2025/26 Student's seminar (77656):
Quantum semiconductor structures and devices

Mentor: Prof. Amir Sa'ar (Saar.Amir@mail.huji.ac.il)

List of seminar topics

1. The double-barrier resonant tunneling diode
2. Semiconductor superlattices
3. Quantum well infrared photodetectors (QWIPs)
4. Quantum cascade (QC) lasers
5. Quantum well (QW) lasers
6. Quantum wire lasers
7. Quantum dot lasers
8. Quantum dots & Perovskites for photovoltaics solar cell applications
9. Inversion layers in MOS (Metal-Oxide-Semiconductor) structures and the formation of 2D (two-dimensional) electron gas
10. Graphene: a 2D structure of Graphite
11. Carbon Nanotubes
12. Porous Silicon: quantum sponge nanostructures of silicon
13. Photonic Crystals: confinement of light into periodic dielectric structures

General Literature:

1. V. Mitin, V. Kochelap & M. Stroscio, "*Quantum Heterostructures: Microelectronics and Optoelectronics*" (Cambridge, 1999).

2. G. Bastard, "*Wave Mechanics applied to Semiconductor Heterostructures*" (Halsted Press, 1988).

3. J. Singh, "*Physics of Semiconductors and their Heterostructures*" (McGraw-Hill, 1993).

4. C. Weisbuch and B. Vinter, "*Quantum Semiconductor Structures*" (Academic Press, 1991).

5. Supriyo Datta,"*Quantum Transport: Atom to Transistor*", (Cambridge, NY 2005).

6. Paul Harrison, "*Quantum Wells, Wires and Dots: Theoretical and Computational Physics of Semiconductor Nanostructures*" (Wiley 2000).

7. Thomas Ihn, "*Semiconductor Nanostructures: Quantum states and electronic transport*" (Oxford University press, 2010).

8. David K. Ferry**,** Stephen M. Goodnick and Jonathan Bird**,** "*Transport in Nanostructures*" (Cambridge, NY 2009).

General Solid State and semiconductor Physics Textbooks:

9. N. W. Ashcroft and N. D. Mermin, "*Solid State Physics*" (Saunders, 1976).

10. J. M. Ziman, "*Principles of the theory of Solids*" 2nd Ed. (Cambridge, 1972).

11. M. Shur, "Physics of Semiconductor Devices" (Prentice-Hall, 1990).

12. S. M. Sze, "Semiconductor Devices" (Wiley, 1985); "Physics of Semiconductor Devices", 2nd Ed. (Wiley, 1981).

13. Peter Y. Yu and Manuel Cardona "*Fundamentals of Semiconductors: Physics and Materials Properties*" (Springer 2010), 4th edition).

14. A. Yariv, "Optical Electronics" (Saunders, 1991); 4^{th} or 5^{th} edition

The double-barrier resonant tunneling diode

- Transmission through double-barrier structures
- Coherent tunneling
- Sequential tunneling
- Current-voltage characteristics and the negative-differential-resistance (NDR) phenomenon
- Advance: single electron transfer and the Coulomb Blockade

References:

E. E. Mendez, in *Physics and Applications of Quantum Wells and Superlattices*, edited by E. E. Mendez and K. v. Klitzing (Plenum, New York, 1987), p. 159.

V. Mitin, V. Kochelap & M. Stroscio, "*Quantum Heterostructures: Microelectronics and Optoelectronics*" (Cambridge, 1999) chapter 8.

S. Luryi and A. Zaslavsky "*Quantum-effect and hot electron devices*" in "*Modern Semiconductor Device Physics*", S. M. Sze ed., (Wiley, 1998) chapter 5.

