MBE Growth of Group III-Based Solar Cells and other Optoelectronic Devices

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Introduction

About Our Customers

Outline

Growth of group-III based materials

- Molecular Beam Epitaxy
- Gallium Arsenide
- Advantages

GaAs solar cells

- p-n junction
- Solar cells limitations/losses
- Stack growth using MBE
- Types of solar cells
- Features and key elements
- Other techniques

Other optoelectronic devices

- Laser Diodes
- Quantum Well Infrared Photodetectors (QWIPs)

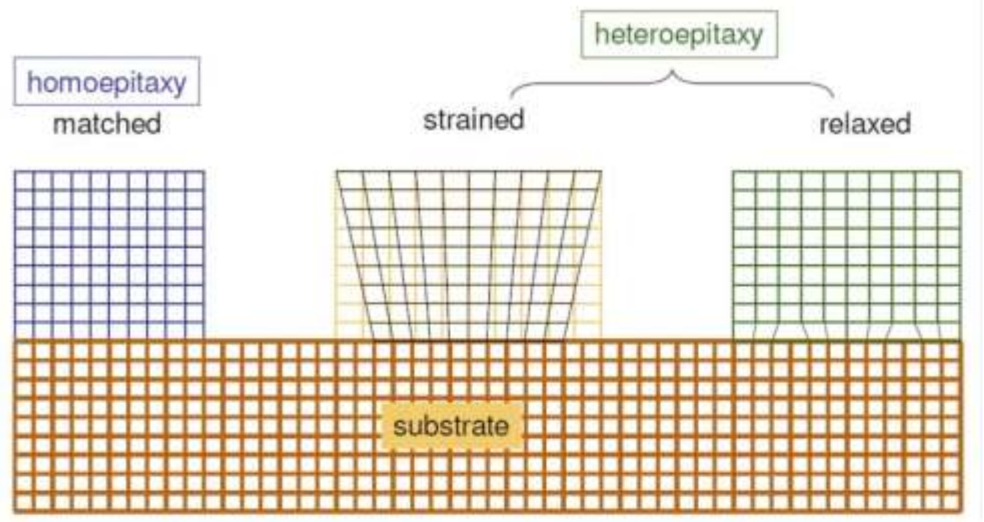
Epitaxy

Epitaxy – Epi + Taxis: “above” + “in an ordered manner”

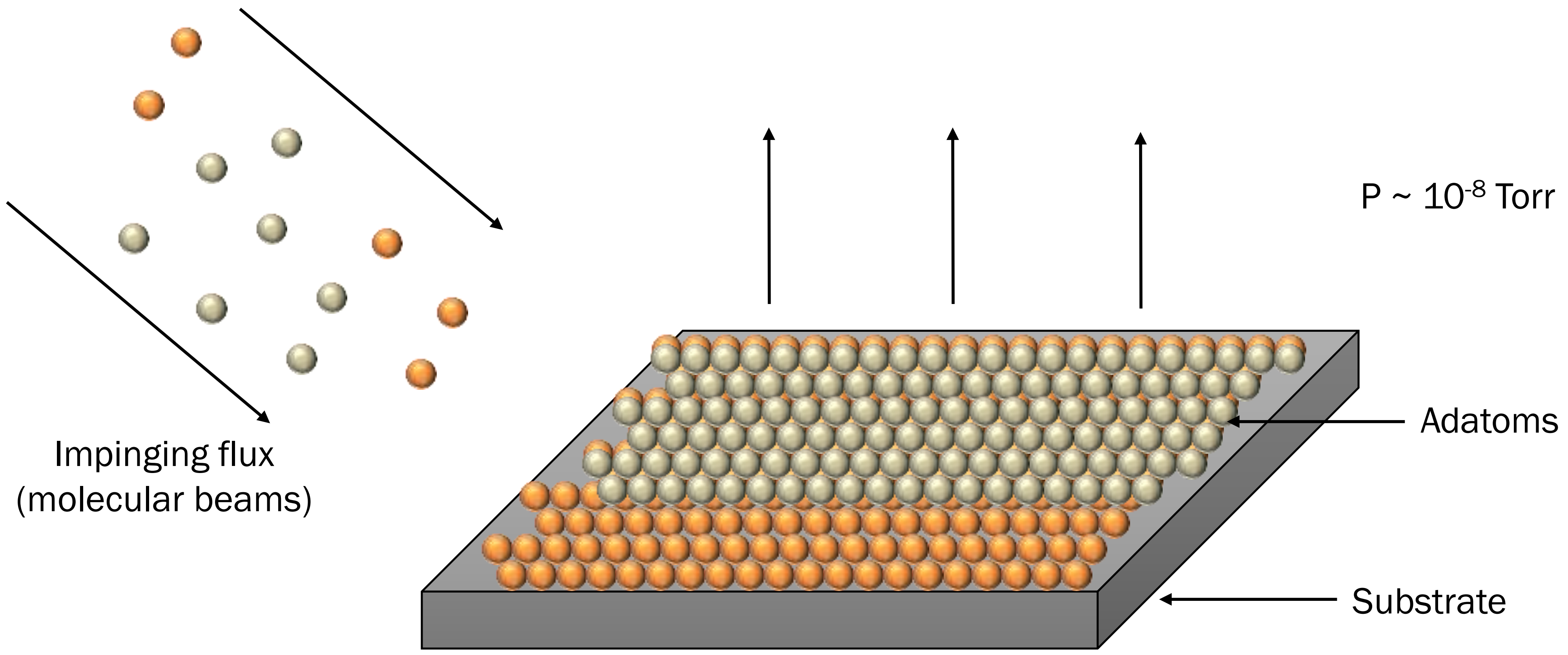
Crystalline (epi-) layers form with one or more well-defined orientations with respect to the underlying substrate

Homoepitaxy: growth of the same material as substrate in an epitaxial manner

Heteroepitaxy: growth of a different material than the substrate



Molecular Beam Epitaxy



Molecular Beam Epitaxy

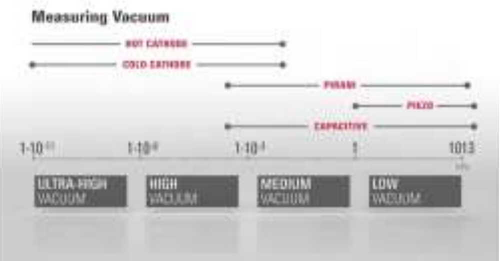
One of the best techniques to grow crystalline wafers

