EEE6212 Lecture 21 "Photodetectors"

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Outline

- Principle of light detection by semiconductors
- Photoconductor
- Photo-Diode
- Avalanche Photo-Diode
- Photo-transistor
- Charge-Coupled Device (CCD) vs. Complimentary Metal-Oxide-Semiconductor (CMOS) detector

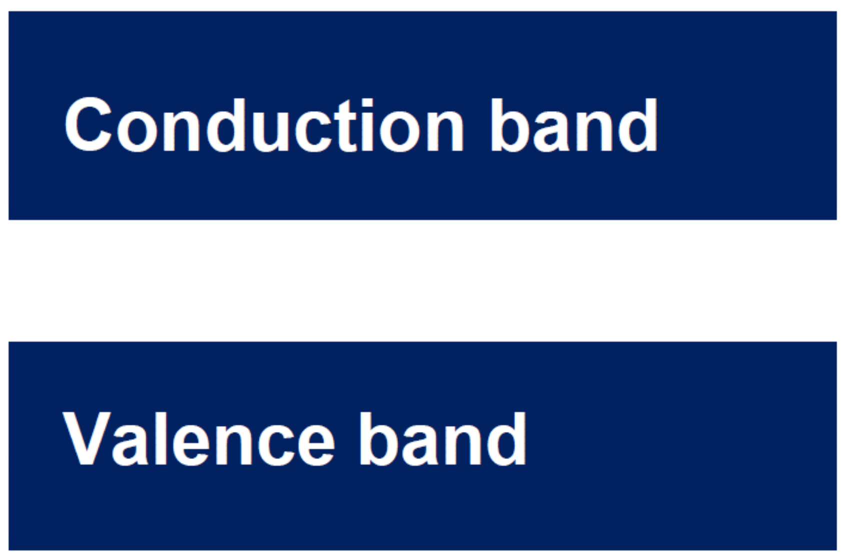
Detection of Light by Semiconductors

General principle – generate an electron-hole pair via an energy transition

In most cases use an intrinsic semiconductor

Generation of Electron-Hole pairs by band-to-band transition if photon energy is at least as large as the band gap

$$\frac{hc}{\lambda} = E_\gamma \geq E_g = eV$$

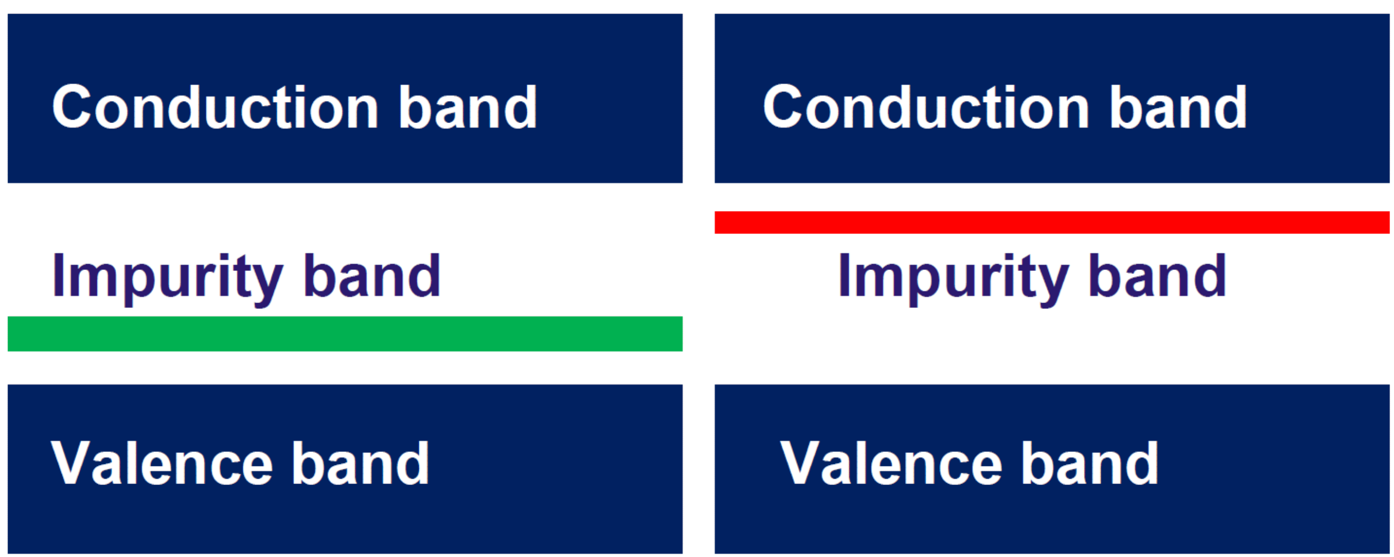


Detection of Light by Semiconductors

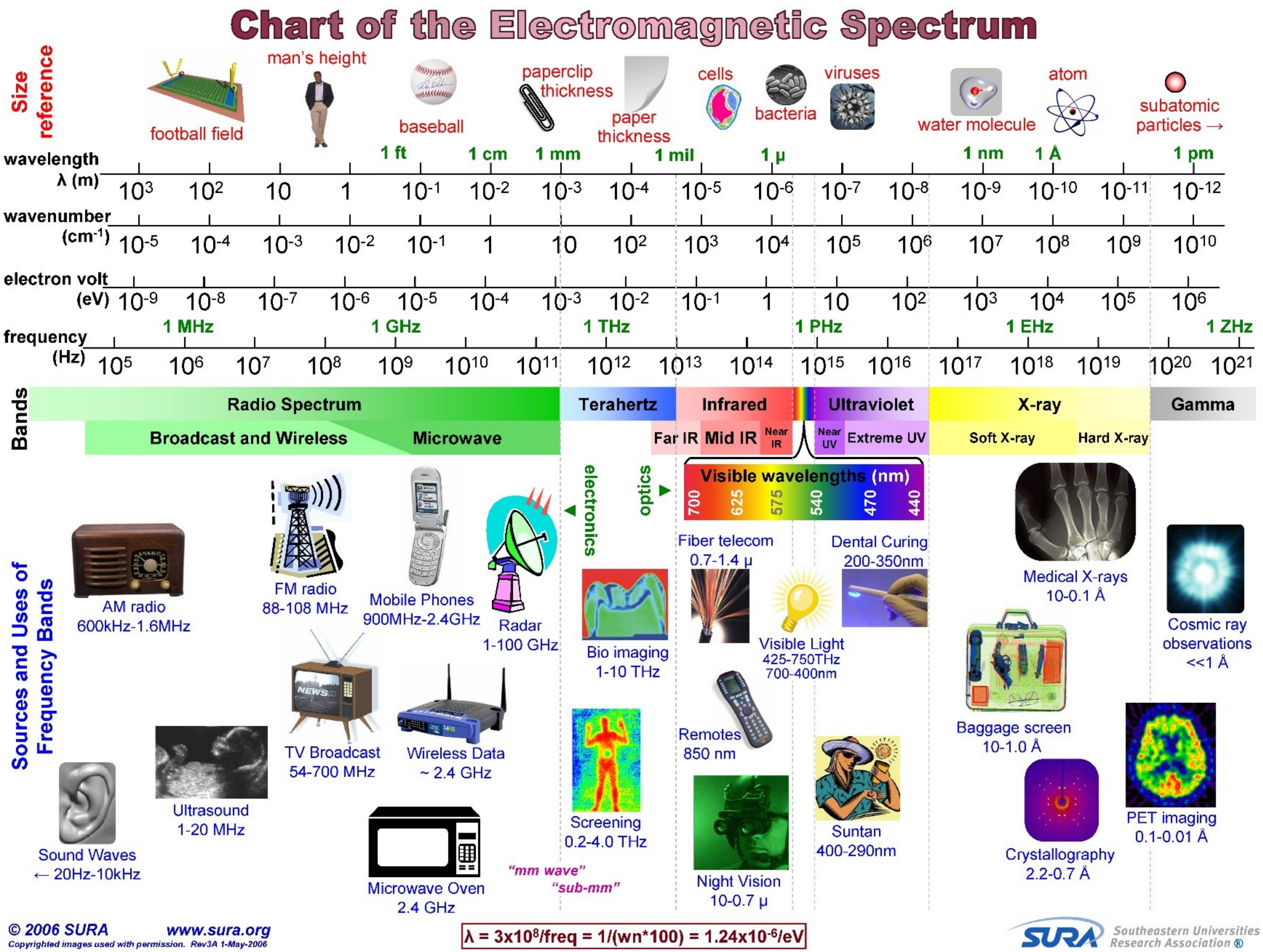
For Infra-Red applications (smaller energies) also extrinsic semiconductors are used: Electron-Hole pair generation from impurity band to band edge (electron from valence to acceptor level or from donor level to conduction band)

$$E_\gamma \geq E_A - E_V \ or \ E_\gamma \geq E_C - E_D$$

Semiconductors do not “see” colours hence we need to modify our device in some way to make it wavelength specific