R. Ricco and M. Ya Azbel, Phys. Rev. B **29** (1984) 1970

D.V .Averin and K. K. Likharev, J. Low Temp. Phys. **62** (1986) 345

Michael Feiginov, J. Infrared, Millimeter and Terahertz Waves **40** (2019) 365

Semiconductor superlattices (SLs)

- Minibands in ideal (infinite) SL and finite SL.
- Dispersion relations
- Electric field effects (biased SLs) and transport
- Magnetic field effects
- Optical transitions (inter-miniband and intra-miniband) and infrared spectroscopy
- Advance topic: Bloch oscillations in SLs

References:

M. Helm, Semicond. Sci. Technol. **10** (1995) 557

K. Leo, Semicond. Sci. Technol. **13** (1998) 249

V. Mitin, V. Kochelap & M. Stroscio, "*Quantum Heterostructures: Microelectronics and Optoelectronics*" (Cambridge, 1999).

Quantum well infrared photodetectors (QWIPs)

- Intersubband optical transitions and infrared absorption in QWs (bound-to-bound; bound-to-continuum, bound-to-miniband etc)
- QWIP's operation (responsivity; dark current; photo-conductive gain)
- Semiconductor systems (GaAs/AlGaAs etc)
- Applications: arrays of QWIPs, infrared imaging
- *Advance topic*: noise in QWIPs; the signal-to-noise (SNR) ratio, the concept of BLIP (background limited infrared performances (or detection; see A. Yariv, "*Optical Electronics*", 4^{th} ed (Saunders 1991) chapter 11).

<u>References:</u>

B. Levine, J. Appl. Phys. **74** (1993) R1

JL Pan and CG Fonstad, Mater. Sci. Eng. **28** (2000) 65

M. O. Manasreh, ed., "*Semiconductor quantum wells and superlattices for long wavelength infrared detectors*" (Artech House, 1993).

Quantum cascade (QC) lasers

- The QC laser Structure
- Transport mechanism
- Optical transitions (intersubband and inter-miniband)
- Gain and losses, laser action
- Advance: THz quantum cascade laser and its applications

<u>References:</u>

J. Faist *et al*, Science **264** (1994) 553

C. Gmachl *et al*, Reports Prog. Phys. **64** (2001) 1533

B. Williams, Nature Photonics **1** (2007) 517

C. Jirauschek and T. Kubis, Appl. Phys. Rev. **1**, 011307 (2014).

S. Soleimanikahnoj, · O. Jonasson,· F. Karimi and I. Knezevic, J. Comput. Electron, **20** (2021) 280.

V. Mitin, V. Kochelap & M. Stroscio, "*Quantum Heterostructures: Microelectronics and Optoelectronics*" (Cambridge, 1999).

"*Semiconductor Laser Theory*", P. K. Basu, B. Mukhopadhyay & R. Basu (CRC Press, FL 2016).

The Quantum well laser (QWL)

- Introduction to lasers: spontaneous versus stimulated emission; population inversion;
- The energy band structure of quantum wells (conduction and valence)
- Optical transitions in quantum wells (interband optical transitions)
- The density of states (DOS) in 2D (two-dimensions); comparison to 3D (bulk).
- The Optical gain, losses and the conditions for lasing
- Comparison with ordinary (3D) semiconductor lasers
- Advance: mode locking of lasers

References:

A. Arakawa and A Yariv, IEEE J. Quantum Electron **22** (1986) 1887

A. Yariv, "Optical Electronics" (Saunders, 1991); 4th or 5th edition.

S. L. Chuang, "*Physics of optoelectronic devices*" (Wiley, 1995)

"*Quantum well lasers*", P. S. Zorry, Jr. Ed (Academic, NY 1993).

"*Semiconductor Laser Theory*", P. K. Basu, B. Mukhopadhyay & R. Basu (CRC Press, FL 2016).

Quantum wire lasers

- Introduction to lasers: spontaneous versus stimulated emission; population inversion;
- The electronic structure and density of states in 1D quantum wires
- The effect of dimensionality on the optical gain and threshold current
- Methods of fabrication
- Comparison with ordinary semiconductor lasers (and QWL)
- Advance: the effect of strain

References:

E. Kapon, chapter 10 in "*Quantum well lasers*", P. S. Zorry, Jr. Ed (Academic, NY 1993); see also: Proc. IEEE **80** (1992) 398.

