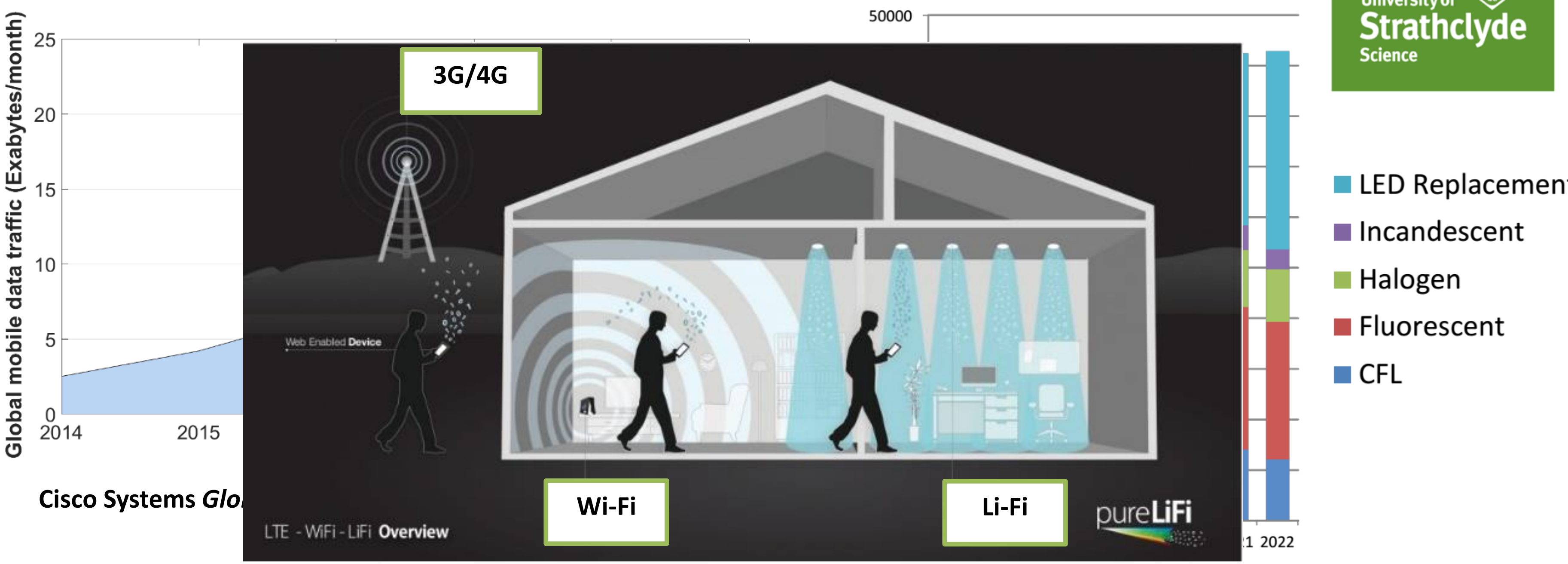
- Up to <u>0.5 Million fps</u>
- Peak emission: **450 nm** (available now). **405** and **510** nm should be available by end of summer 2022.
- Grayscale brightness control: 32 levels (5 bit)
- Optical output power per pixel: ~25 μW @ 450 nm
- Display brightness: 2.8×10^4 cd/m^2

Modes of operation

- Global shutter, rolling shutter, nanosecond pulsed
- Pulsed operation: 4 ns min. pulse duration, 0.08 pJ (single pixel), max pulse repetition rate: 100 MHz

N. Bani-Hassan *et al.* "Ultra-high frame rate digital light projector using chip-scale LED-on-CMOS technology", *Photonics Research*, **10** (10), p2434 (2022)

"Li-Fi"



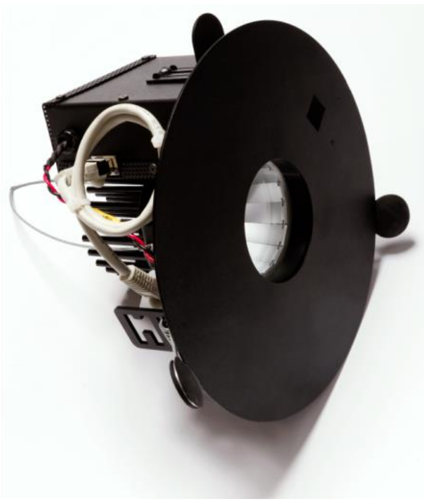
Cisco Systems *Glo*

Image from www.purelifi.com

National Research Council
***Assessment of Solid-State Lighting, Phase Two* (2017).**

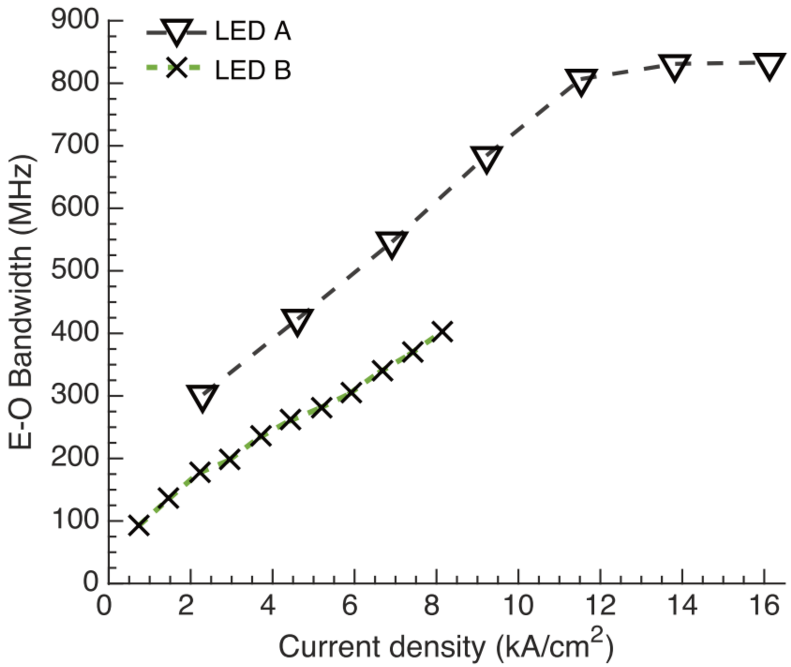
- Rapid growth in wireless data traffic projected to outstrip improvements in existing RF tech
- Improved efficiency and cost of LED "retrofit" units is driving rapid growth of installed LED fixtures
- Light Fidelity, "Li-Fi" , a complete bi-directional wireless network system, analogous to Wi-Fi
- Opportunity for GaN LEDs to complement existing technologies:
    - High modulation bandwidth (MHz) compared to incandescent/fluorescent sources
    - Licence-free bandwidth in the visible spectrum

