JASPRIT SINGH
UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN USA

CHALLENGES IN OPTOELECTRONIC DEVICES
Optoelectronic Devices: Light Emitters, Detectors, Energy Convertors, Modulators,..

- Electrons to photons: LEDs’ lasers, modulators
- Photons to electrons: solar cells thermoelectric devices, ..The Sun gives a kilowatt of power per square meter
Electromagnetic Spectra
Materials and Devices

### Important Material Systems

**In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$**; $x = 0.47$, $y = 0.53$

- Lattice matched to InP.
- Wide range of emission energies can be accessed (~0.8 to 1.35 eV).
- Material technology is quite advanced and can be exploited for communication applications.

- $E_g = 1.35 - 0.72y + 0.12y^2$ eV

**AlGaAs**

- Lattice matched to GaAs.
- Technology is quite advanced and can be used for LANs.

- $E_g = 1.43 + 1.25x$ eV; $x \leq 0.35$

**GaAs$_{1-x}$P$_x$**

- Material becomes indirect at $x = 0.45$.
- With $N$ doping the LED can operate even if the material is indirect and green light emission ($\lambda = 0.55$ μm) can be achieved.
- The versatile material can provide red (GaAs$_{0.6}$P$_{0.4}$), orange (GaAs$_{0.35}$P$_{0.65}$:N), and yellow (GaAs$_{0.15}$P$_{0.85}$:N) as well.

**SiC, GaN, ZnS, ZnSe — large gap materials which can emit blue light and beyond**

- Important materials for blue light emission (for displays, memories).
- Technology is not mature, but rapid progress is being made.
Bandgaps and Photon energies in materials

![Graph showing bandgaps and photon energies in materials](image-url)

- **GaAs**
- **GaInAsP**
- **InP**
- **AlGaSb**
- **GaSb**
- **HgCdTe**

**Band Gap (eV)**
- GaAs: 1.4
- GaInAsP: 1.3
- InP: 1.0
- AlGaSb: 0.8
- GaSb: 0.7
- HgCdTe: 0.4

**Lattice Constant (Å)**
- 5.6
- 5.7
- 5.8
- 5.9
- 6.0
- 6.1
- 6.2
- 6.3
- 6.4
- 6.5

**Absorption Edge (µm)**
- λ = 1.3µm
- λ = 1.55µm

**Emitter materials**
- **Detector materials**

*Jaspreet Singh*
Fiber Communication: Laser needs

![Graph showing fiber attenuation and wavelength dependence.](image)
Electromagnetic Spectra: What Semiconductor Technology can Do

- Transistors: Can go up to 500 GHz. Limitations arise from lithography, material properties (carrier transport) and device physics.
- Lasers can provide emission in the range of 25 THz to $10^{15}$ Hz. Limitations arise from material bandgap and Auger effects. Small bandgap materials have a strong non-radiative channel: $e+e+h \rightarrow e + \text{heat}$. At very high injection densities Auger processes can dominate.
Electromagnetic Spectra: Challenges and Unmet needs

- Emission: Window between 0.5 THz to 25 THz. Important window for sensing molecules, thermal imaging.
- Photons with energy beyond 3 eV are important for memory applications, lithography, chemistry, medical diagnostics, …
What Optoelectronics Enables

- Information reception/detection
- Information manipulation
- Information enhancement/amplification
- Information transfer
- Information generation
- Information display

Information retrieval from memory

Jasprit singh
What Optoelectronics Enables

- Immunity to electromagnetic interference
  - Can be transmitted without distortion due to electrical storms, etc.
- Non-interference of two or more crossed beams
  - Unlike electrical signals, optical signals can cross each other without distortion
- High parallelism
  - Two-dimensional information can be sent and received
- High speed-high bandwidth
  - Potential bandwidths for optical communication systems exceed $10^{13}$ bits per second
- Beam steering for reconfigurable interconnects
  - Free space connections allow versatile architecture for information processing
- Special function devices
  - Interference or diffraction of light can be used for special applications
- Wave nature of light for special devices
- Nonlinear materials
  - New logic devices can be created
- Photonics-electronics coupling
  - The best of electronics and photonics can be exploited by optoelectronic devices
What Optoelectronics Enables

Optoelectronic devices: laser diodes; light emitting diodes; detectors; modulators