The Electromagnetic Spectrum



http://www.sura.org/commercialization/terahertz.html

Spectrum and Absorption Windows

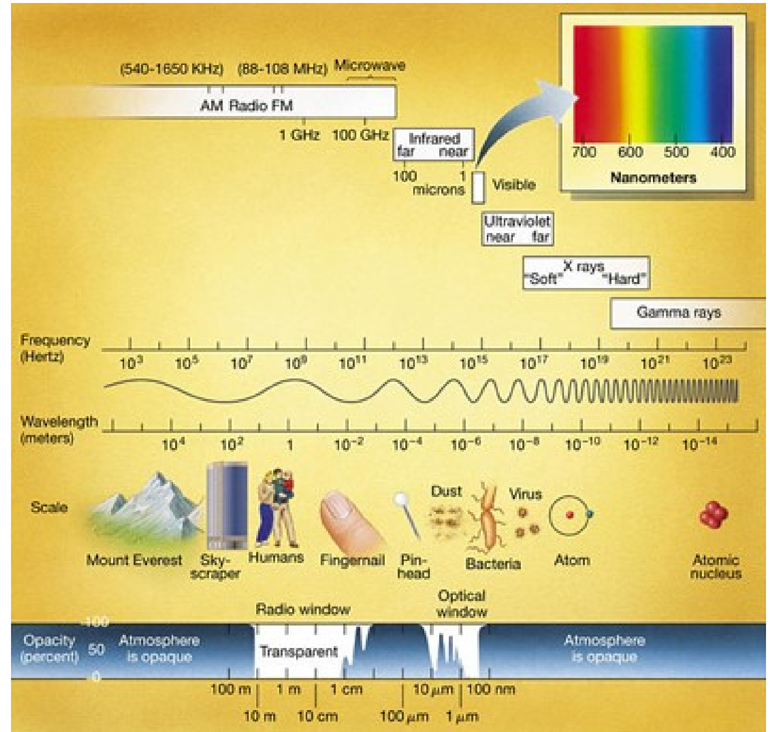
Semiconductors

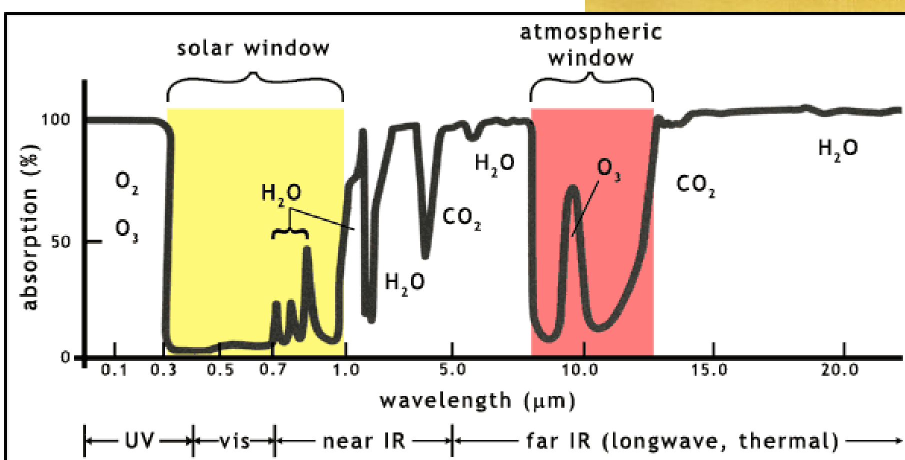
$$E_g \approx 0.6 \rightarrow 6.0\ eV = hf$$

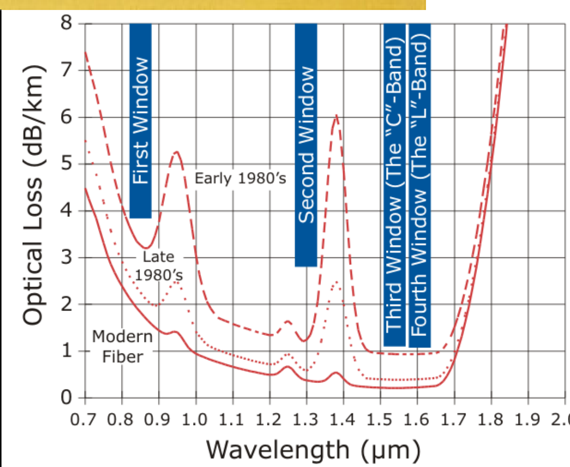
$$f = 1.45 \times (10^{14} \rightarrow 10^{15}) Hz$$

$$\lambda = \frac{c}{f} = 0.2 \rightarrow 2\mu m$$

Covers the range from UV-vis-NIR







Detector bands

Common wavelength bands for detectors

Band 1	UV-vis-NIR	$0.19 - 1.0\mu m$	Reflected sunlight
Band 2	Short wave IR (SWIR)	$1.0 - 2.6\mu m$	Some reflected sunlight and some emitted radiation
Band 3	Mid wave IR (MWIR)	$3 - 5\mu m$	Emitted thermal radiation
Band 4	Long wave IR (LWIR)	$8 - 14\mu m$	
Band 5	Far IR (FIR)	$> 15\mu m$	

Common wavelength windows for telecommunications are centred around the H_2O absorption minima of the red/IR spectrum

1st window	red	800-900nm	**Si**, GaAs
2nd window	SWIR I	~1300nm	**InGaAs**, Ge
3rd window	SWIR II	~1550nm	**InGaAs**, Ge, HgCdTe

Types of detector

Photo-conductor (PC)

Doped semiconductor with metal contacts

Cheap

Photo-Diode (PD)

p-i-n diode with metal contacts

unity gain (1), high quantum efficiency, fast $(10^{-9} \rightarrow 10^{-11} s)$

Avalanche Photo-Diode (APD)

Diode operated near reverse breakdown voltage

High gain $(10^{2} \rightarrow 10^{4})$, fast $(10^{-10} s)$, potentially noisy

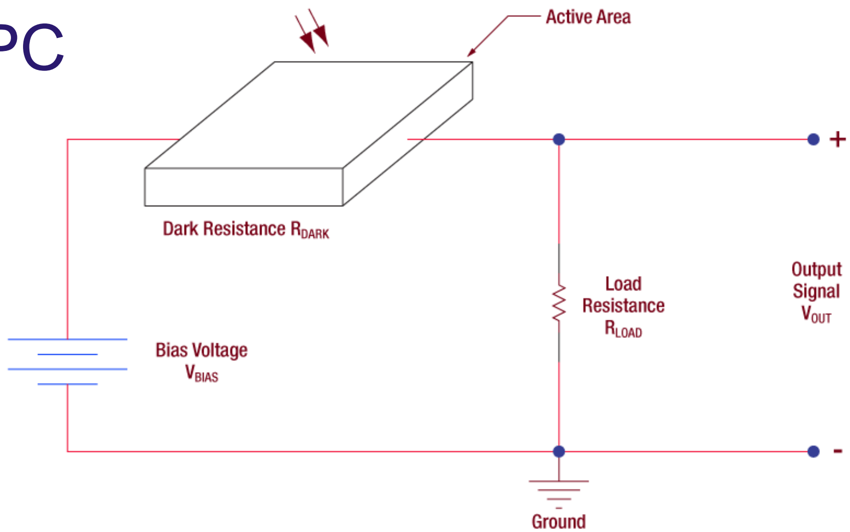
For a detailed description see EE337 Lecture 4