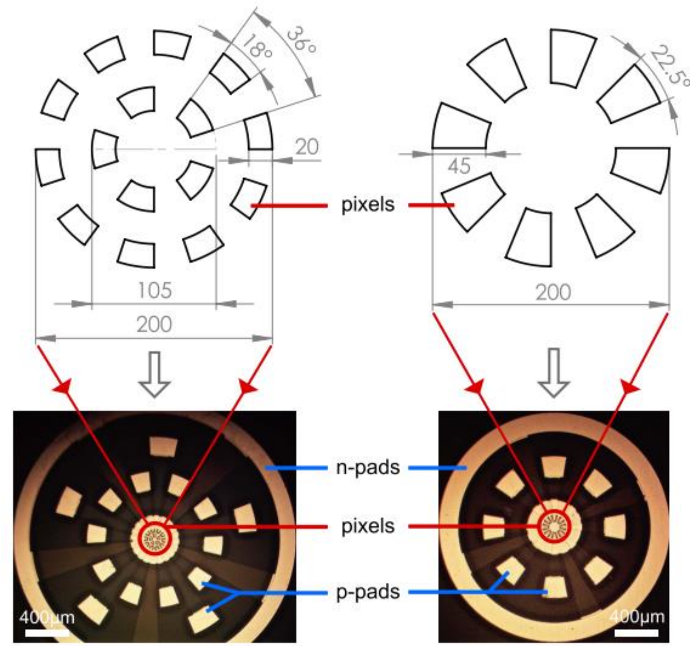
Commercial Li-Fi



- PureLiFi, OLEDComms, Lucibel, Sygnify (Philips Lighting), Linmore & others
- Li-Fi enabled battens and downlights. Lighting retrofit.
- Multiple user support, Bi-Directional, 45 Mb/s + downlink
- Early adoption by those wanting secure wireless (e.g. banking, government, healthcare, defence)
- Candidate technology for 5G networks

Micro-LEDs for VLC

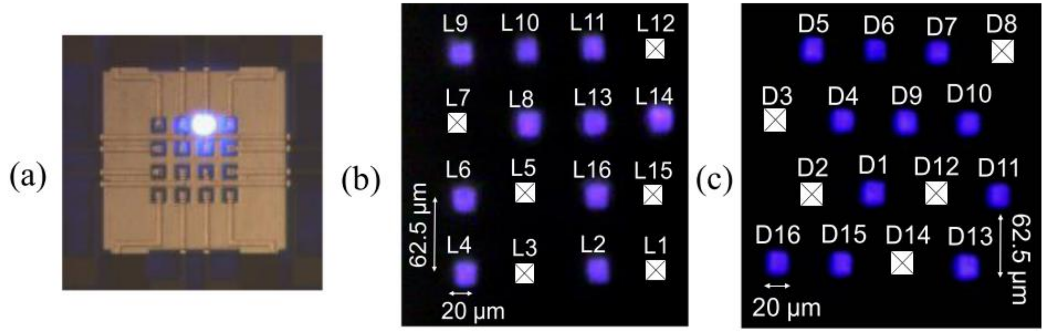




- Existing Li-Fi data rates limited by the typical bandwidth of LEDs (≈ 10-20 MHz)
- Bandwidth of micro-LEDs in excess of **800 MHz** – <u>micro-pixellation delivers higher bandwidths</u>.
- Performance limited by carrier lifetime, τ, rather than capacitance.
- Optical data transmission at rates >5 Gb/s **per pixel**

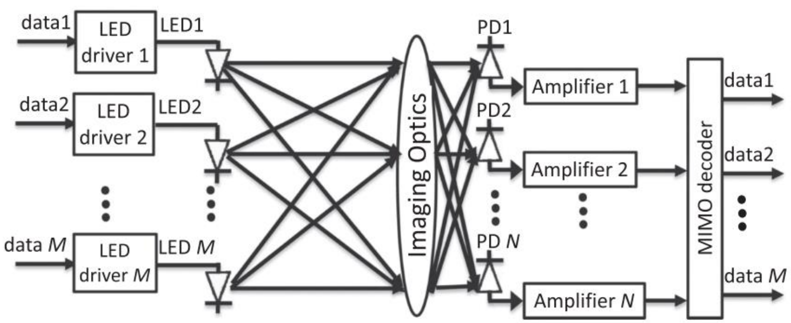
R. Ferreira *et al.*, Photonics Tech. Letters, **28**, 19, 2023-2026 (2016)

Micro-LEDs for VLC (2)



Bamiedakis *et al.*, Journal of Lightwave Tech., Vol 37 (13), p3305, 2019.