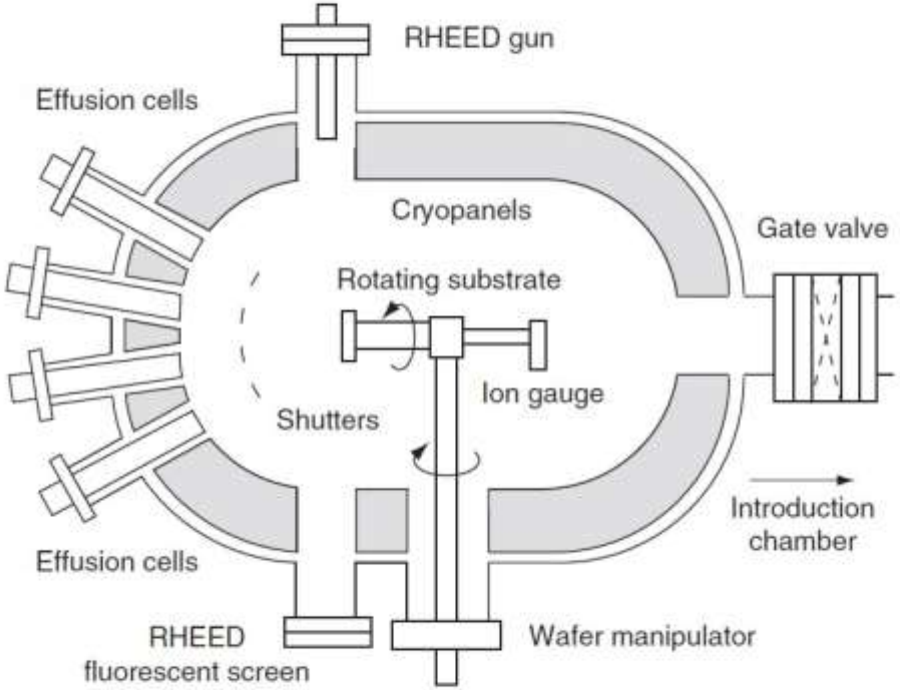
Ultra high vacuum ~10^{-11} Torr

Slow deposition rate (<1 μm per hour) – allowing epitaxial deposition

RHEED to monitor growth

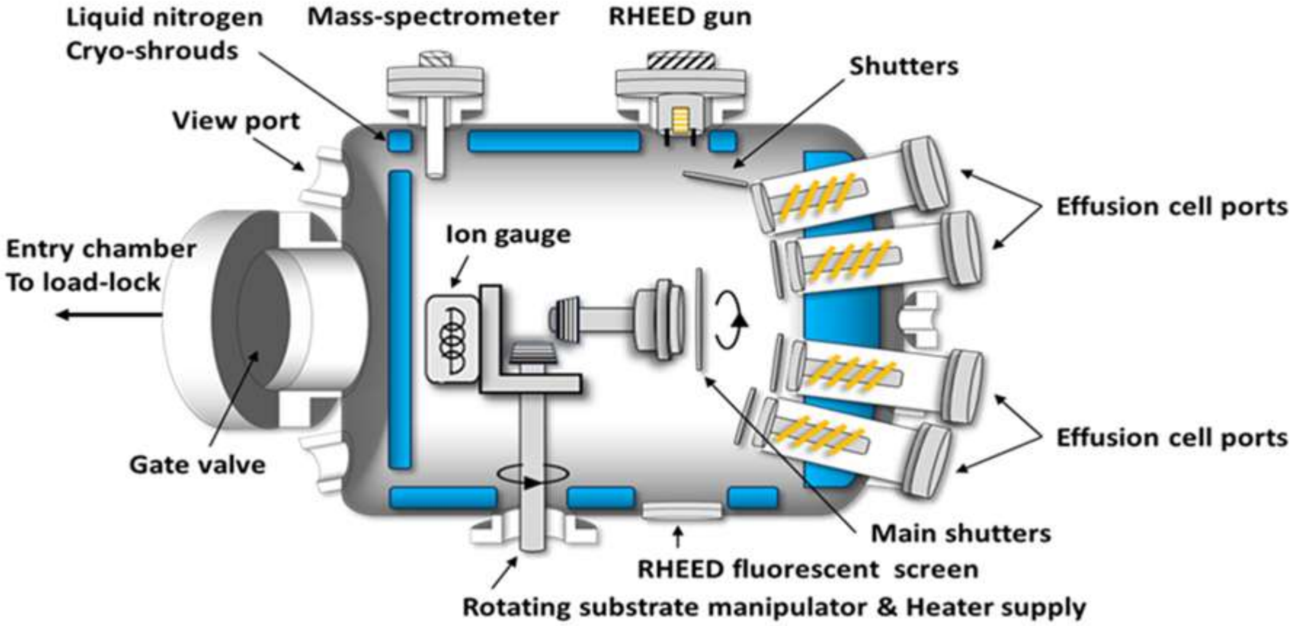
Atomically flat, abrupt heterostructures





Non equilibrium process (what is an equilibrium process?)

Operation



MBE operates in ultra high vacuum (UHV)

Liquid nitrogen (LN_2) flow through cryo panels

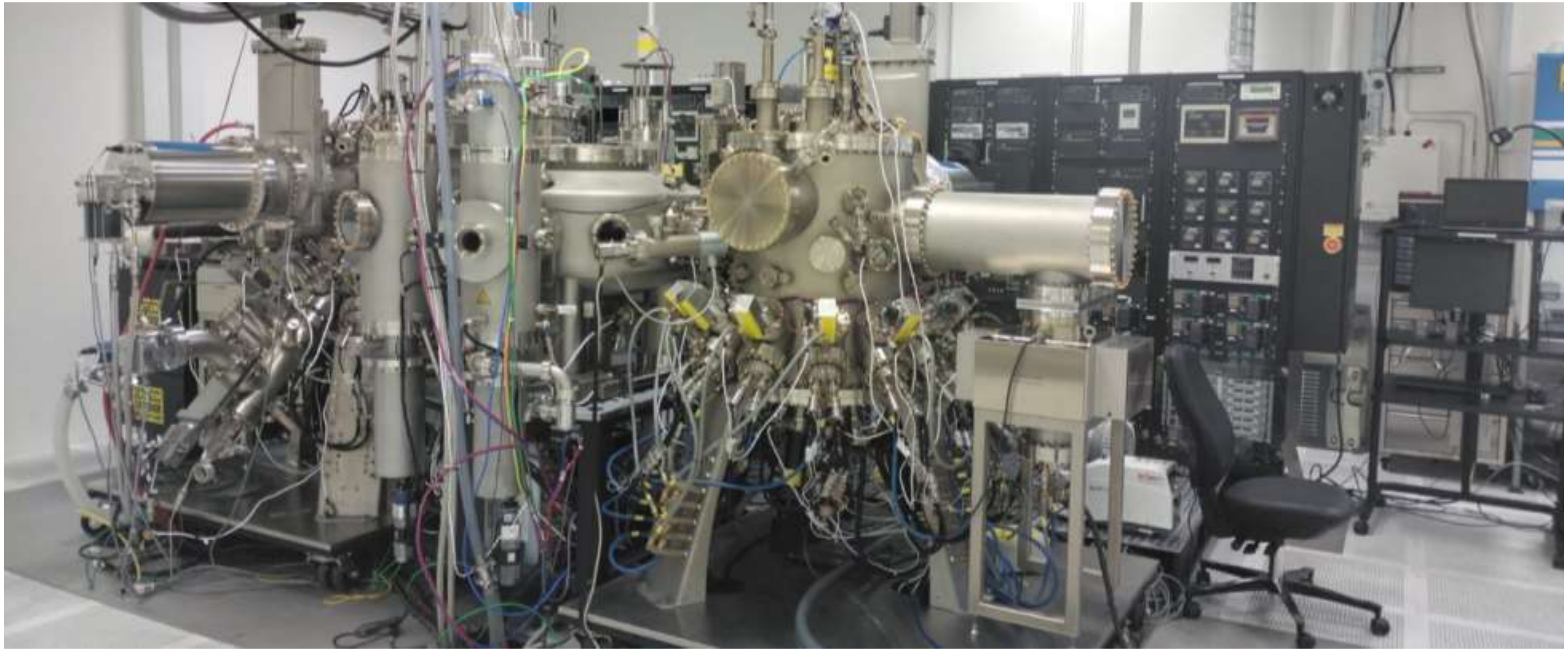
Heat k-cells (Knudsen cells)

Heat substrate, monitor RHEED

Open shutters, close RHEED when not required

Recipe for multilayer growth

Molecular Beam Epitaxy



Molecular Beam Epitaxy

Advantages

1. Good for making high quality semiconductor crystals from compounds or from several different elements
2. Extremely thin films can be fabricated in a precise, controlled manner
3. High purity, clean surfaces due to UHV conditions
4. In-situ monitoring and control of individual layers
5. Multiple sources offer variety in possible compounds such as alloys and heterostructures
6. Flexible technique, parameters controlled independently

Disadvantages

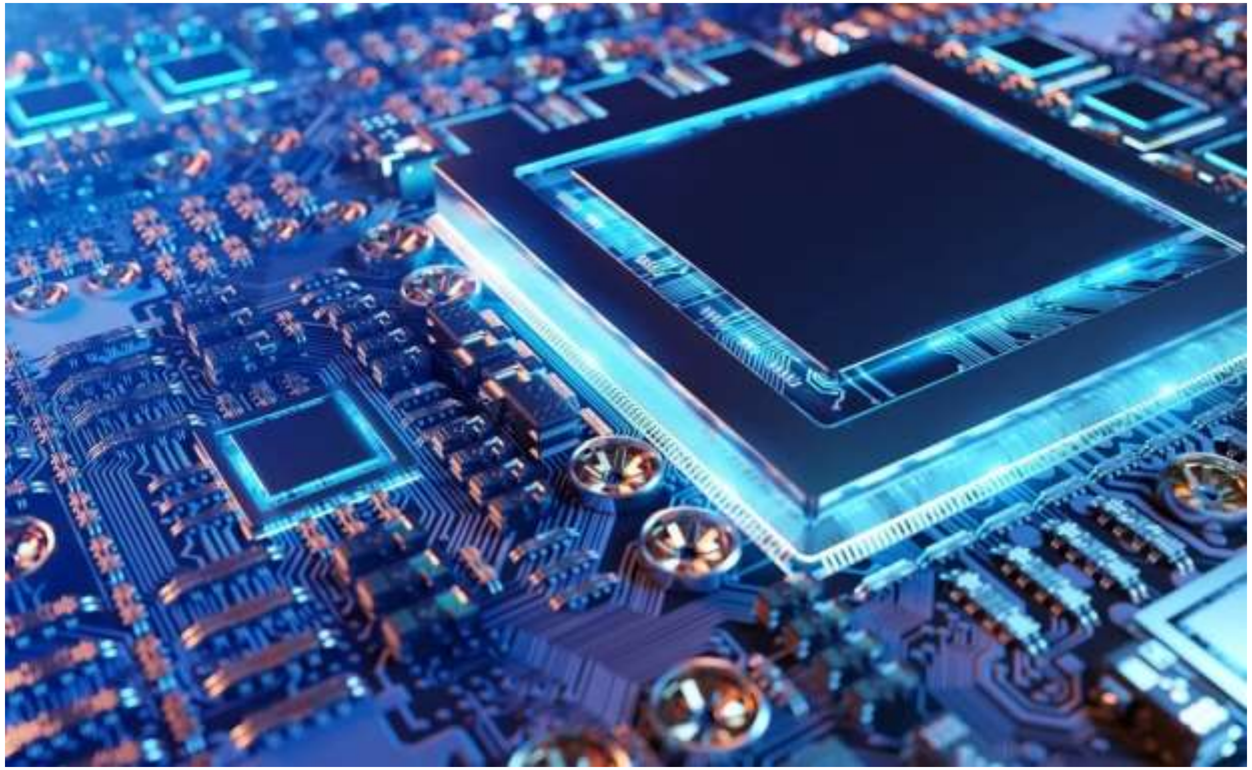
1. Extremely slow and laborious process (growth rate is ~ 1.0 µm/h
2. Equipment involved is complex and very expensive