Photo-Transistor (PT)

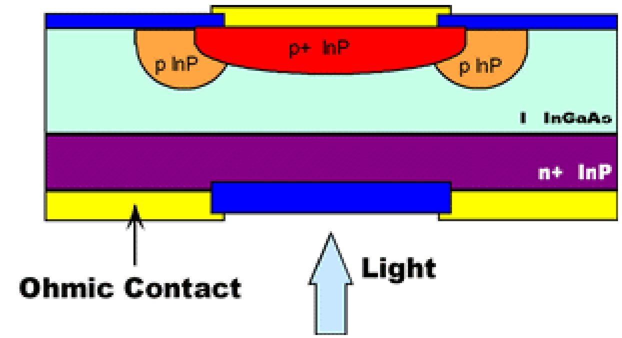
Medium high gain $(10^{2} \rightarrow 10^{3})$, slower $(10^{-6} s)$

Types of detector

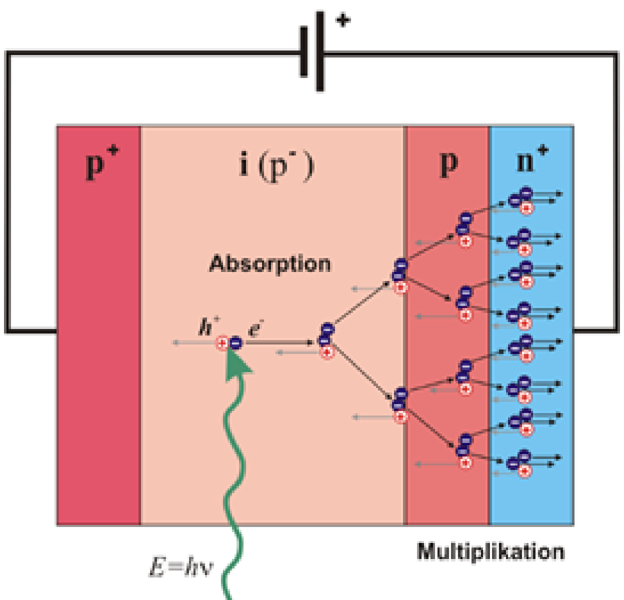
PC



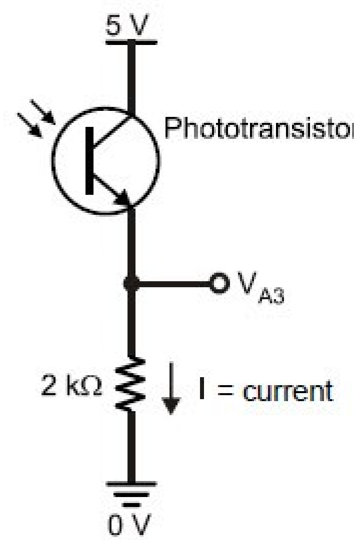
PD



APD



PT



http://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=9020
http://www.olson-technology.com/mr_fiber/glossary-pq.htm#Photodiode
Von Kirnehkrib - Eigenes Werk, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=17725203
http://learn.parallax.com/tutorials/robot/shield-bot/robotics-board-education-shield-arduino/chapter-6-light-sensitive-11

Quantum Efficiency

Definition of (external) quantum efficiency (EQE=η)

Number of electron-hole pairs generated per incident photon

$$\eta = \frac{\left(\frac{I_{photo}}{e}\right)}{\left(\frac{P_{opt}}{hf}\right)} = \frac{I_{photo} \times hf}{e \times P_{opt}}$$

Where, I_{photo} is the measure photocurrent, P_{opt} the incident optical power and the photon energy is hf

To maximise efficiency, carrier loss due to recombination within the semiconductor must be minimised. This is achieved in a p-i-n diode by confining illumination and absorption to the depleted i-region, and by separating this from the carrier multiplication region (in APDs)

Carrier loss through recombination must be minimised by surface passivation, wide band gap p and n layers can be used to reduce the "dark current"

Photon absorption and QE

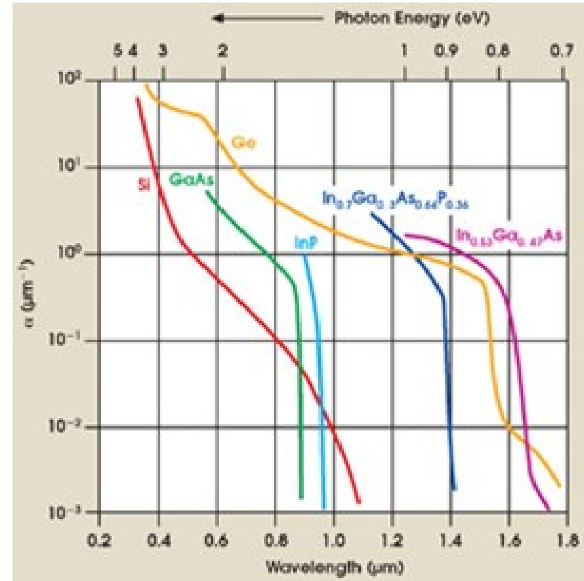
When light falls on a semiconductor its intensity falls exponentially with depth

$$I(z) = I_0 e^{-\alpha z}$$

With an absorption coefficient

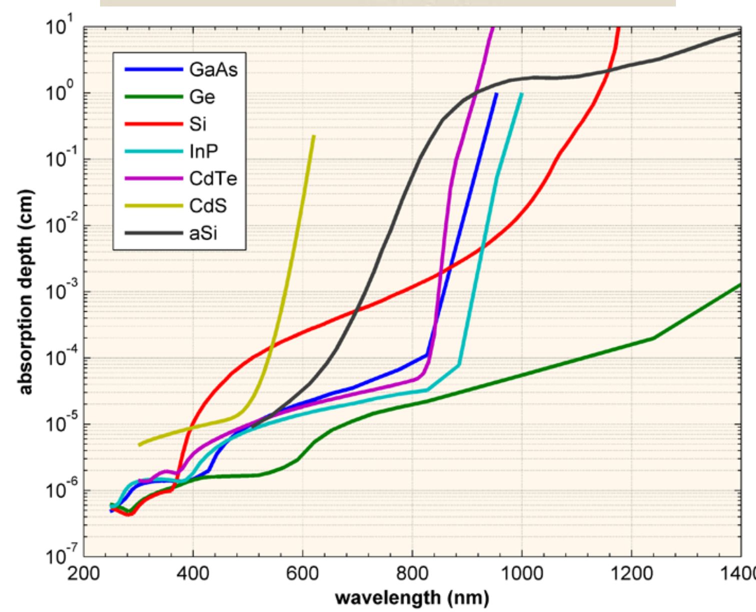
$$\alpha = 2\kappa k = \frac{4\pi\kappa}{\lambda} \sim 10^6 \rightarrow 10^8 m^{-1}$$

above the band edge



Within the depletion region of area A and total depth d for a reflectivity R at the semiconductor surface the generation rate for electron-hole pairs is

$$g(z) = (1 - R)\left(\frac{P_{opt}}{Ahf}\right) e^{-\alpha z}$$



http://www.photonics.com/ http://pvcdrom.pveducation.org/

Photon absorption and QE

Assuming light is absorbed in the intrinsic region only, the generated photocurrent in the depletion region is