- Electrical interconnects face issues of EMI and high power consumption
- Micro-LED arrays can be matched to 2D polymer waveguides for "board to board" or "chip to chip" *optical* interconnects
- 2.5 Gb/s per channel (0.5 Tb/s/mm^2 data density)

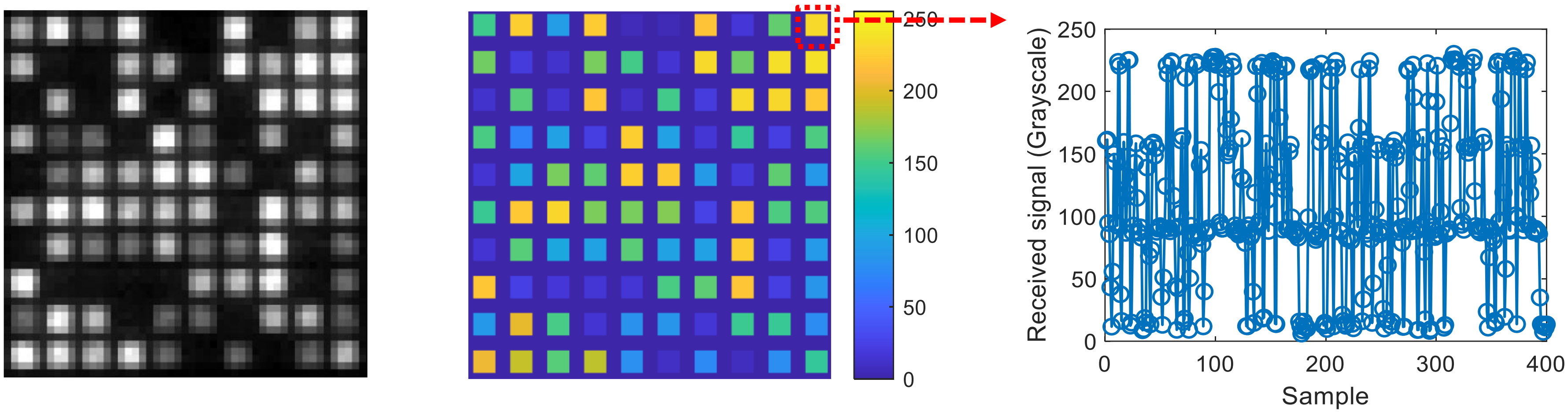


Rajbhandari *et al.*, Semiconductor Sci. Tech., Vol 32, p023001, 2017.

Rajbhandari *et al.*, Journal of Lightwave Tech., Vol 35, p4358, 2017.

- Increased data throughput using MIMO for parallel data transmission
- If the channel-to-channel crosstalk is characterised, the signal at each receiver can be recovered.
- 7.48 Gb/s obtained using a 9-channel micro-LED MIMO system

MegaProjector OCC

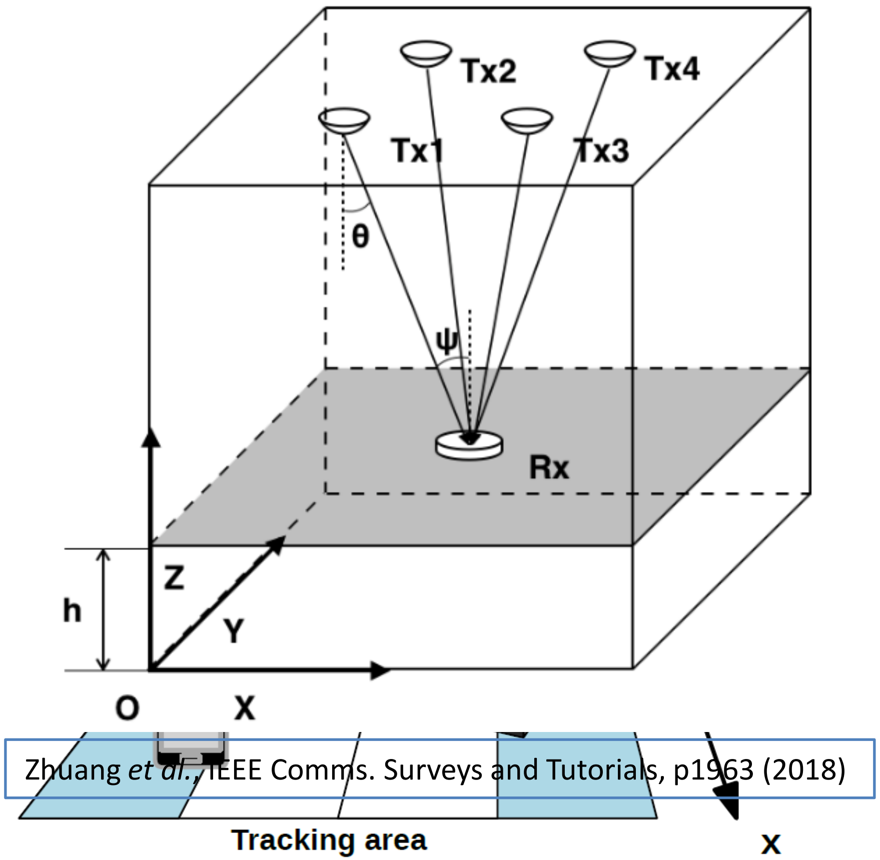


- Megaprojector encodes data in the state of each pixel in the array during each transmitted frame
  - $x \times y$ pixels $= x \times y$ symbols/frame
- Each pixel can encode *m* bits/symbol, using 2^m brightness levels
- Scaling to full Megaprojector capability = $x \times y \times m$ bits/frame = 81,920 bits/frame
- This would yield nearly 40 Mb/s using a 960 fps Smartphone camera
- Early demonstration of **101.2 Mb/s** (128×13×2×40kfps×76% pixel yield)

Y Shao *et al.* "High-Speed Optical Camera Communication Using CMOS-driven Micro-LED Projector", *IEEE Photonics Conference*, November 2022.