Mostly Broken Equipment
Many Boring Evenings
Mega-Buck Evaporation

Molecular Beam Epitaxy

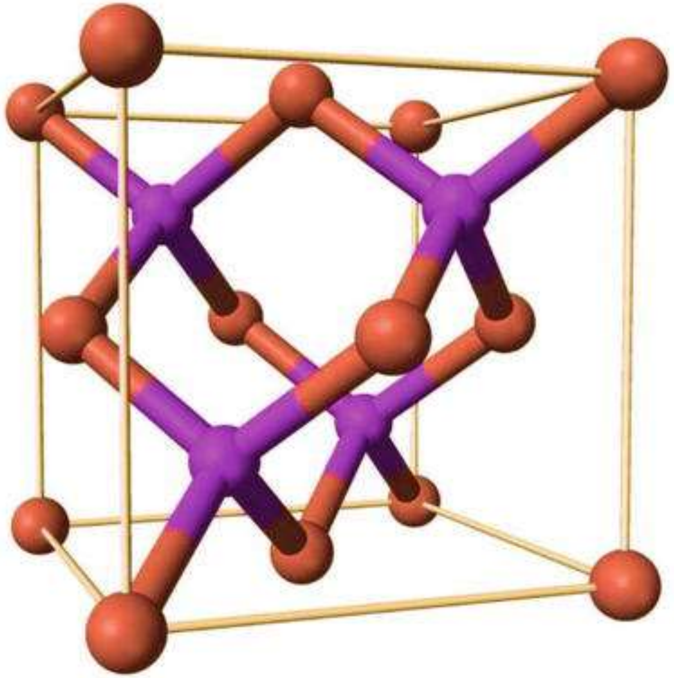
Applications

- Transistors (HEMTs, FETs)
- Optoelectronic devices (LASERs, VCSELs, Solar cells, LEDs)
- Microwave devices
- Nanostructures
- Superlattices
- Quantum wells



Gallium Arsenide

- Gallium Arsenide (GaAs) is a III-V semiconductor
- Zinc Blende crystal structure
- Direct band gap of 1.43 eV
- Intrinsically low carrier concentration – semi insulating substrates (high ρ of 10^7-10^9 Ω.cm)
- Useful for high frequency devices, insensitive to overheating



Gallium Arsenide

GaAs material importance

- Direct wide band gap – efficient light absorption/emission
- Superior electronic properties than silicon
- Higher saturated electron velocity, mobility – higher frequency transistors

Silicon importance

- Cheaper, stable and good thermal conductor – dense packing of transistors
- Native oxide (SiO_2) – useful in device integration, engineered for electrical properties
- High hole mobility for pFET

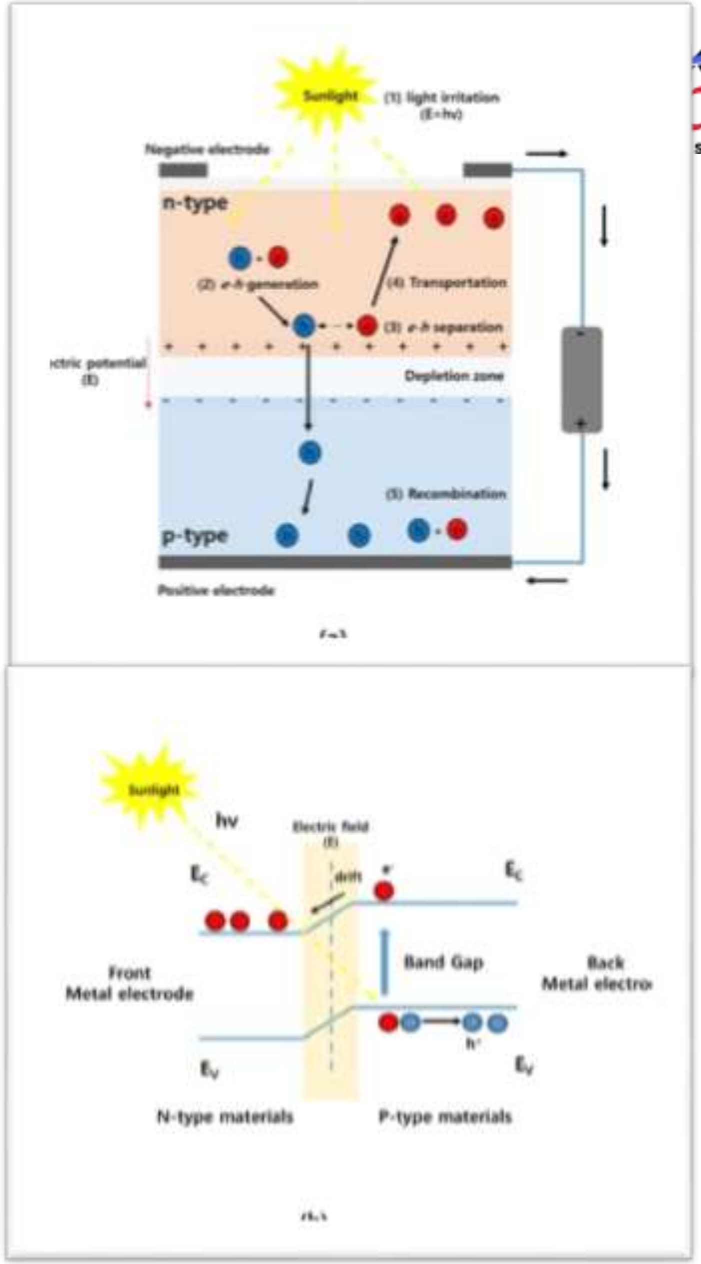
Comparison with silicon

Higher electron mobility of GaAs gives an advantage in fabricating high speed devices. Direct band gap allows for efficient photon emission in LEDs and LASERs.

	Silicon	GaAs
Minority carrier lifetime	0.003	1E-8
Electron mobility	1500	8000
Hole mobility (cm^2/Vs)	600	400
Band gap (eV)	1.12(indirect)	1.43(direct)
Vapor pressure	$1E^{-8}$@930 ° C	1@1050°C

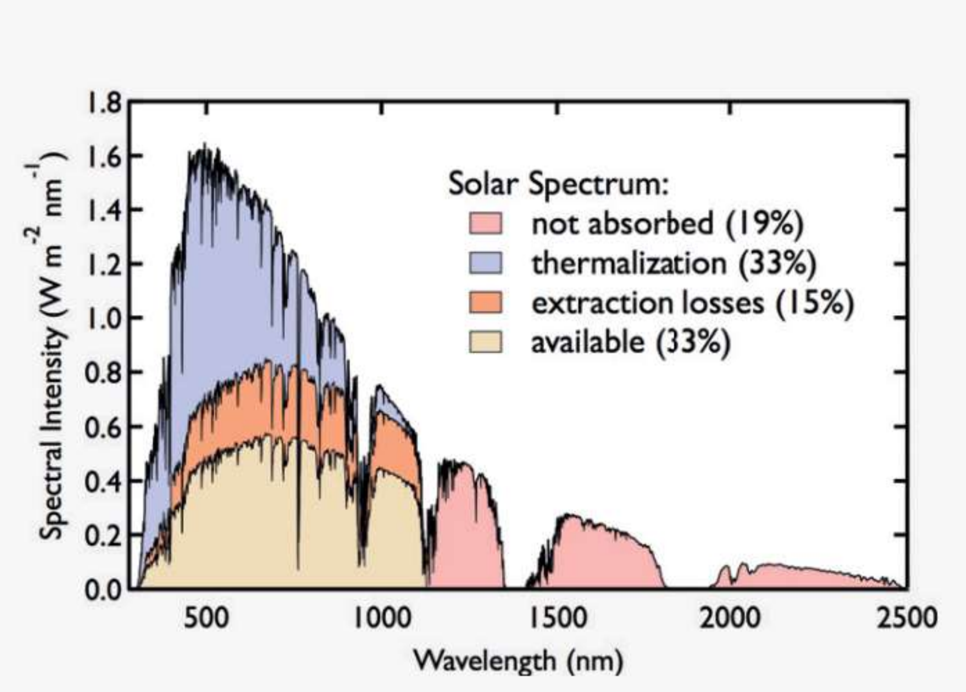
p-n junction solar cell

- Light incident on the p-n junction gives rise to charge carriers
- Charge carriers separate due to the electric field in the depletion region
- Electrons gain energy from photons and get excited to conduction band
- Eventually the electrons flow towards the top of the cell and reach the negative electrode which is connected to an external load
- Repeated movement of electron through the circuit generates electricity