$$I_{photo} = eA\int_0^d g(z)\,dz$$

$$= e(1-R)\left(\frac{P_{opt}}{hf}\right)\int_0^d e^{-\alpha z}\,dz$$

$$= e(1-R)\left(\frac{P_{opt}}{hf}\right)[1-e^{-\alpha d}]$$

Insert this into the expression for the quantum efficiency

$$\eta = \left(\frac{I_{photo}}{e}\right)\times\left(\frac{hf}{P_{opt}}\right)$$

$$\eta = (1-R)[1-e^{-\alpha d}]$$

Photon absorption and QE

$$\eta = (1 - R)[1 - e^{-\alpha d}]$$

This shows that

Reflection at the interface to air must be minimised $(R \to 0)$

Need for anti reflective coatings and "window" layers

The depth of the depletion region d must be made large

However the latter can be costly for epitaxy

so typically $d \sim 1/\alpha$ ~ several μm is chosen

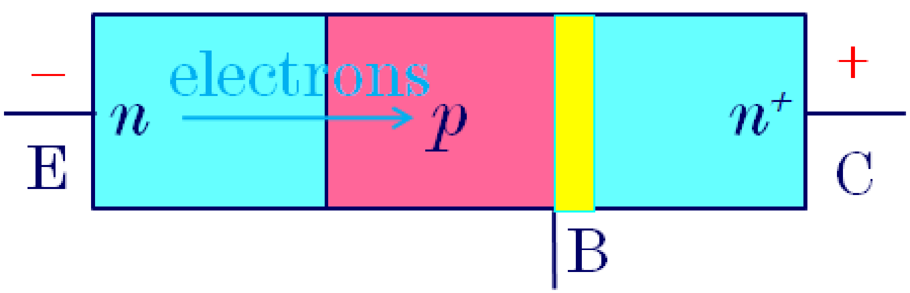
Further increases would reduce the response speed, given by the time it takes the carriers to transit the depletion region

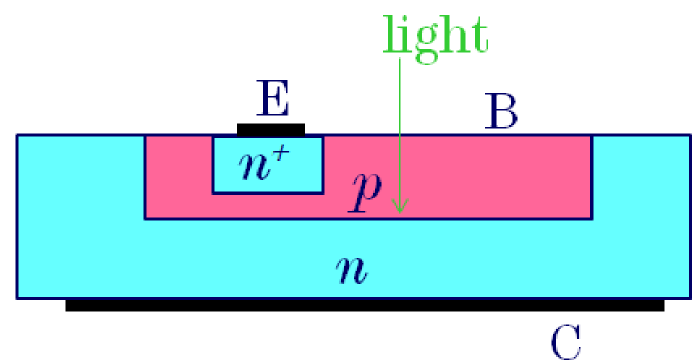
(which is $\propto 1/d$)

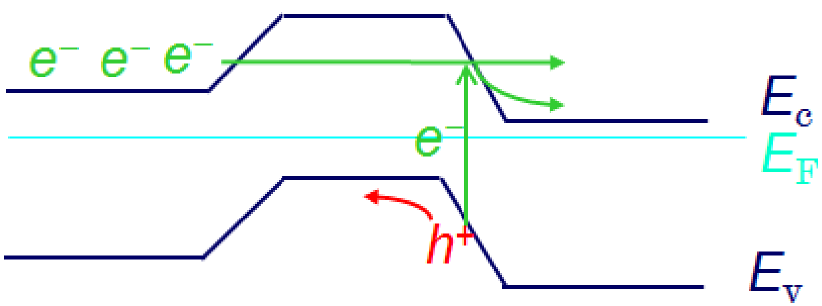
Photo-transistor

Principle fabrication steps for a lateral BJT

1) n-type substrate for npn [p type substrate for pnp]
2) Create base region by p [n] doping a wider region several μm deep
3) Form emitter by n+ [p+] doping a small part of that sub region
4) Deposit metal contacts for E and C (for B not necessary)



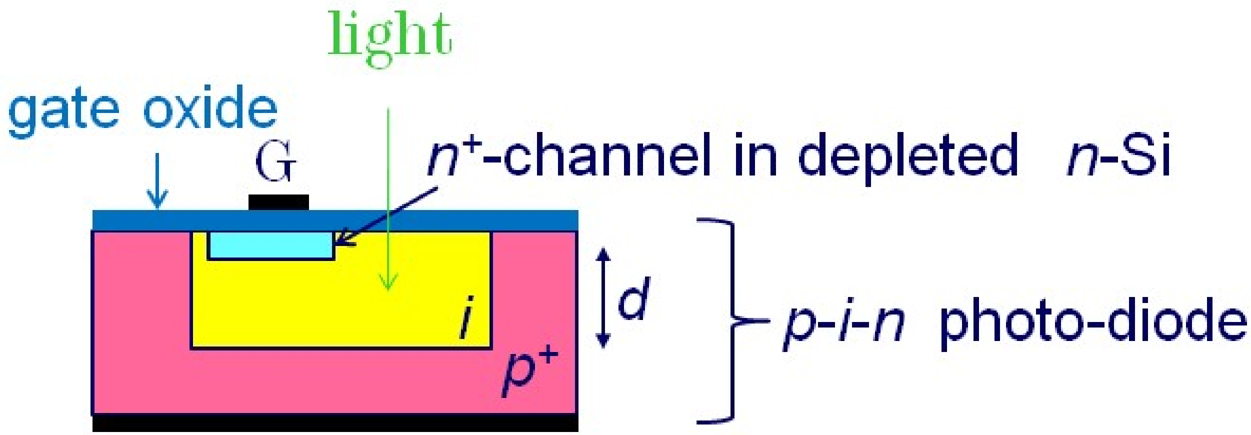


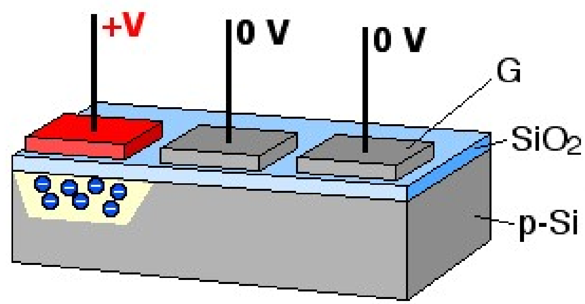


holes (h^+) generated predominantly at the lower part of the base accumulate in the base. Electrons (e^-) can move to the collector. If they reach it, a high photo current can flow from E to C, due to carrier injection at E, giving gain>>1.

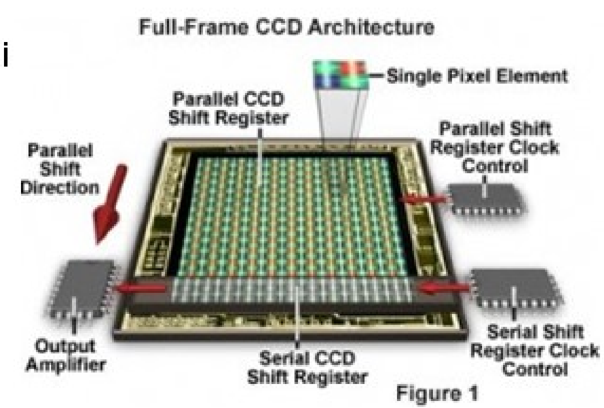
Charge-Coupled Devices (CCDs)

Principle: Up to 10^5 electrons accumulate in n-type channel under gate on top of photo-diode and are read out serially by charge transfer along the surface from one pixel/row to the next ("shift register")