N. Ledentsov *et al*, IEEE J. Lightwave Technol. **26** (2008) 540

S. Arai and T. Maruyama, IEEE J. Quantum Electon.. **15** (2009) 731

"*Semiconductor Laser Theory*", P. K. Basu, B. Mukhopadhyay & R. Basu (CRC Press, FL 2016).

The Quantum dot lasers

- Comparison of low-dimensional semiconductor lasers (bulk, QW, QWR and QD lasers):
  The density of states (0D versus the others)
  The effect of dimensionality on the optical gain and threshold current
- Methods of fabrication: top-down versus bottom-up approaches
- Advance: temperature dependence of the threshold current in QD lasers

References:

L. V. Asryan and D. A. Suris, Semicond. **38** (2004) 3

D. Bimberg *et al*, J. Phys. Condens. Matter **15** (2003) R1063.

N. Ledentsov *et al*, IEEE J. Lightwave Technol. **26** (2008) 1540

W. W. Chow and F. Jahnke, Progress Quantum Electron. **37** (2013) 109

H. Jung, N. Ahn & V. Klimov, Nature Photon. **15** (2021) 643-655

Y – S. Park *et al*, Nature Rev. Mater. **6** (2021) 382-401

C. Shang *et al*, ACS Photon. **8** (2021) 2555-2566

Colloidal Quantum dots & Perovskites for Photovoltaic solar cell applications

- Fundamental of photovoltaic solar cells and *p-n* junctions (the classical solar cell)
- The role of quantum dots in photovoltaic solar cells
- Basic electronic and optical properties of quantum dots and quantum dot solar cells
- Preparation of colloidal quantum dots and quantum dot sensitized solar cells
- Advance: perovskites based solar cells

References:

I.J. Kramer and E,H. Sargent, ACS Nano. **5** (2011) 8506

J. Tang and E. Sargent, Adv. Matter **23** (2011) 12.

A.J. Nozik *et al*, Chem. Rev. **110** (2010) 6873

O.E. Semonian *et al*, Mater. Today **15** (2012) 508

R. S. Selinsky *et al*, Chem. Soc. Rev. **42** (2013) 2963

L. M. Nikolenko and V. F. Razumov, Russian Chem. Rev. **82** (2013) 429

V. Gonzalez-Pedro *et al*, Nano Lett.**14** (2014) 888

P. Tonui *et al*, Renewable & Sustainable Energy Rev. **91** (2018) 1025

N. -G Park, Mater. Today **18** (2015) 65

L. Schmidt-Mende *et al*, APL Mater. **9** (2021) 109202.

Inversion layers in MOS (metal-oxide-semiconductor) structures and the formation of 2D (two-dimensional) electron gas

- The classical MOS field effect transistor (MOSFET).
- Inversion layers and quantum size effects.
- Polarizability (the response to electromagnetic field) and screening in 2D electron gas.
- Self-consistent calculations of the energy levels and formation of subbands.
- Advance: The triangular potential approximation and analytical solution of the self-consistent problem.

References:

T. Ando, A. B. Fowler and F. Stren, Rev. Mod. Phys. **54** (1982) 437

C. Hamaguchi, "*Basic Semiconductor Physics*", 2nd Ed. (Springer-Verlag, Berlin 2010);

S. M. Sze, "*Physics of Semiconductor Devices*", 2nd Ed. (Wiley, 1981);

M. Shur, "*Physics of Semiconductor Devices*" (Prentice-Hall, 1990)

Graphene: a 2D (two-dimensional) structure of Graphite

- The Carbon atoms and the 3D structure of Graphite.
- The 2D structure of Graphene.
- The energy band structure of Graphene: π and σ bands; dispersion relations near the K points.
- Dirac states in graphene: the relativistic-like characters of graphene.
- Synthesis and applications.
- Defects in Graphene
- Advance: Beyond graphene - Van der Walls 2D materials & multilayers