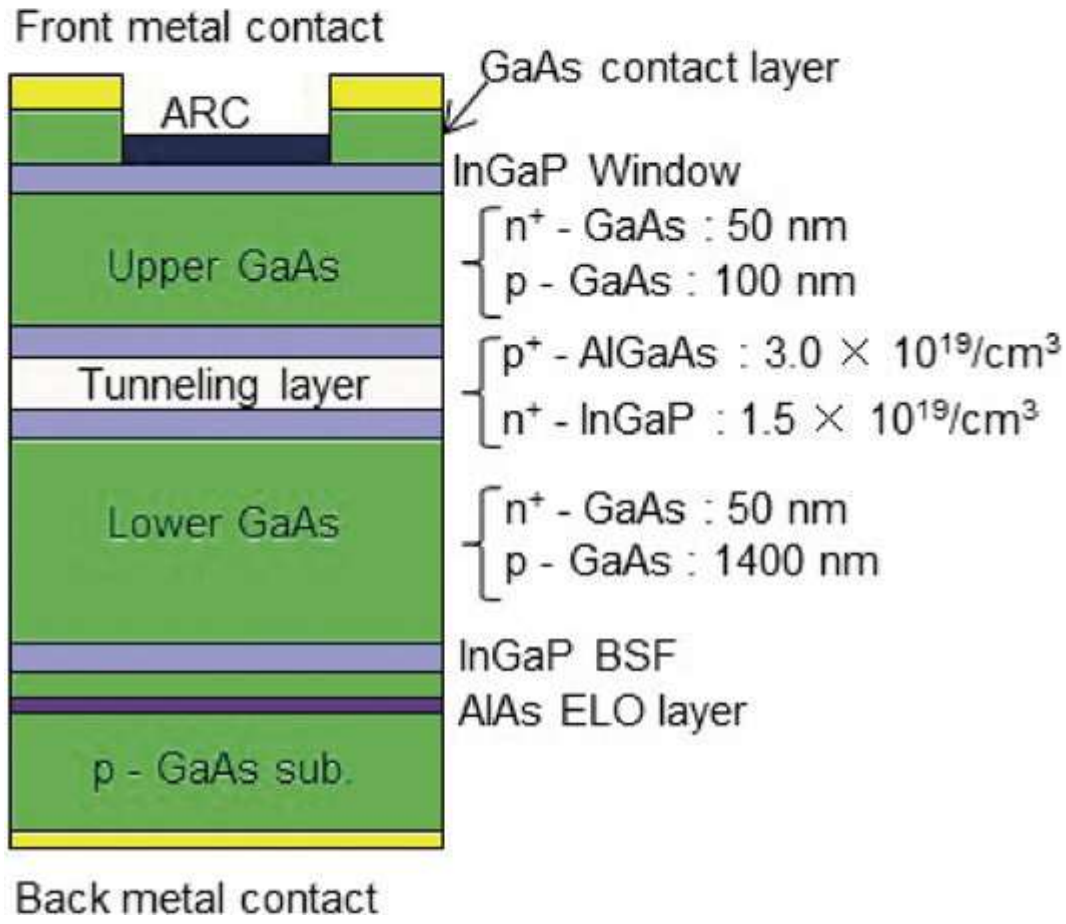
Solar cell: Limitations and losses

- Shockley-Quiesser limit: Theoretical cap on the efficiency of a single layer solar cell
- Yellow: Maximum available theoretical energy from a standard single junction cell
- Orange: Charge extraction losses from technology and material defects
- Blue: Losses from heat after photon absorption and emission
- Pink: Losses due to insufficient photon energy



MBE growth of GaAs solar cell

- Growth carried out in layers starting from bottom – whole structure is called a “stack”
- Control over layer thickness and sharp interface – fast shutter speed
- Excellent control over doping levels

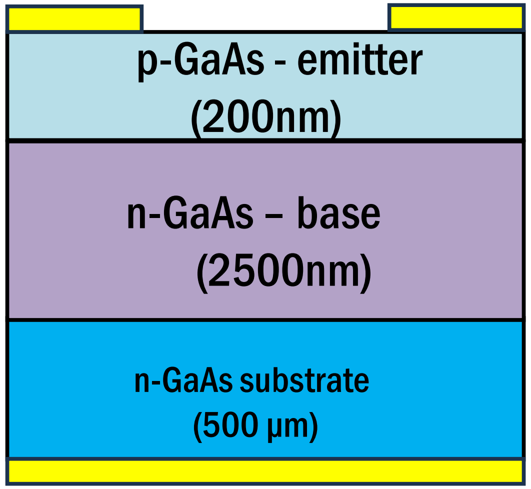


Types of solar cells

- ❖Single homojunction
- ❖Heterojunction
- ❖Multiple heterojunction (Tandem)
- ❖GaAs on Si/Ge
- ❖Re-usable substrate

Single homojunction

- MBE grown p-n junction using only one compound (GaAs)

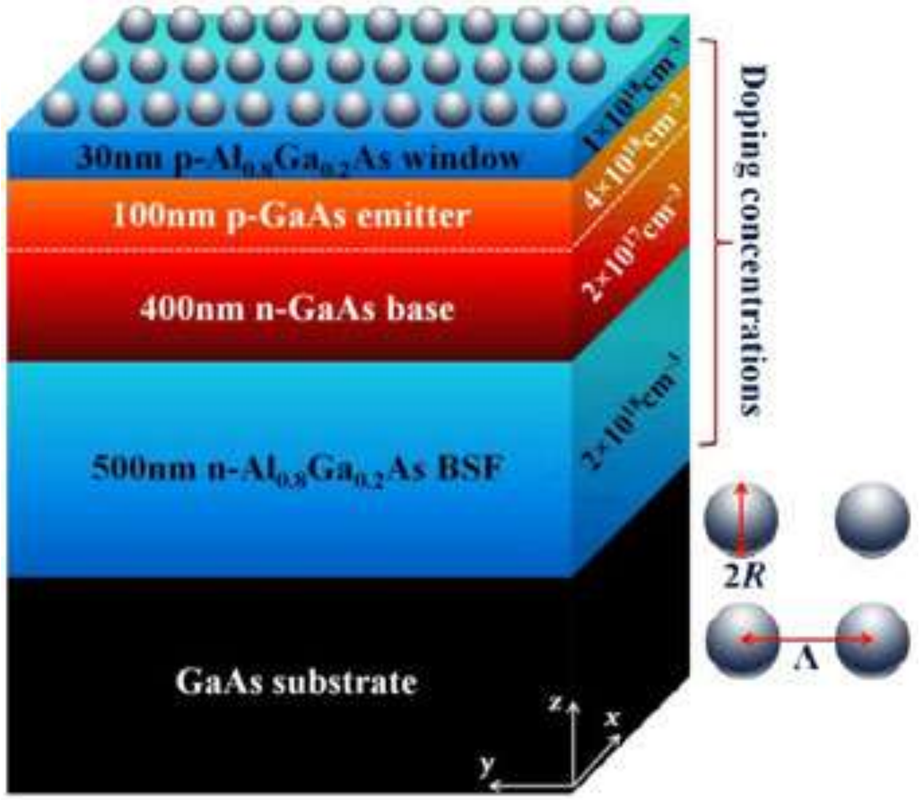


Drawbacks

- GaAs has high surface recombination velocity
- No native oxide to passivate the surface
- Passivation schemes add to process complexity

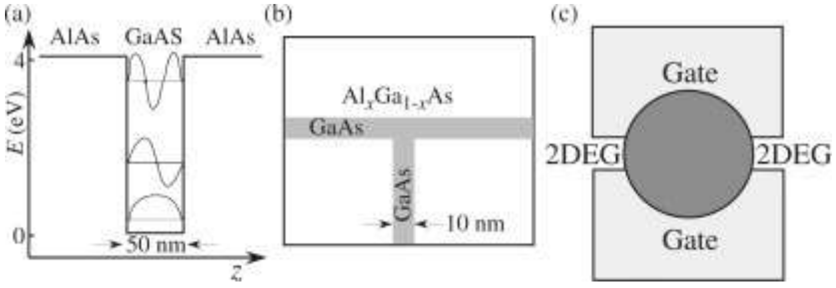
GaAs heterojunction solar cell

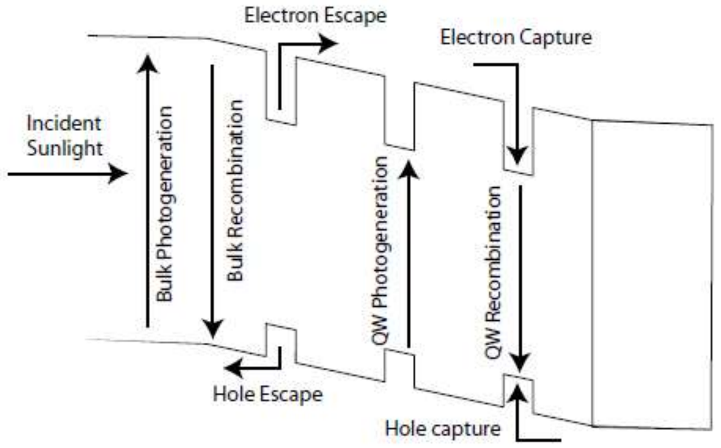
- Multiple layers deposited from bottom to top
- Recipe used – control of <1 ML
- Band gap engineering to absorb different wavelength
- Band gap reduces from top to bottom of the cell – higher energy radiation absorbs at top
- Heavily doped AlGaAs based window layer to let in maximum photons, reduce parasitic resistance, increase V_{oc}
- Efficiency > 46% reported, target to cross 50%



Quantum wells

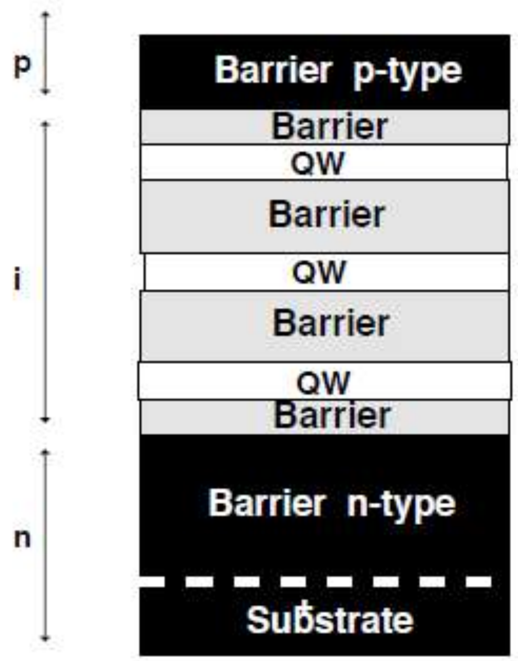
- Heterostructures where a low band gap material is sandwiched between two higher band gaps
- Conduction electrons in the middle layer have lower energy and are trapped in that layer
- Solar cells: Confine the charge carriers in 2 dimensions