Navigation using LEDs

- GPS not suitable for indoor applications
  - Accuracy of a few m not always practical
  - GPS signals don’t reliably penetrate into buildings
- LED lighting infrastructure can be used as “beacons” for navigating
  - E.g. triangulate position from Transmitters (with known positions) by measuring received signal strengths.
- However, this require processing effort at the Rx
  - Not necessarily suitable for low-power “Internet of Things” devices
- Alternative approach – use patterns from micro-LED arrays to encode spatial information.
  - Moves the complexity from the Rx to the Tx



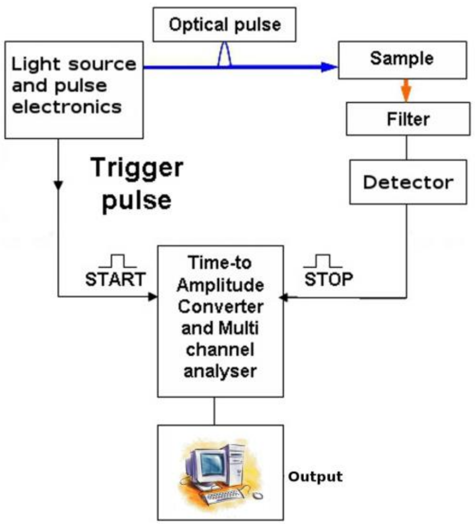
Zhuang *et al.*, IEEE Comms. Surveys and Tutorials, p1963 (2018)

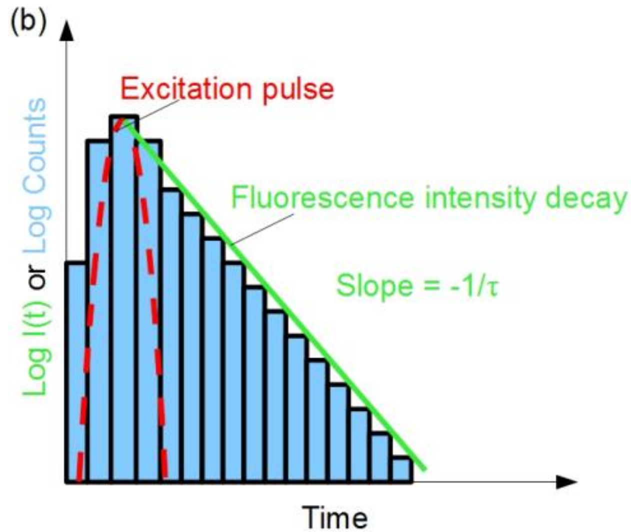
Navigation using LEDs (3)

- Position update rate 6 Hz
  - Limited by ADC (Arduino Uno) sampling rate
  - 100 Hz with oscilloscope & offline processing
- On-line decoding by micro-processor
- Possible application in cubesat-to-cubesat comms.

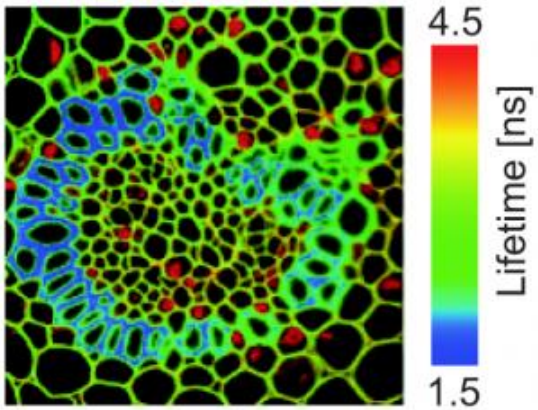
Herrnsdorf *et al.*, Journal of Lightwave Tech., Vol 35 (12), p2339, (2019).

Fluorescence lifetime measurements





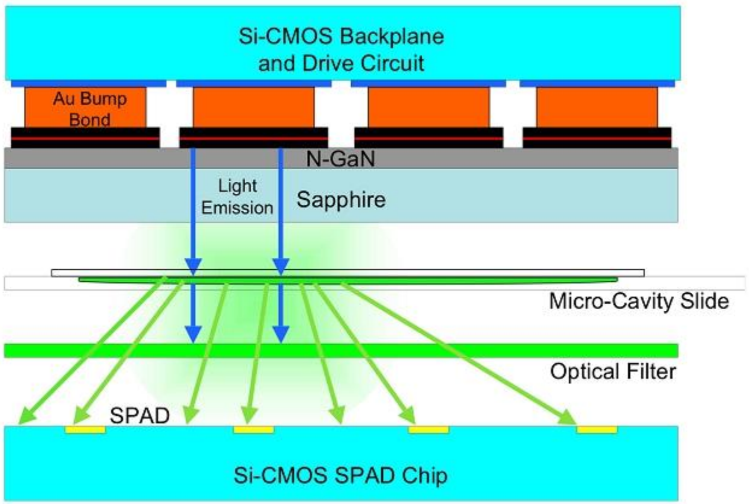
FLIM

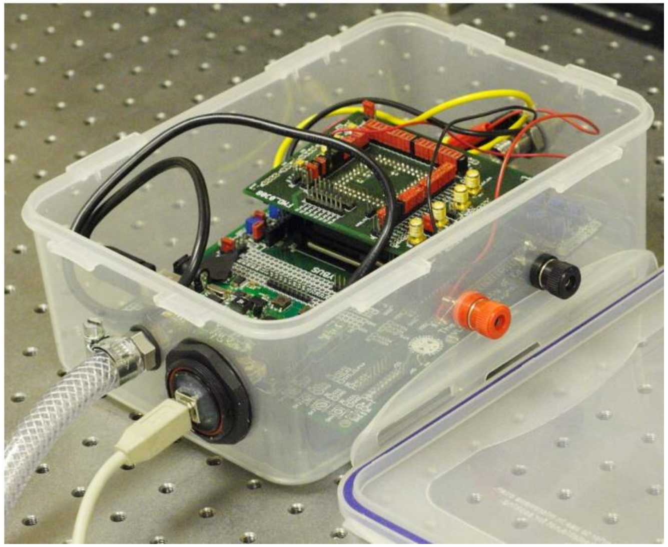


https://www.picoquant.com/applications/category/life-science/fluorescence-lifetime-imaging-flim