References:

A. H. Castro *et al*, Rev. Mod. Phys. **81** (2009) 109

M. Orlita and M. Potemski, Semicond. Sci. Technol. **25** (2010) 063001

Y. Zhu *et al*, IEEE Adv. Mater. **22** (2010) 3906.

F. Bonaccorso *et al*, Nature Photonics **4** (2010) 611

R. Saito, G. Dresselhaus and M. Dresselhaus, "*Physical properties of Carbon nanotubes*" (Imperial College, 1998).

H. -S. Philip Wong and Deji Akinwande, "*Carbon Nanotube and Graphene Device Physics*" (Cambridge University Press, 2011).

X. Li *et al*, Appl. Phys. Rev. **4**, 021306 (2017).

P. Avouris, T. Heinz, and T. Low, *2D Materials*, (Cambridge University Press, Cambridge, 2017).

A. V. Kolobov and J. Tominaga, *Two-Dimensional Transition-Metal Dichalcogenides*, (Springer, Switzerland, 2016).

Carbon Nanotubes (CNTs)

- Synthesis of CNTs: Multi-walled and single-walled CNTs.
- Electronic properties of single-walled CNTs.
- Optical properties of CNTs.
- Advance: other novel properties and applications of CNTs.

References:

R. Saito, G. Dresselhaus and M. Dresselhaus, "*Physical properties of Carbon nanotubes*" (Imperial College, 1998)

V. N. Popov, Mater. Sci. Eng. R **43** (2004) 61

M. Dresselhaus *et al*, **Annual Review of Physical Chemistry.** **58** (2007) 719.

M. Terrones, Annu. Rev. Mater. Res. **33** (2003) 419

R. Saito *et al*, Appl. Phys. A **78** (2004) 1099

H. -S. Philip Wong and Deji Akinwande, "*Carbon Nanotube and Graphene Device Physics*" (Cambridge University Press, 2011).

Porous Silicon: A quantum sponge structure

- Direct versus indirect bandgap semiconductors.
- The effect of confinement on silicon: silicon nanocrystals and porous silicon.
- Methods of preparation of porous silicon.
- Optical properties: photoluminescence (PL) and multilayer of thin films
- Advance: the vibron model for the photoluminescence from porous silicon.

References:

A. G.Cullis, L. T. Canham and P. Calcott, J. Appl. Phys. **82** (1997) 909

O. Bisi, S. Ossicini and L. Pavesi, Surf. Sci. Reports **38** (2000) 1

A. Sa'ar, J. Nanophoton, **3** (2009) 032501;

A. Sa'ar, Chapter 25: "Photoluminescence from Silicon Nanostructures", *Handbook of Nanophysics*: *Nanoelectronics and Nanophotonics*, Vol. **6**, K. D. Sattler Ed., CRC press (Taylor & Francis Group, 2011).

V. Lehmann, "*Electrochemistry of silicon*" (Wiley-VCH, 2002)

Photonic Crystals: confinement of light into periodic dielectric structures

- 1D photonic crystals: periodic multilayer structures.
- 2D and 3D photonic crystals.
- Symmetries and photonic bandgaps (or dispersion relations).
- Advance: Defects in photonic crystals and formation of cavities.

References:

P. Yeh, A. Yariv & C-H Hong, "*Electromagnetic propagation in periodic stratified media. I. General theory*", J. Opt. Soc. Am. 67 (1977) 423

S. G. Johnson and J. D. Joannopoulos, "*Photonic crystals: the road from theory to practice*" (Kluwer academic 2002)

J. D. Joannopoulos, R. D. Meade, J. N. Winn, "*Photonic crystals: molding the flow of light*" (Princeton University press, 1995)

K. Sakoda, "*Optical properties of photonic crystals*" (Springer series in optical sciences 80, 2001).

M. Notomi, Reports Prog. in Phys. **73** (2010) 096501