Data communication
- Local area network
- Factory automation

Optical communications
- Cable TV
- Longhaul communication
- Loop distribution

Defense applications
- Laser guided systems
- Radar

Consumer electronics product
- Compact disc
- Laser printer
- Night vision, thermal imaging
- Video disc libraries
- Flat panel displays for laptop computers
What Optoelectronics Enables

- Refigurable circuits
  - Free space beam steering
    - Optical devices based on novel physical phenomenon: quantum stark effect; non-linear effects...
      - Massive memory chips (> 10^{12} bits)
      - Optical "computer"
        - Highly parallel architectures
        - Neural network based computers
      - New coding/detection schemes
      - Optical communications
      - Full use of fiber bandwidth
      - "Intelligent" glasses
What Optoelectronics Enables

Sub-2D Systems for Lasers

Advantages
- High material gain at low injection
- Greater ease in polarization tunability

Challenges
- Extremely difficult fabrication technology
- Serious problems in achieving high fill factor and high optical confinement
- Serious challenges in charge injection from contacts—carrier thermalization problems

Jasprit singh
What Optoelectronics Enables

- **Strained Quantum Wells**
  - Adjusting bandgap to reach a certain emission wavelength
  - Up to 150 meV variation in bandgap can be achieved
  - Reduction in hole masses to achieve lower threshold current lasing
  - Hole mass can be reduced by up to a factor of 3 by using strain
  - Strain can allow laser emission to have tailored polarization
  - By using appropriate strain, one can have TE, TM, or unpolarized light
  - Reduction in Auger rates
  - Reduced hole masses can result in lower Auger rates
  - Improved laser reliability
  - Built-in strain may suppress defect migration into the active region

Jasprit Singh
Light Emitters: Lasers

ADVANCED LASER STRUCTURES

- Tunability of electronic spectra
  - Quantum wells
  - Strained quantum wells
  - Quantum wires
  - Quantum dots

- Tunability of photonic spectra
  - DFB, DBR gratings
  - DBR for surface emission
  - Microcavities for altering spontaneous emission
  - Periodic dielectrics for photon bandgaps
Light Emitters: Lasers

Demands placed on laser linewidth by various communication systems

- **Local area networks using single λ.**
  - 20-30 Å quite adequate
  - for some applications, 200-300 Å (LED output) can be adequate

- **Long distance networks using single λ.**
  - 1-2 Å if repeater spacings are to approach ~100 km
  - need DFB lasers

- **Multi-λ (WDM) systems**
  - 1-2 Å for ~20 different wavelengths communication

- **Coherent detection schemes**
  - KHz to MHz linewidths are needed
    (1 Å = 12.5 GHz at 1.55 μm)
Light Emitters: Lasers

ADVANCES IN SEMICONDUCTOR LASERS

Optimized optical and electronic properties
- Electronic properties: quantum well, quantum wire, and strained structures
  - Optical properties: DFB, SEL, and microcavity structures
  - Advanced mirror technologies

New material systems
- Large bandgap lasers: ZnSe, ZnTe, ZnS, GaN, AlGaN...
- Narrow bandgap lasers: HgCdTe, InSb, PbTe...

OEICs
- OEIC Transmitters: Integration of laser with FET, HBTs

Jaspreet Singh
Laser Diodes for Communications
Surface emitters: Challenges in sub-wavelength emitters; DBR confinement; metal confinement; electron-plasmon based confinement.
Detectors and emitters: Cascade lasers have become important as long wavelength sources.
Light Emitters

(a) Low Temperature
- a low leakage current

(b) High Temperature
- a injected charge is spread out in energy
- a higher leakage current
Light Modulation

**OPTOELECTRONIC MODULATION and SWITCHING DEVICES**

- **Alter the optical properties of the device by an electronic signal**
  - **Physical effect**
    - Electro-optic effect in bulk and quantum well systems
  - **Devices**
    - Waveguide modulators
    - Directional couplers
    - Vertical incidence modulators (programmable spatial light modulators)

- **Alter the electronic properties of the device by an optical signal**
  - **Physical effect**
    - Electro-absorption in quantum wells using confined Stark effect
  - **Devices**
    - Negative resistance effects in quantum well diodes
    - Optical switches and logic gates
    - Optical memory
Solid State Lighting: Issues

How do we get white light devices?

Red, Green, Blue LEDs or Blue LED +phosphors?

Red LEDs: GaAs based devices can have very high quantum efficiency (approaching 100%).