- Fluorophore optically excited
- Energy released as fluorescence by molecules after a random time delay, but with a characteristic average “lifetime”, τ
- τ not affected by concentration, absorption or excitation intensity
  - Enhanced contrast in microscropy (FLIM)
- τ can affected by other environmental factors (temperature, pH, viscosity…)

Compact explosive vapour sensor



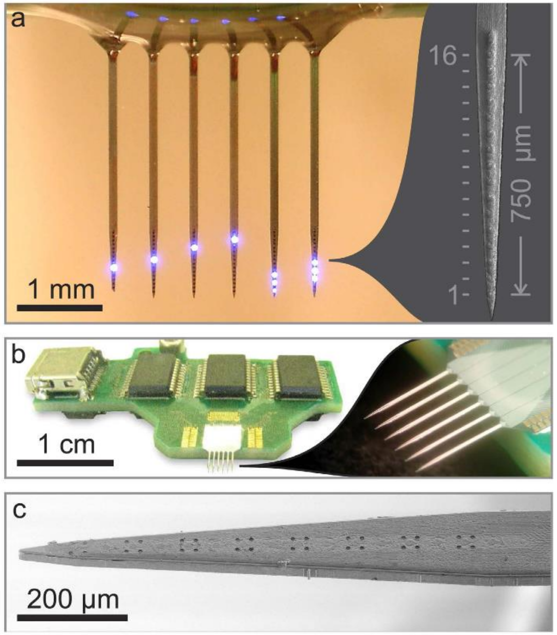


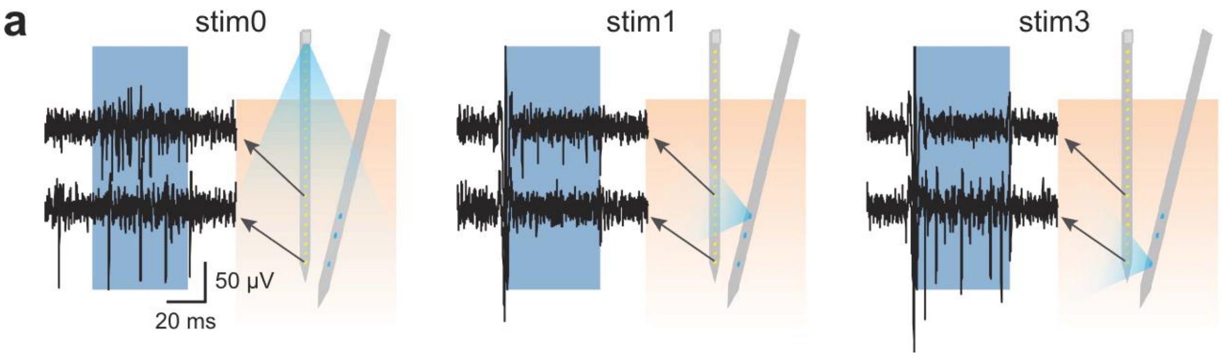
- Light-emitting polymer excited by pulsed micro-LEDs
- Fluorescence lifetime measured using SPAD array
- Vapour flowed through airtight container containing the sensor
- Polymer lifetime decreases when vapour binds to polymer
- Sensitivity of 10 ppb

Wang *et al.*, AIP Advances, Vol 1, p032115 (2011)

Optogenetics

- Optogenetics is a technique that allows light to control, and study, the behaviour of cells
  - e.g. light to activate or supress neurons
- Initial method used an optical fibre to optically excite a volume of tissue from the surface (*stim0*)
  - Imprecise – all neurons within a volume are excited, can't target specific layers
- Using an array of micro-LEDs along a needle-like shank, specific layers within the brain can be targeted (*stim1, stim3*)
- Electrodes on shank record electrical activity