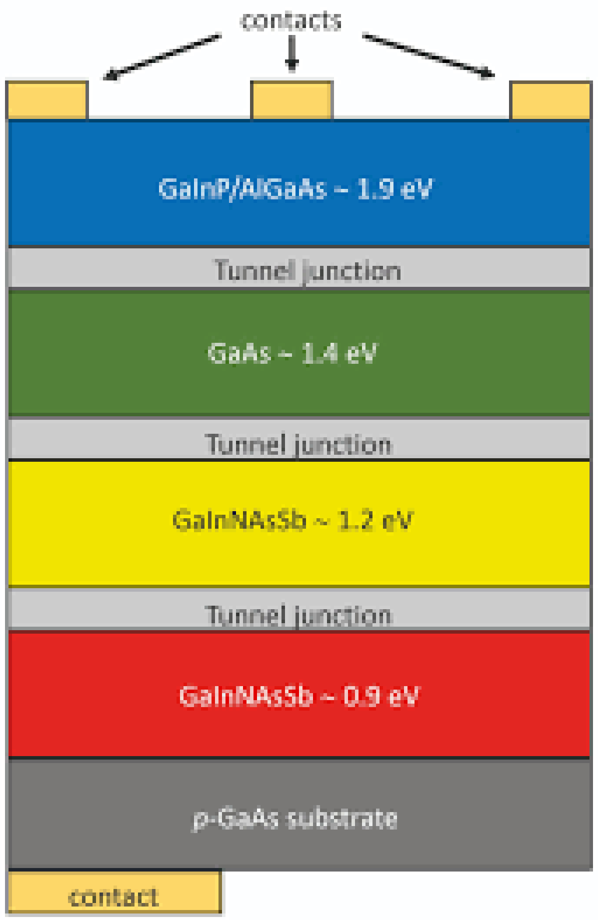
Current generation

- Quantum well solar cells are composed of a p-i-n diode structure
- Photoexcitation causes generation of charge carriers in the well
- Before recombination, the carriers escape the well in a combination of thermal and tunneling processes
- Escape processes are faster, can assume that all photogenerated carriers cause photocurrent and there is no recombination



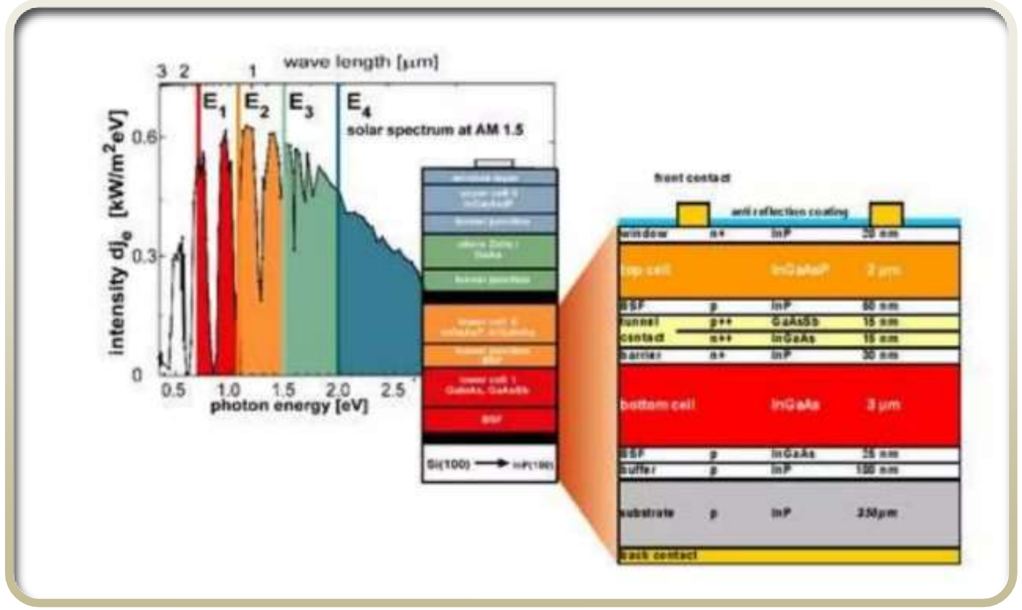
Multijunction/Tandem Solar cell

- Stack of individual solar cells with different band gaps to absorb the solar spectrum more efficiently
- Photons are absorbed primarily by the material with largest band gap
- Lower energy photons are transmitted to the next band gap cell
- Higher total conversion efficiency as larger part of the solar spectrum is absorbed
- Efficiency > 46% in lab, commercial >30%
- Increased complexity, manufacturing price



Features

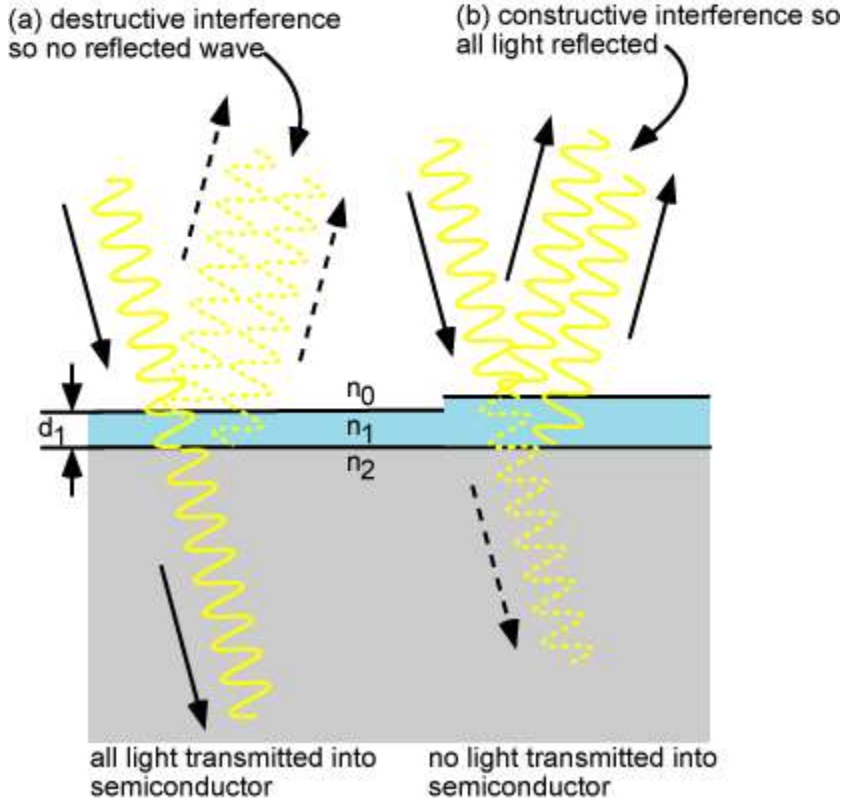
- Focus on low band gap region of a multi junction
- Challenge in realization of a cell with absorber material in the range of 1 eV
- Low band gap tandem cell developed with optimized band gaps of 0.75 eV and 1.15 eV
- InGaAs (E_g = 0.75 eV) and InGaAsP absorbers connected by an InGaAs/GaAsSb Esaki-tunnel-diode-like junction



- Prohibitive cost is the biggest barrier for the success of GaAs cells
- Cost reduction by either growth of GaAs on cheap substrates like silicon or germanium
- Re-using substrate by removing the GaAs substrate after growth

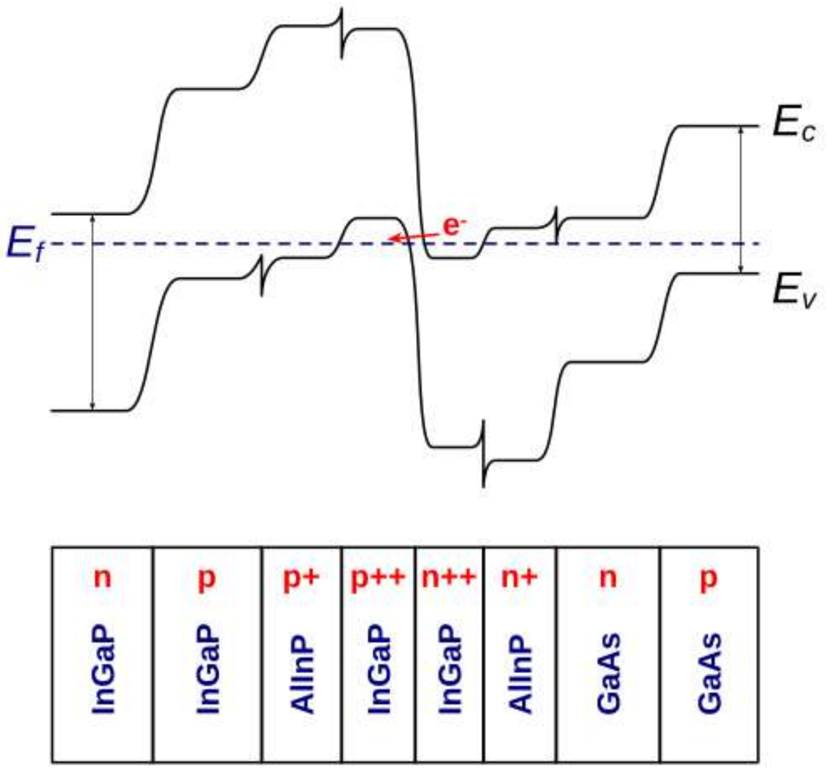
Key elements – AR coating

- Anti Reflective (AR) coating: Several layers, top layer usually NaOH surface roughened with pyramids to increase the transmission coefficient and efficiently trap light
- Thickness of AR coating chosen to get (i) destructive interference, (ii) minimize reflectance at wavelength for which photocurrent is lowest
- JSC is maximized due to current of all cells being matched – e.g. current of bottom layer is greater than top cells, so thickness of AR is modified so IR transmission corresponding to bottom cell is degraded while UV transmission of top cell is upgraded