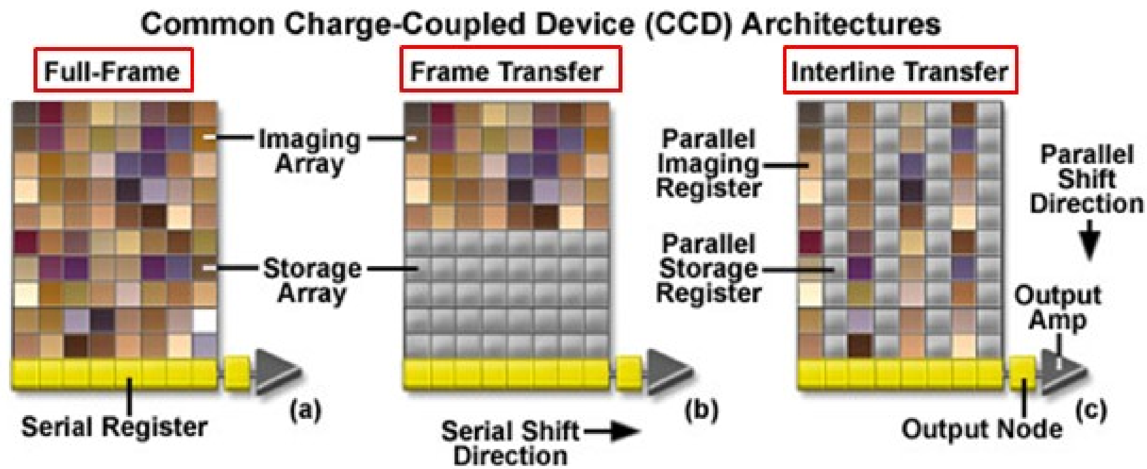


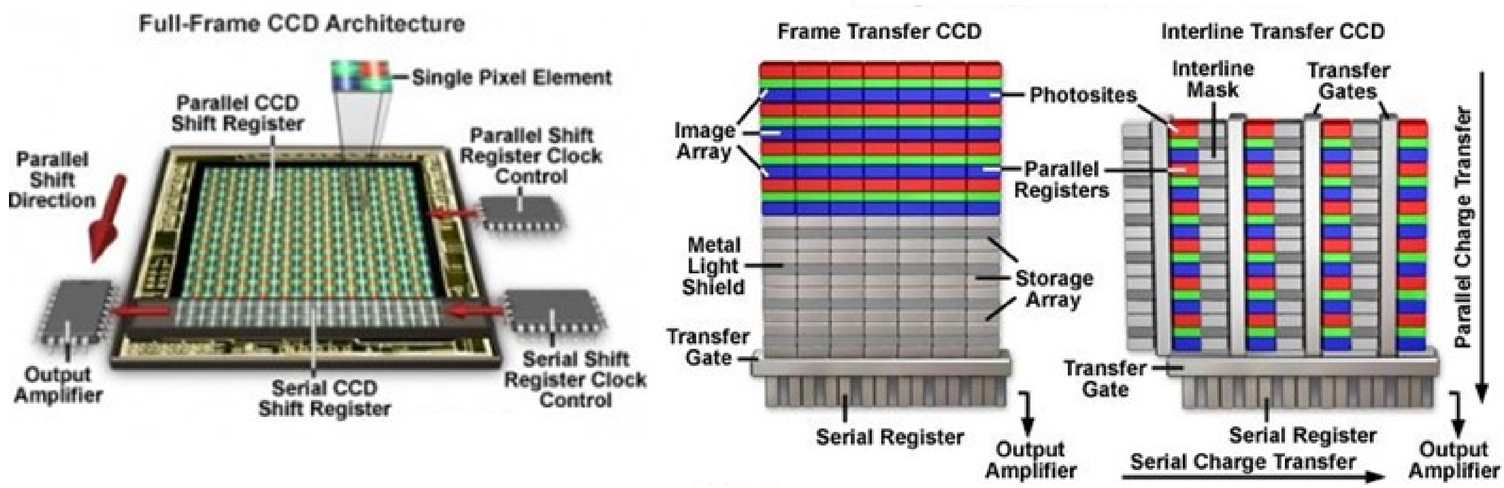


The last capacitor in the array dumps its charge into an op-amp. As charge collected is proportional to light intensity the response is **linear over a large range**, the quantum efficiency can be very high, commonly $\eta = 0.7 \rightarrow 0.95$



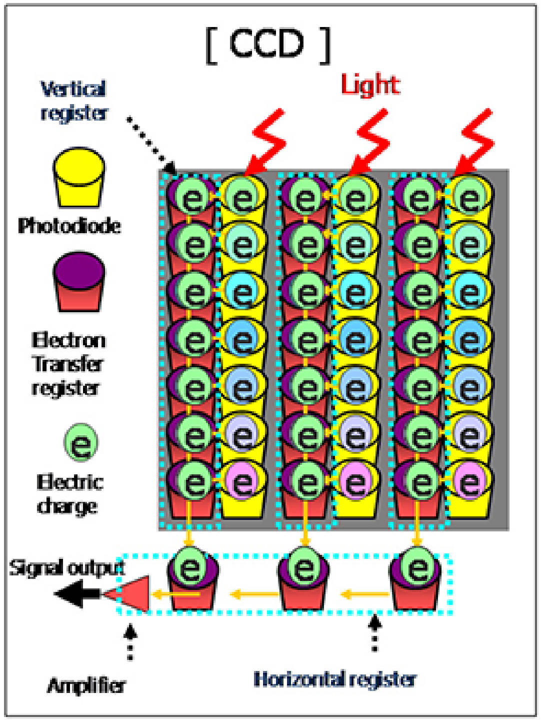
CCD architectures

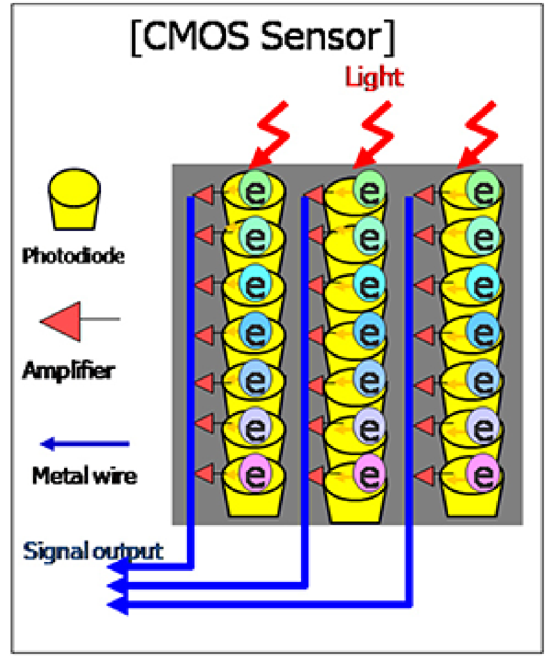




charge transfer method	from one pixel to next, line-by-line, column-by column	into separate storage array	into neighbouring column
shutter	mechanical (slow)	electronic	mechanical (fast)