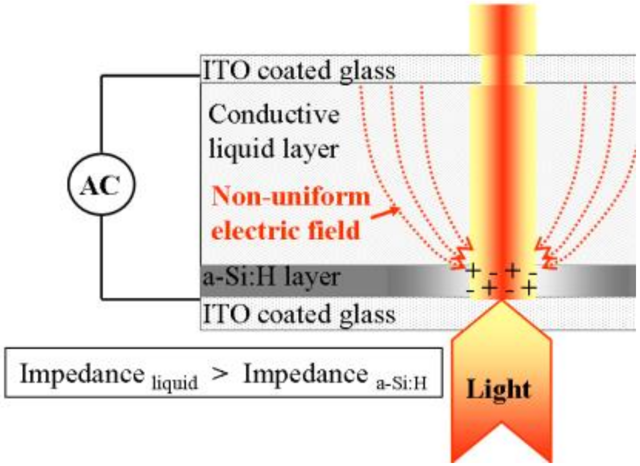


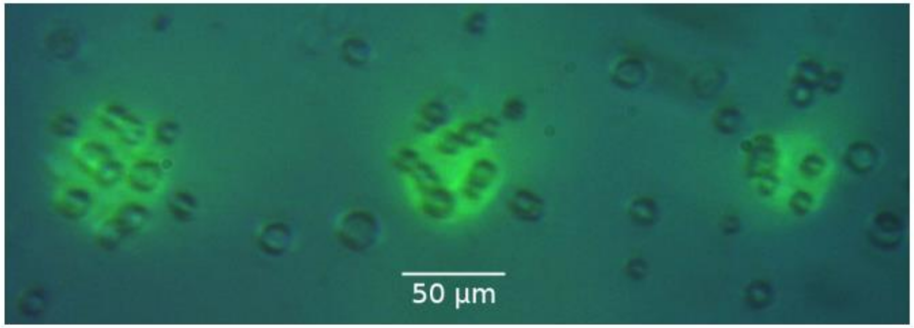


Scharf *et al.*, Scientific Reports, Vol 6, p1, June 2016

Other applications

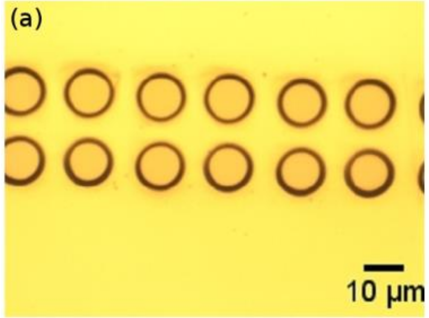
A. Zarowna-Dabrowska *et al.*, *Optics Express*, 19 (2011)

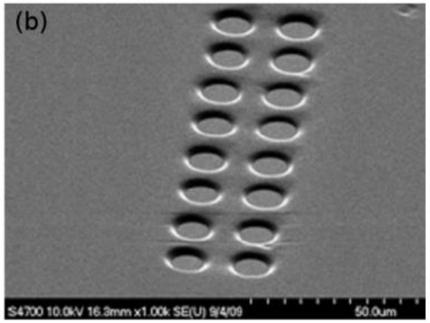




Opto-electronic trapping

- Localised electrical field created where photoconductive layer is illuminated
- Compact portable cell-trapping system using a Micro-LED display





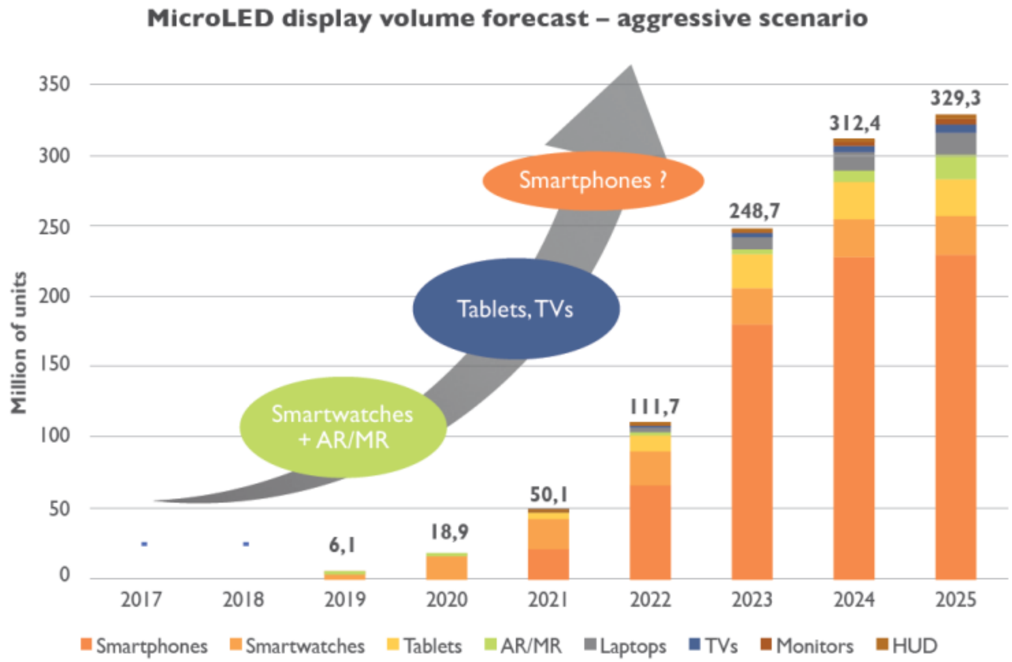
D. Elfström *et al.*, *Optics Express*, 17 (2009)

Mask-free photolithography

- Photoresist exposed by UV micro-LEDs
- Patterns can be created without the need for hard photolith masks

Summary and future prospects

- Micro-LED technology is drawing an increasing amount of commercial interest:
  - $100 million raised by startups in 2019
  - Estimated $1.5 to $2 billion invested by Apple so far
  - Samsung, Oculus (Facebook), LG, Kyocera, Sharp…
- Driven by display market
- Significant roadblocks remain in terms of small die efficiency, transfer and manufacturability. Not yet competitive with OLED displays



Yole Developpment, report:
"**MicroLEDs: status and reality check**" (2019)

As we have demonstrated, there are many applications beyond displays for micro-LEDs which should benefit in future from the development of commercial micro-LED displays

Acknowledgements

IOP Photonic Devices & Materials Group
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- Dr Gabor Varkonyi

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Pioneering research and skills

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- Prof Harald Haas (now Strathclyde)

University of Oxford
- Prof Dominic O'Brien

University of Cambridge
- Prof Richard Penty
- Prof Ian White

University of St. Andrews
- Prof Graham Turnbull
- Prof Ifor Samuel

Fraunhofer Centre for Applied Photonics
- Dr Henry Bookey
- Dr David Stothard
- Dr Gerald Bonner
- Dr Yingjie Shao

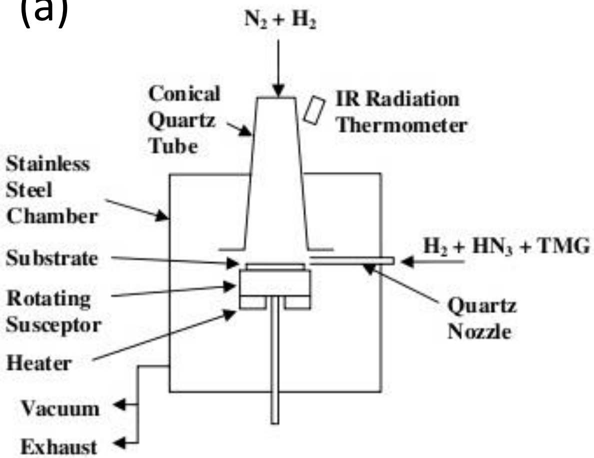
…and many others!