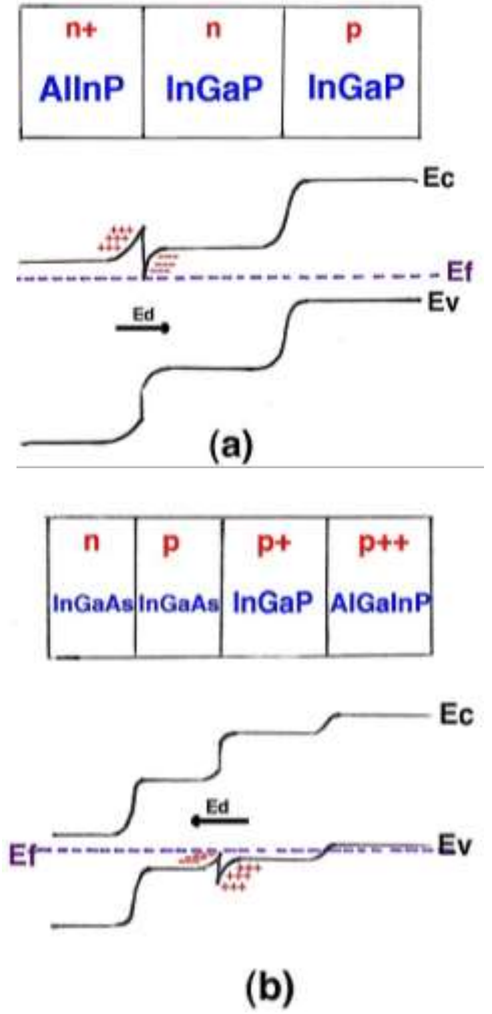
Key elements – Tunnel junctions

- Tunnel Junctions: Used as a spacer layer between two consecutive pn junctions
- Low resistance and optically low loss connection
- Low voltage – easy tunneling – high current density
- Absence causes opposite pn junction to form – parasitic diode – lower photocurrent
- Wide band gap, highly doped diode



Key elements – Window layer/Back Scattering Field (BSF)

- Window layer: Reduce surface recombination velocity
- BSF: Reduces scattering of carriers towards the tunnel junction
- Same structure: Highly doped heterojunction



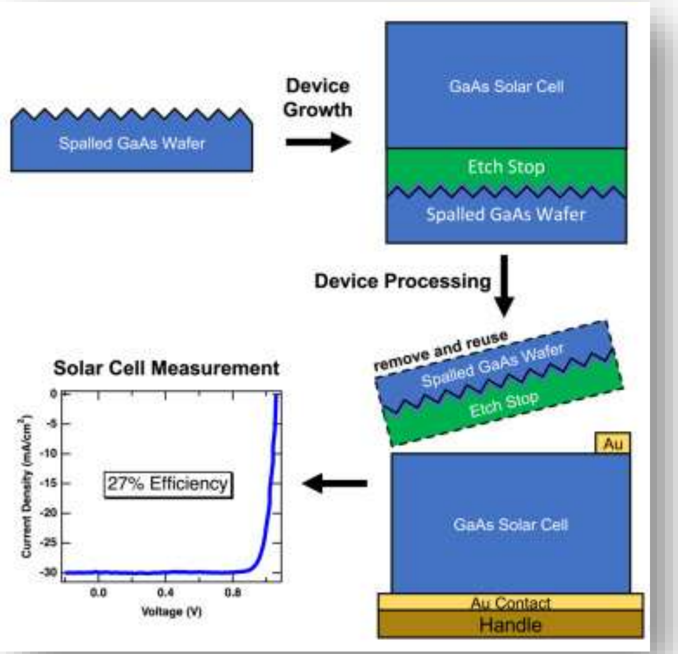
GaAs on Si/Ge

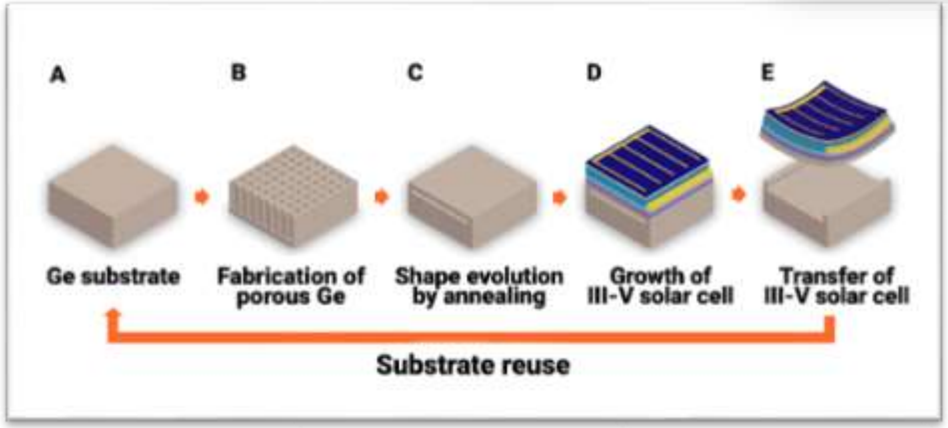
- Growth of good quality crystal requires lattice as well as thermal matching with substrate
- Using Si or Ge causes defects in the overgrown GaAs crystal
- Buffer layers are grown to incorporate these defects so that the later film grows defect-free
- Solar cells grown on Si/Ge exceeded 22% efficiency in 1989
- In 2008, IMEC reported a conversion efficiency of 24% for a single junction GaAs solar cell grown on Ge

- Continuous improvement of single junction solar cell leads to development of multi junction solar cell
- Current focus is on top cells made of III-V materials and bottom cells comprising of Ge based compounds
- Conversion efficiency of >35% is targeted

Re-usable substrate

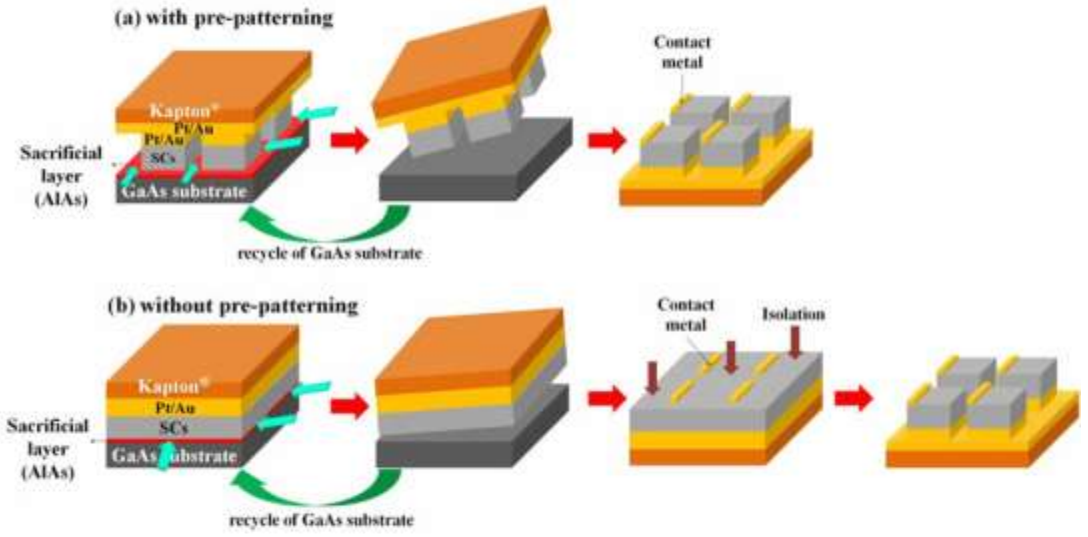
- Thin films of single-crystal GaAs are grown on thick, reusable GaAs substrates
- Overgrown films are peeled off the substrate and used in a PV device
- Substrates are reused to grow similar films again
- PV cells made using this process exhibited efficiency > 24% and their incorporation in an experimental flat-plate module gave a record efficiency of > 20%





Epitaxial Lift-Off (ELO)

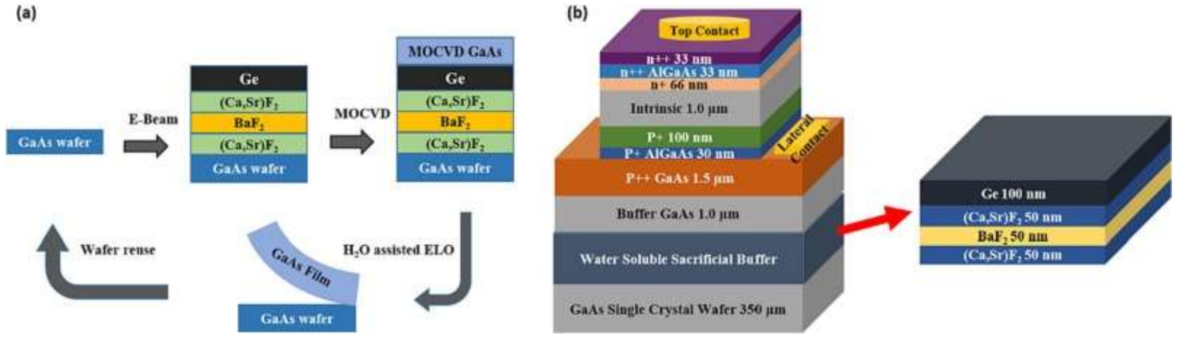
- Epitaxial Lift-off (ELO) refers to selectively etching away of the substrate once a layer has been grown over it to release the thin film
- Steps:
  1. Sacrificial Layer Deposition: Thin film of a material that can be selectively etched away is grown epitaxially on the GaAs substrate – usually high Al content AlGaAs
  2. Film growth: Desired stack (e.g. MJSC) grown on top of the sacrificial layer
  3. Lift-off: Substrate is immersed in an etchant, usually hydrofluoric acid (HF) to selectively etch the sacrificial layer
  4. Release: The overgrown thin film (MJSC) is released, leaving the substrate intact for reuse