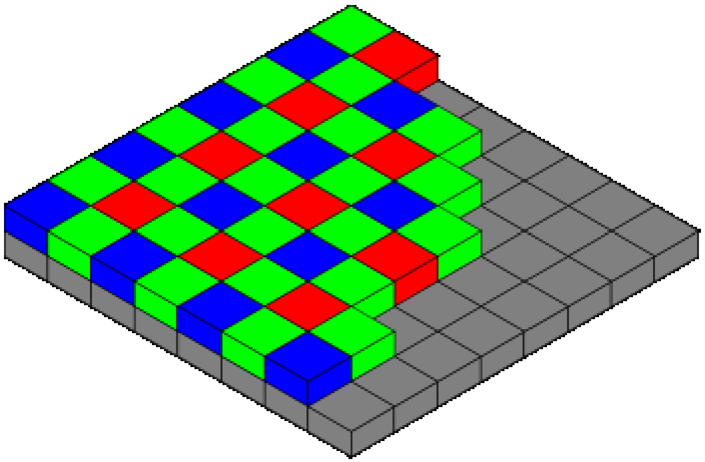
CCD vs CMOS detectors

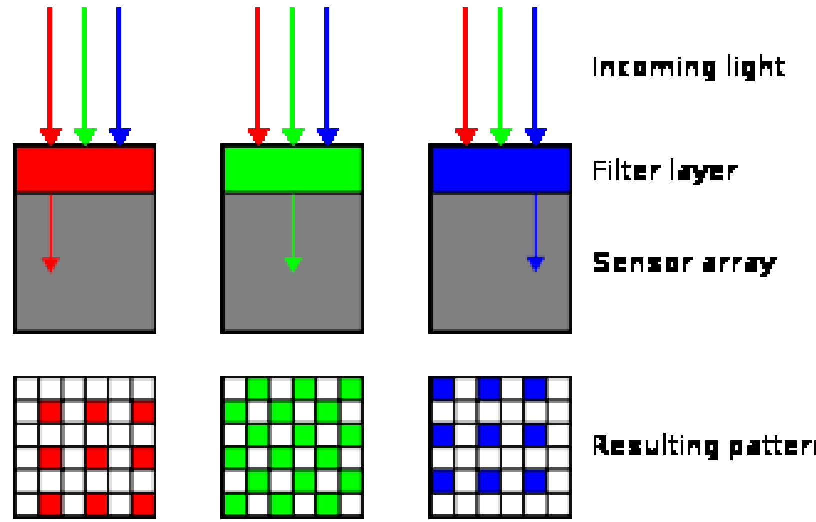




Pixel	photodiode with capacitor	photodiode with transistor
Read out	successive by shift register	direct for each pixel
Speed	slow	fast
Price	expensive	cheap (since late 90s)
Signal cross talk	vertical smear (“blooming”)	weak blooming
Noise level	low	higher

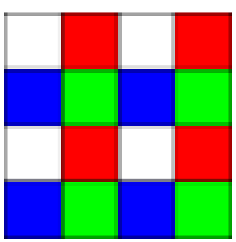
Colour Filters for 2D detectors



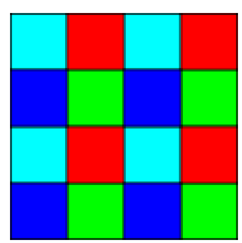


standard Bayer filter (G-RGB), needs additional anti-moiré filter

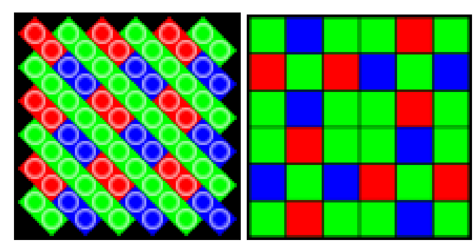
other colour filter schemes



RGB-W filter by Kodak



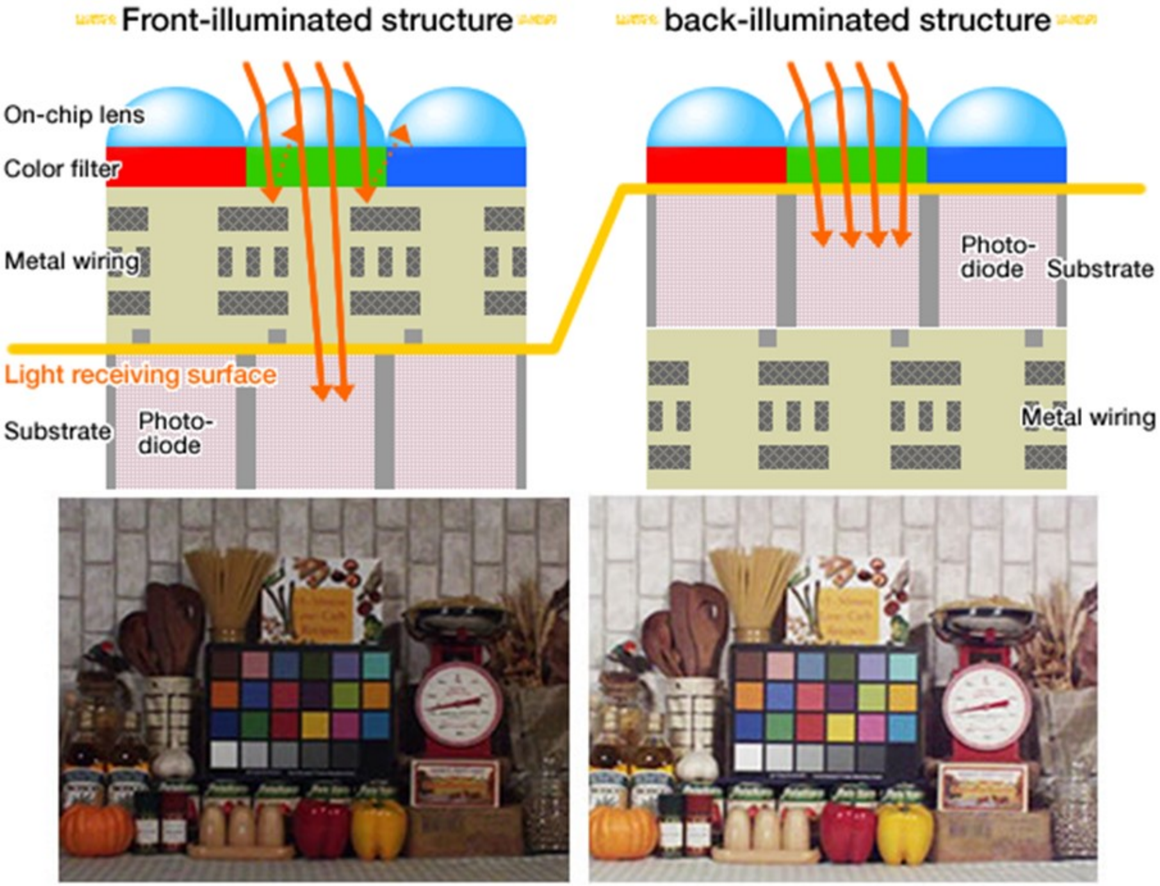
RGB-E filter by Sony



EXR and X-Trans filter by Fuji

University of Sheffield

Front vs back-illumination



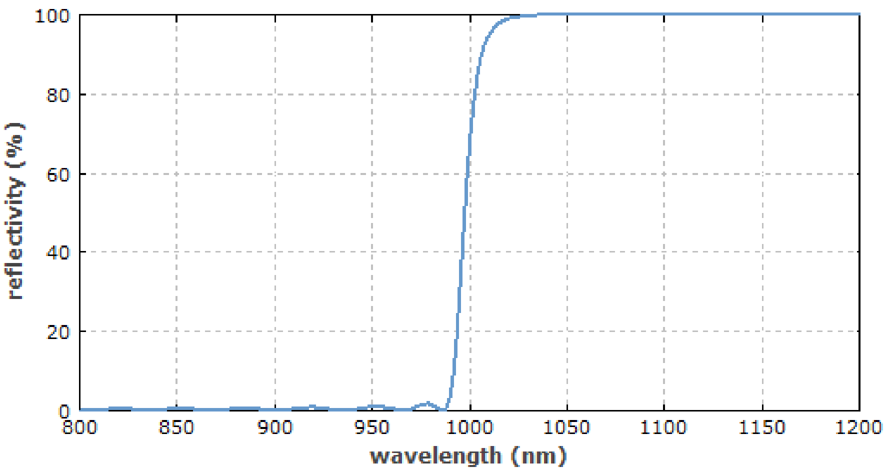
Front-illuminated Structure Back-illuminated Structure

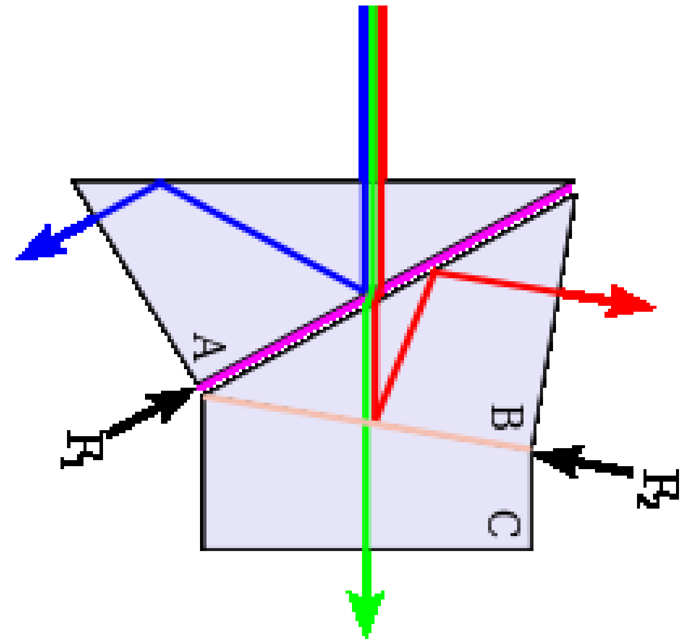
Flipping the processed wafer over places the photo-diodes directly under the colour filter.