Nitride based Green LEDs have quantum efficiencies close to 10% and at high injection (more than 200 A/cm$^2$ the efficiency drops rapidly.

Nitride based blue LEDs have poor efficiencies beyond 500 A/cm$^2$. 
Nitride Based LEDs

- Understanding InGaN quantum structures for light emission applications?

1. Very strong quantum confined Stark effect (QCSE) exists in wurtzite GaN quantum well system due to the piezoelectric polarization effects.
2. Electron-hole overlap is small due to polar fields especially at low injection.

![Graph showing strain between InN and GaN with ε ~ 10%]
Issues in InGaN quantum wells

1. Strong piezoelectric polarization effect.
   \[ \langle \phi_c | \phi_v \rangle \ll 1 \]

2. Difficulties in screening the piezoelectric polar charges.
   Piezoelectric polarization charge density > \(10^{13} \text{ cm}^{-2}\). To generate such high carrier density to screen piezoelectric polarization, we will find that the Fermi level would be higher than the barrier, which leads to current overflow.

3. Even in non-polar GaN technique, large lattice mismatch will still lead to In clustering effects so that polarization effects may be present.
Device Performance Issues

- Contact grading
- Carrier capture e-h overlap non-radiative recombin.
- Access resistance: IR drop at high injection
- Contact grading

Jaasprit Singh
1. Our study shows that if we can increase the p-type doping as high as possible, we can enhance the injection of holes.
2. One drawback of blocking layer is that the turn-on voltage might increase.
Technology Challenges in Highly Strained LEDs.

Dislocations InGaN / GaN

For most LED devices, the dislocation densities are around $10^8 - 10^{10}$ cm$^{-2}$

If we consider the dislocation densities are around $10^8$ cm$^{-2}$ → dislocations are separated by 1 µm.

Vertical and lateral transport are important to understand for radiative and non-radiative recombination
Carrier Recombination

Path ① : radiative
Path ② : non-radiative

Lateral diffusion (mobility is critical)
Lateral distance travelled in time $t_{e-h}$ is

$$t_{e-h} \sim \tau_r = 1 \text{ ns}$$
Lighting: Where is the energy going?

Energy Efficiency of Incandescent and Fluorescent Lamps

- **Generating Plant**
  - Prime Energy Input 188 Joules
  - Conversion Loss 122 Joules (65%)
  - Resistive Losses 6 Joules (10%) 60 Watts

- **Distribution Grid**
  - Waste Heat (98%) 55.65 Joules

- **Light Source**
  - Light Energy Output 1.35 Joules (900 Lumens)
  - Resistive Losses 1.5 Joules (10%) 15 Watts
  - Waste Heat (91%) 13.65 Joules

- **15 Watt Fluorescent Lamp**
  - Light Energy Output 1.35 Joules (900 Lumens)

- **60 Watt Incandescent Lamp**
  - Light Energy Output 1.35 Joules (900 Lumens)
Solar Energy and Conversion

Roughly 1 kilowatt/m² of solar radiation!
Solar Energy and Conversion

Broad spectra: Single bandgap solar cells cannot reach high efficiency.
Hybrid cells: Combination of materials, embedded quantum dots;
Challenges: Charge extraction from the cells

What materials to use?
Silicon: poly; amorphous, crystalline;
GaAs; higher efficiency but expensive
II-VI s; organics …
Solar Energy and Conversion

Tremendous opportunities: Utility companies; power distribution issues, …But COST ISSUES?

Concentrators?
Low cost mirrors, lenses
Heat extraction/use
Semiconductors: Energy Conversion

Energy conversion: Photovoltaics

Status: Challenging environment
Niche applications: off grid
Slowly becoming competitive
With a 25 year lifespan solar energy is becoming competitive in developed markets.
Cost is about 3 cents per kWhr. However, some subsidies and tax breaks are needed.
Upfront costs are high.
Impact is higher in less developed markets.
Semiconductors: Artificial Photosynthesis

Energy conversion: Photons to electrons-holes to chemical reactions
Semiconductors: Photons Driving Chemical Reactions

Energy conversion: Photons and holes

Oxidation and reduction to cause photosynthesis: $\text{CO}_2$ and water to $\text{O}_2$ and carbohydrates

Challenges: Find reliable catalysts, inexpensive semiconductor particles so voltages of $\sim 1 \text{ V}$ can drive chemical reactions
Hydrogen, methane, “gasoline”, …