Thank you for your attention

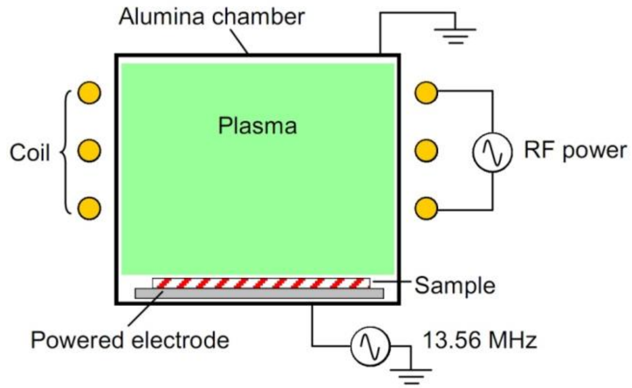
University of Strathclyde Glasgow

Epitaxial growth and processing

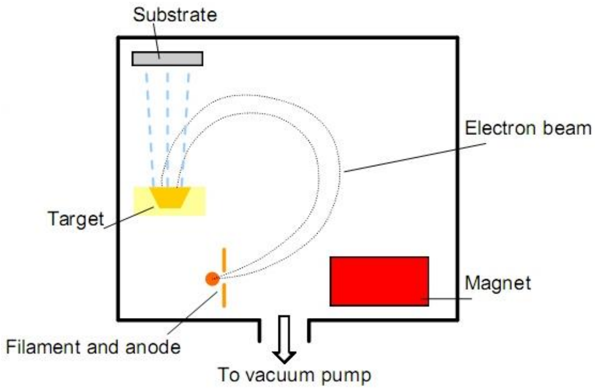
(a)



(b)



(c)



(a) **Epitaxial growth** by Metal Organic Chemical Vapour Deposition (MOCVD)
- Material in gas phase deposited on substrate by chemical reaction
- Substrate heated to very high temperatures (as much as 1000°C)
- 0.5 µm/hour growth rates

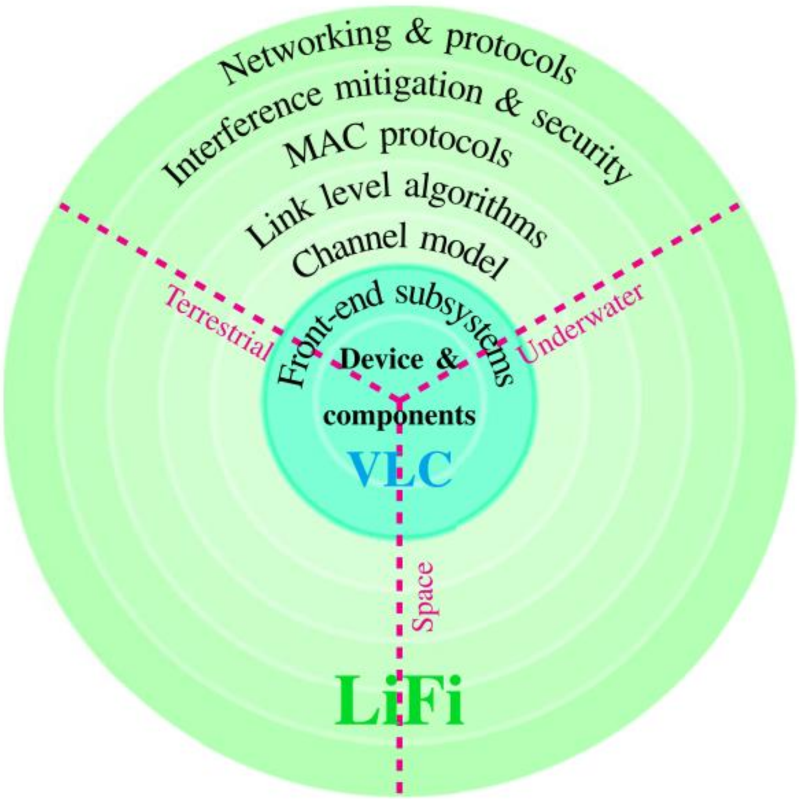
(b) **Etching** by Inductively-Coupled Plasma (ICP) reactor
- Ions accelerated towards substrate to etch
- ≈ 1µm/minute etch rates

(c) **Metal deposition** by Electron-Beam Evaporation
- E-Beam heats target (e.g. Au) to evaporate it
- Evaporated material condenses on the substrate

Photolithography used to define areas affected by etching and deposition

Not an exhaustive list!