More light reaches them, giving more intensity and less noise.

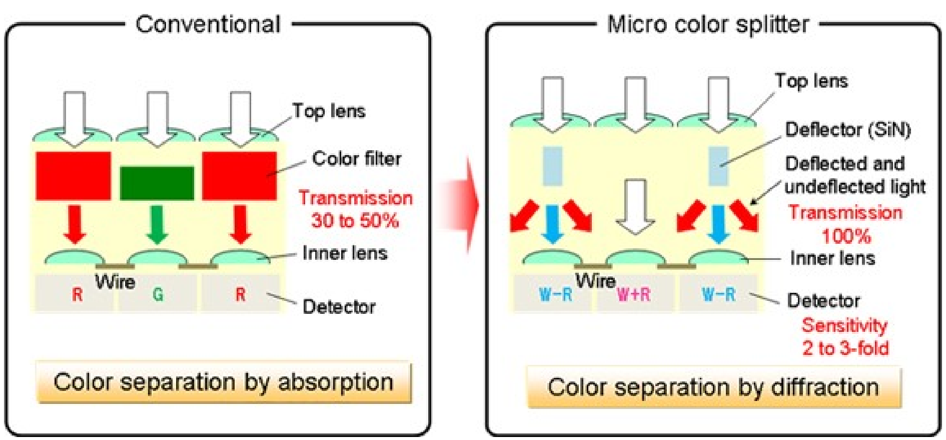
Alternative approaches for colour (I)

Double dichroic (trichroic) colour separation by double prisms used as beam splitters



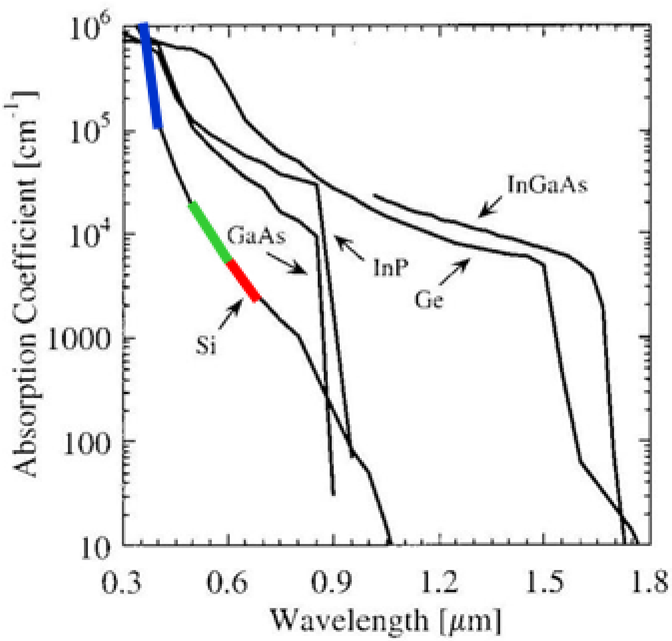


Colour separation by diffraction grating as a deflector whose angular separate is proportional to the wavelength

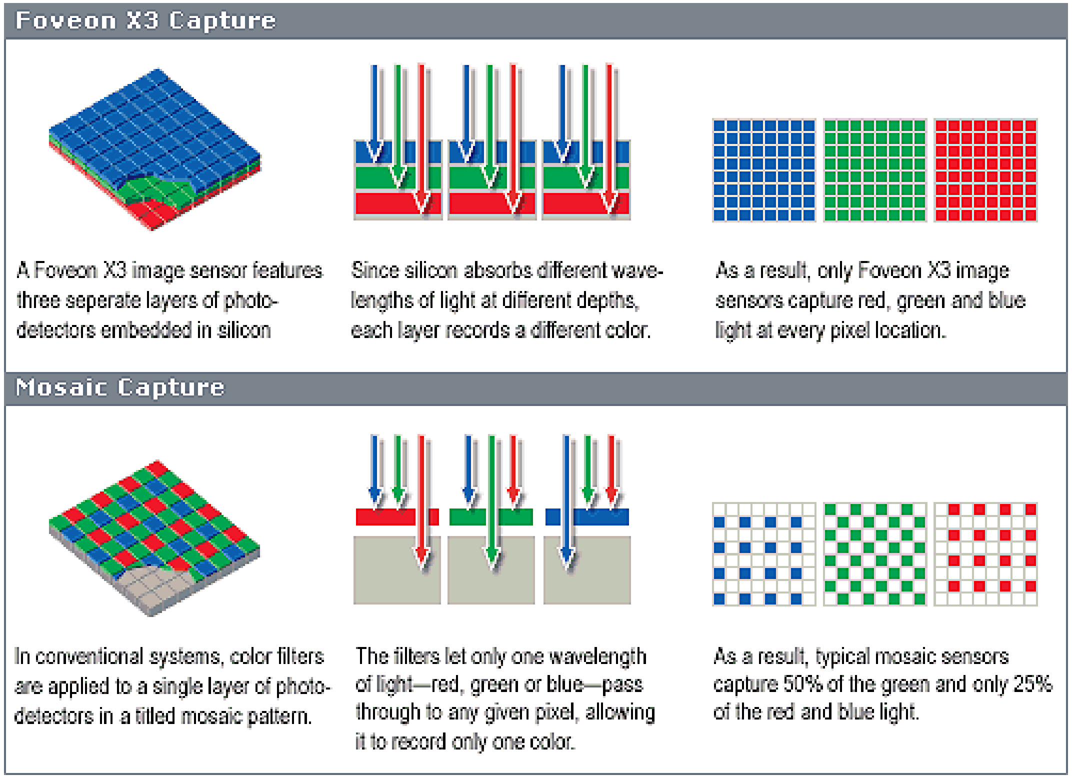


https://www.rp-photonics.com/dichroic_mirrors.html

Alternative approaches for colour (II)



Handbook of Optical Constants of Solids, edited by Edward D. Palik, (1985), Academic Press NY.



Optimisation of depth dependent absorption in 3 individual layers of CMOS sensors stacked on top of each other

Summary

- Principle of light detection by semiconductors
- Photoconductor
- Photo-Diode
- Avalanche Photo-Diode
- Photo-transistor
- Charge-Coupled Device (CCD) vs. Complimentary Metal-Oxide-Semiconductor (CMOS) detector

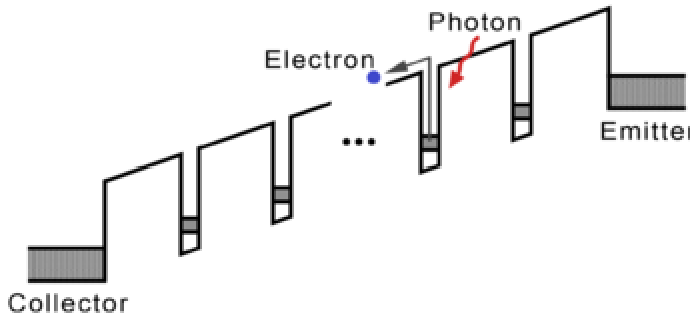
What have we not discussed?