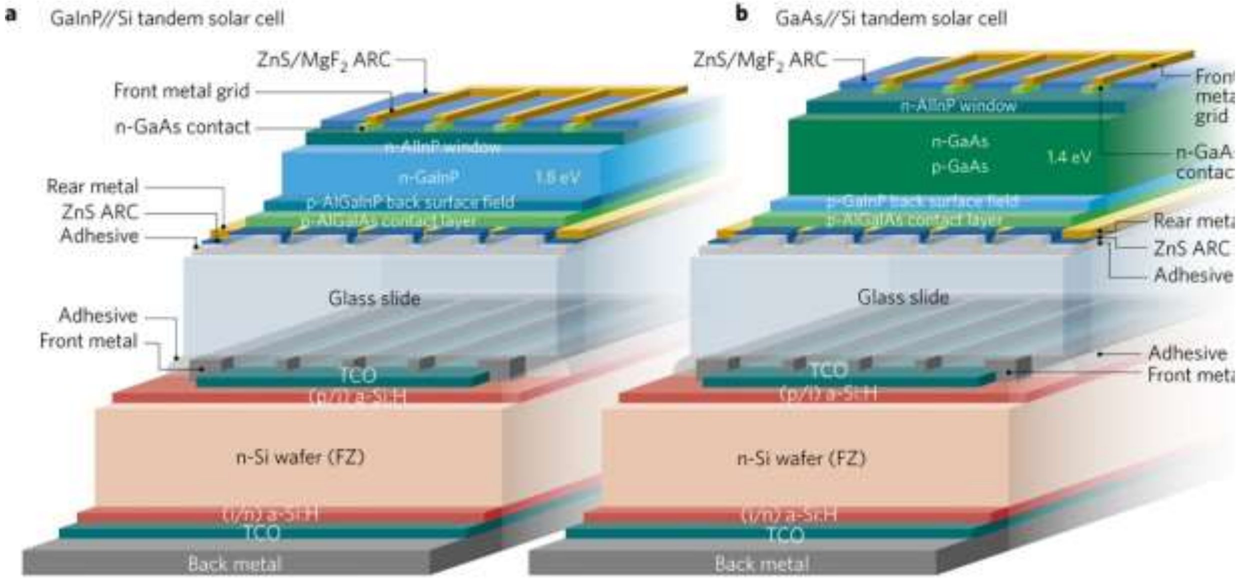


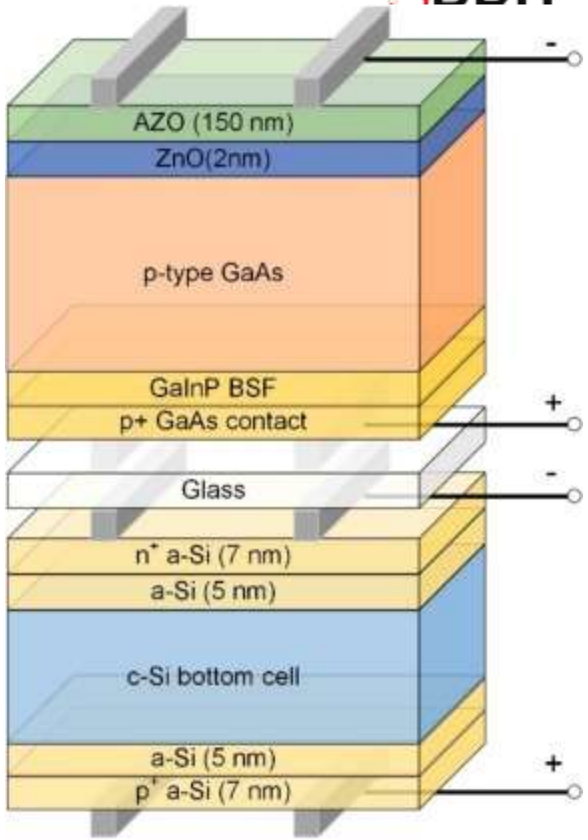
ELO issues

- Microscopic cracks in the lifted-off films
- Cracks increase with area – scaling up is difficult
- Polymer support layer causes strain resulting in cracks
- Thin photoresist with silicon support layers gave crack-free lift off

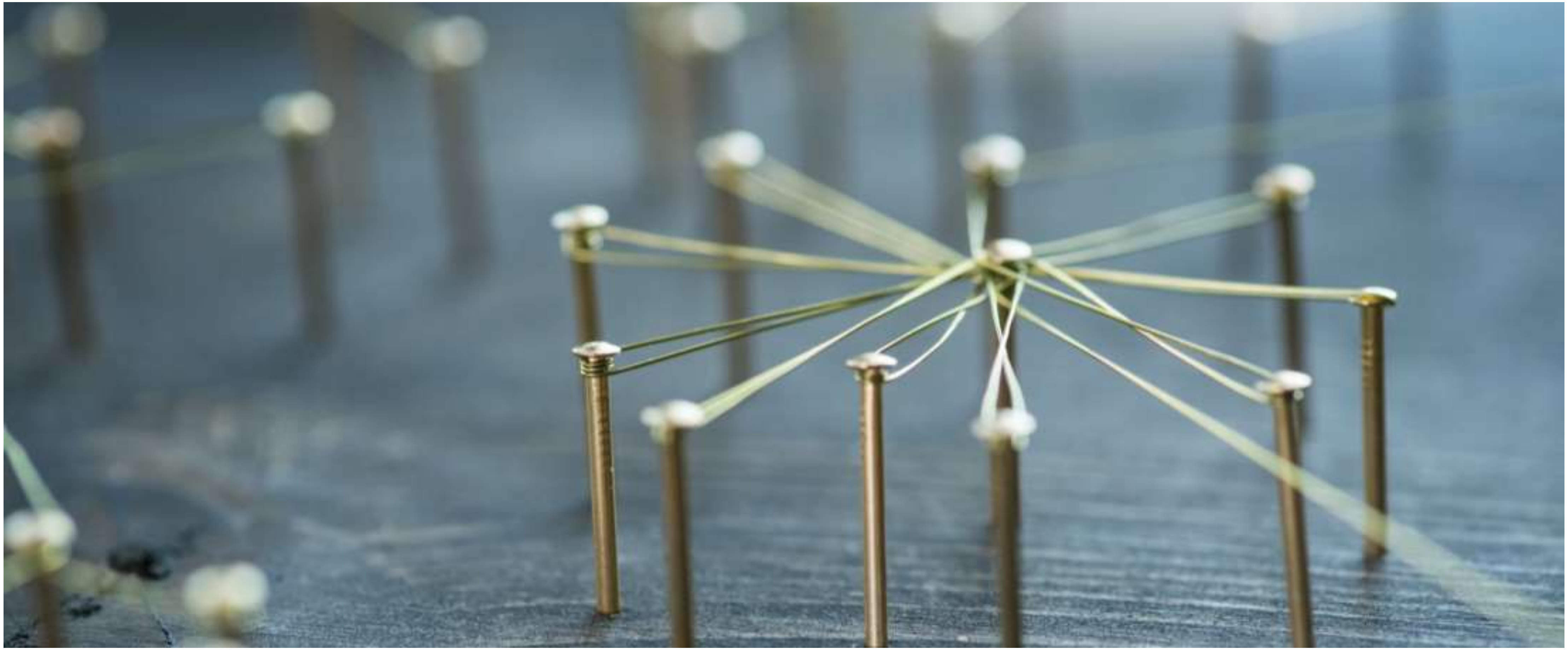
Achievements





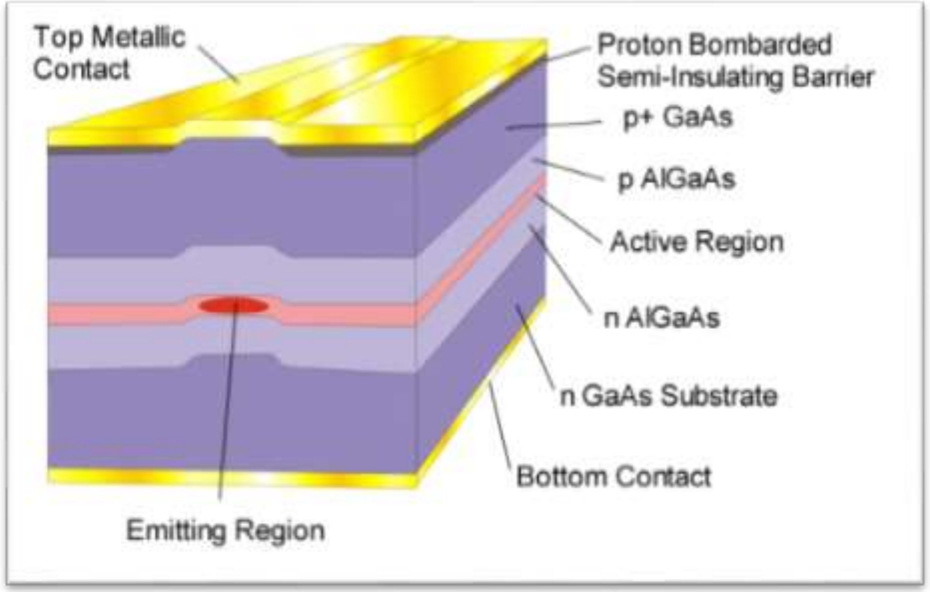


Other optoelectronic structures of group-III materials using MBE

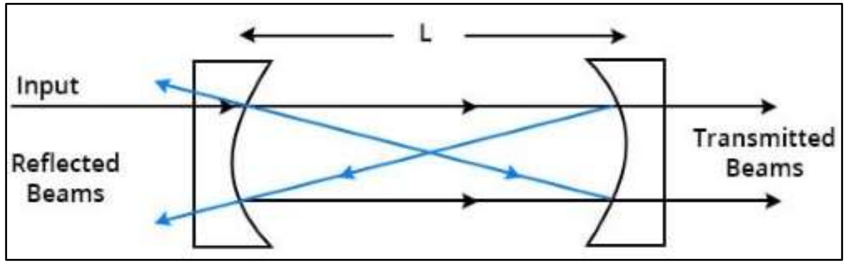


Laser Diodes

- Typical edge emitting laser
- Structure resembles PIN diode
- Active region between n and p type – gain is achieved
- Higher refractive index in active region allowing for lateral confinement of light
- Fabry Perot laser diode consists of an active region enclosed within a Fabry Perot cavity
- Highly reflective (HR) and partially reflective (PR) – facets at end of cavity