Visible Light Communications

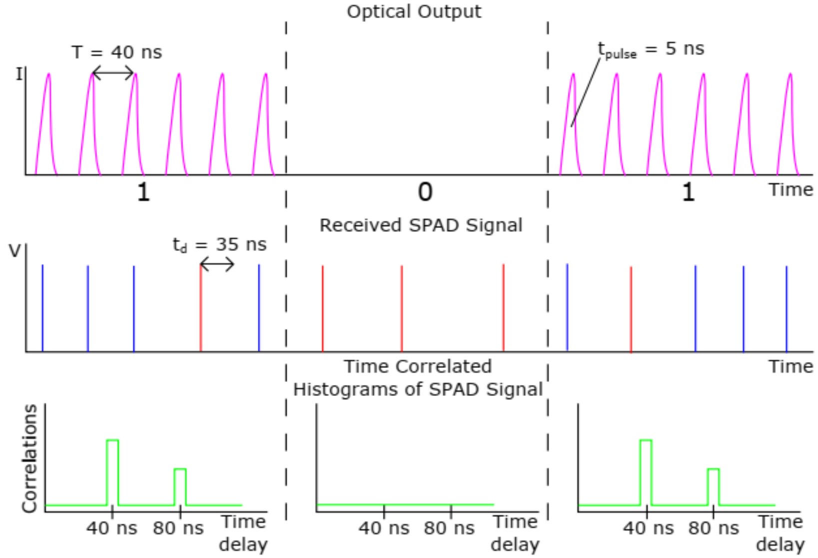


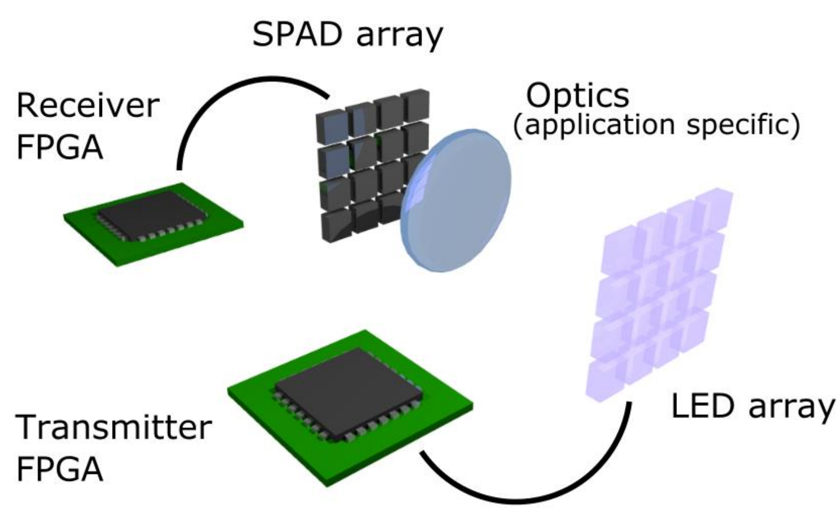
H. Haas, *Journal of Lightwave Tech.*, Vol 34, p1533 (2016)

- **Visible Light Communication** uses visible light sources (e.g. LEDs or lasers) to transmit data by intensity modulation
- Applicable to free-space, polymer waveguides, and underwater wireless
- **VLC** generally only includes the devices & component frontend
- On the other hand, **"Li-Fi"** encompasses a complete bi-directional wireless network system with multiple access

Low light level comms

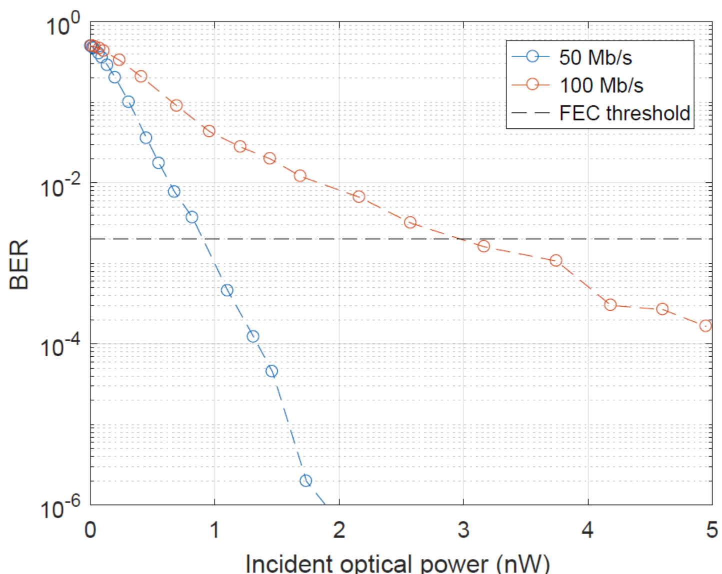
- Short optical pulses from micro-LEDs used to transmit data
- Low SWAP systems
  - GaN LEDs, Si SPADs
- Funding from EPSRC
  - Glasgow 'QuantIC' Quantum Hub
  - Collaboration with Scottish Centre for Excellence in Satellite Applications, Clyde Space and Scottish Microelectronics Centre





Data Rates

- 2 kb/s – 100 Mb/s depending on:
  - Hardware
  - Received power
  - Background noise conditions
- 100 Mb/s @ -55.2 dBm
- 50 Mb/s @ -60.5 dBm
- Up to 5 Mb/s at virtually any type of background, incl AC-modulated



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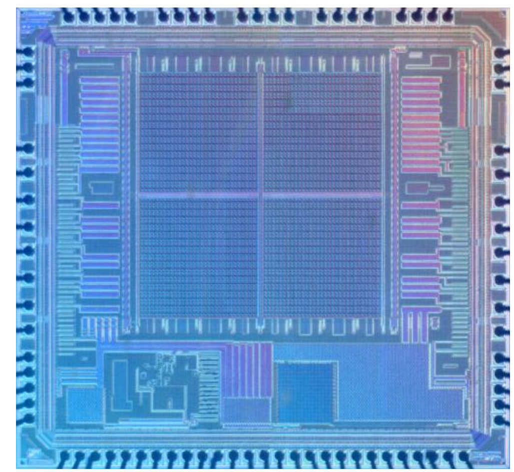
THE UNIVERSITY of EDINBURGH
CMOS Sensors & Systems Group



- 2.6 x 2.8 mm Chip in 130nm CMOS
- 4096 SPADs
- 43% SPAD fill factor
- Digital operation
- 1 GigaPhoton/s count rate
- High-speed digital readout