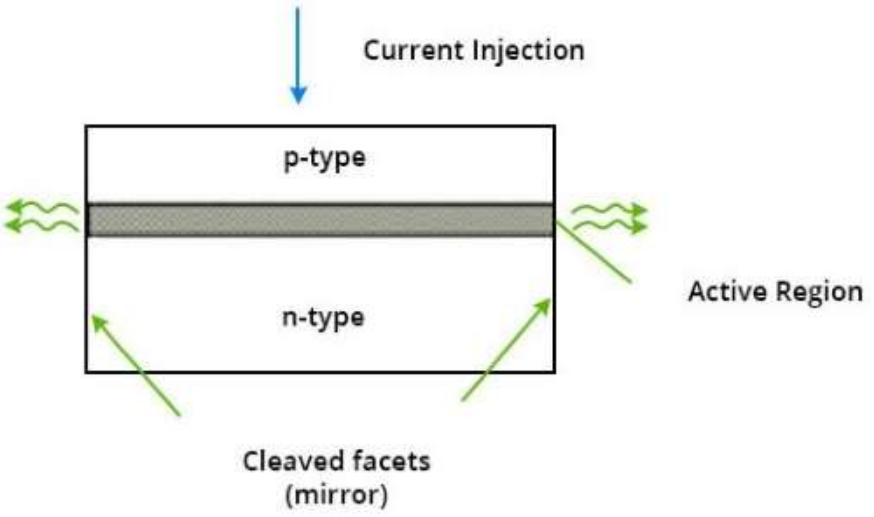


Fabry-Pérot laser



Working Principle

- Voltage applied across the laser diode leading to injection of current
- Current flowing causes electrons and holes to enter active region and recombine – emission of photons
- Photons in active region stimulate emission of more photons through stimulated emission – coherent laser output
- Only certain wavelengths forming standing waves

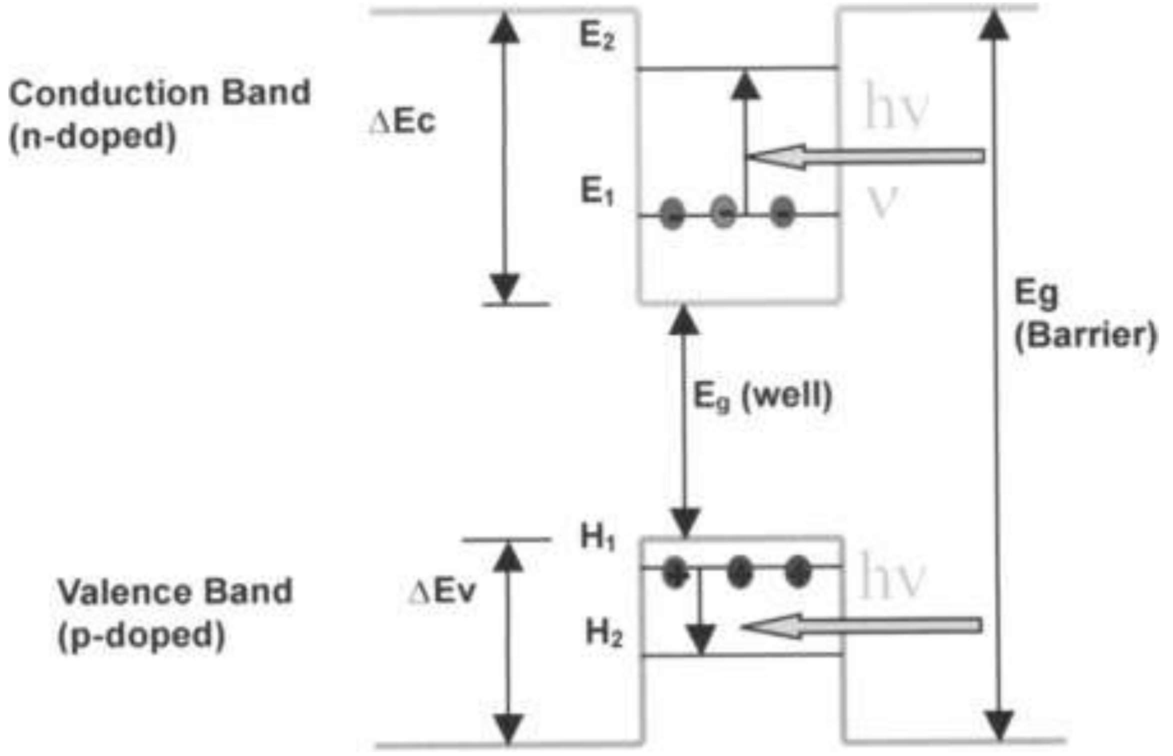


$$2nL = m\lambda$$

n = refractive index of cavity medium
L = length of cavity
m = mode number (integer)
λ = wavelength of light

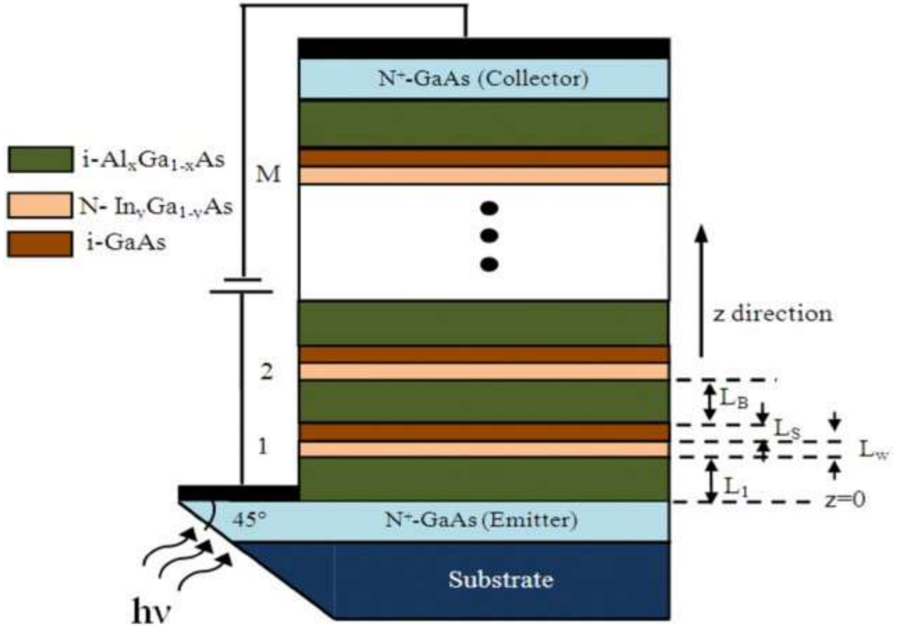
Quantum Well Infrared Photodetectors (QWIPs)

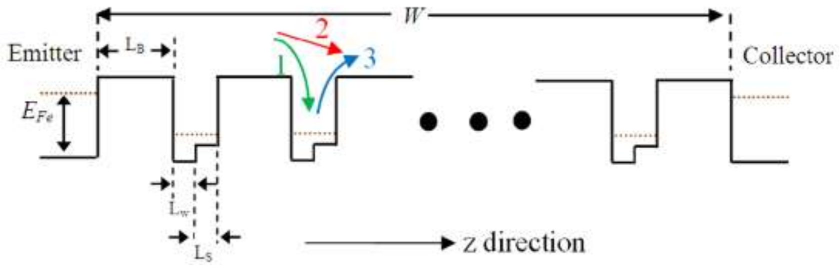
- Infrared photon detectors relying on intersubband transition within the conduction (n-type) or valence (p-type) band
- QWIP of III-V use quantum wells as bulk layers do not absorb in IR
- Quantum well structure designed to collect photoexcited carriers trapped in the wells as photocurrent



Quantum Well Infrared Photodetectors (QWIPs)

- Infrared photon detectors based on photoelectric effect
- Low IR absorption – polarization dependence
- Multiple Quantum wells (MQW) used to improve efficiency





Conclusion

✓ High control and clean films

✓ Expensive and complex instrumentation

✓ In-situ monitoring, atomic control

✓ Latest technologies – III-V, II-IV transistors, optoelectronics

✓ Slow and long process times

Take Home Message

- MBE is a complex, expensive instrument that has some very specialized uses
- Primarily used in R&D, it also finds use in industry device fabrication

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