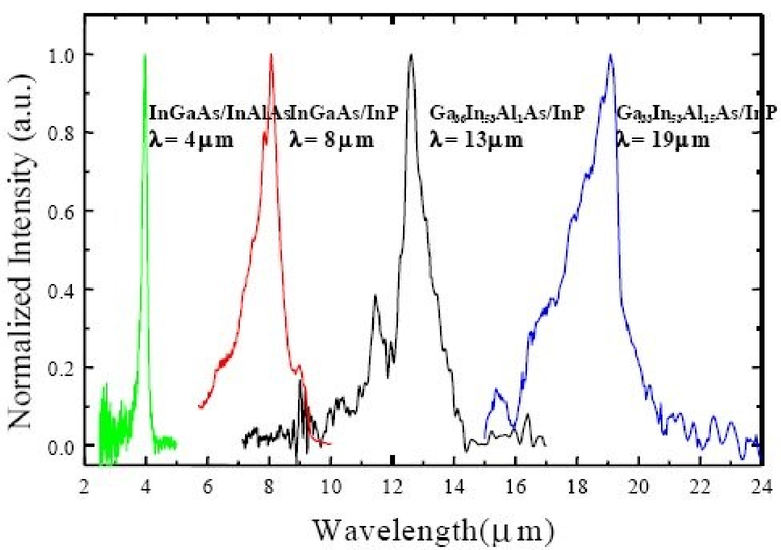
Quantum Photodetectors…

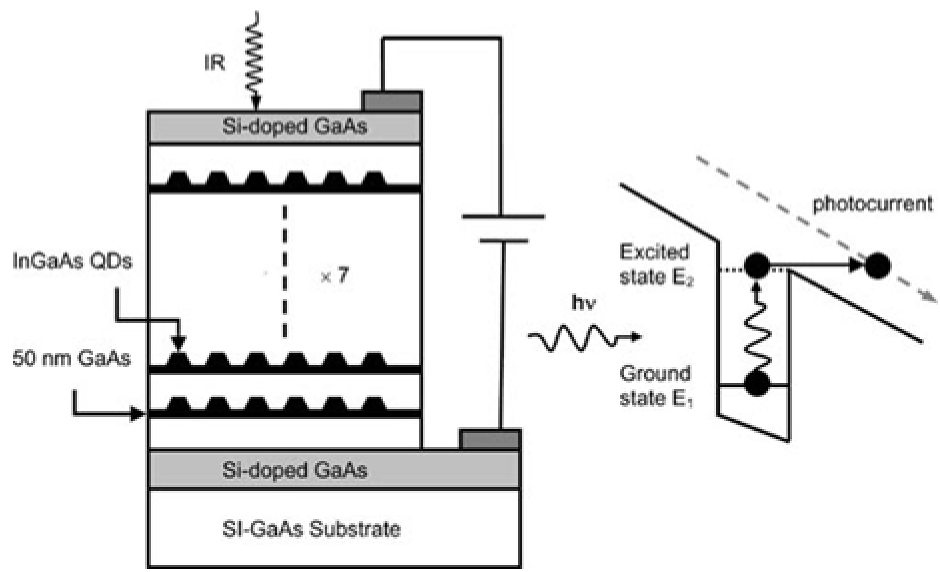
Using the wavelength specific nature of the energy transitions of Quantum Wells, Wires or Dots to tune the absorption to regions of interest

Quantum Well Infra-Red Photodetector (QWIP)
Quantum Dot Infra-Red Photodetector (QDIP)
Quantum Cascade Photodetector (QCD)

Operating temperature of detectors
Eg. Cooling a detector to reduce noise and/or dark currents etc.







“The practical……”

Wednesday’s lecture

“If you wont come to see me, I’ll come to see you!”

On Wednesday I’ll go over the general ideas behind the practical and give an example of the XRD + PL fitting approach as suggested in all the material you have been given so far (Lecture 11 notes, practical handouts, growth sheets, two sets of “next steps”, “software” slides etc.)

I will **not** do it all for you but can only try to help!

EEE6212 Lecture 22 "Nanotechnology…"

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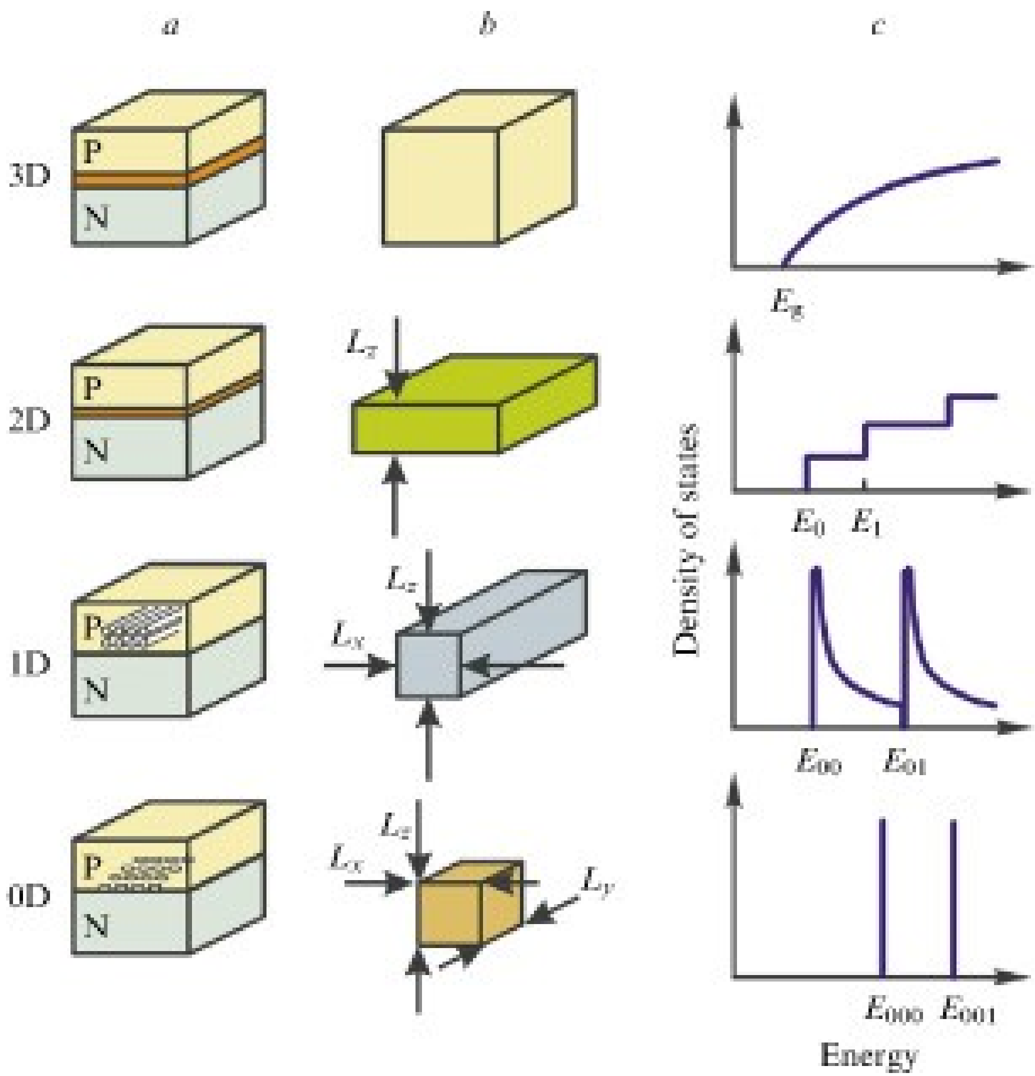
Outline

- “How to?” – fabrication methods for nano-technology
- “What for?” – nano-technological devices
- “Where?” – typical application areas

Motivation – DOS overview – 1



Type of confinement

None = 3D

Potential well or Quantum Well confines particles to movement in the (x,y) plane = 2D

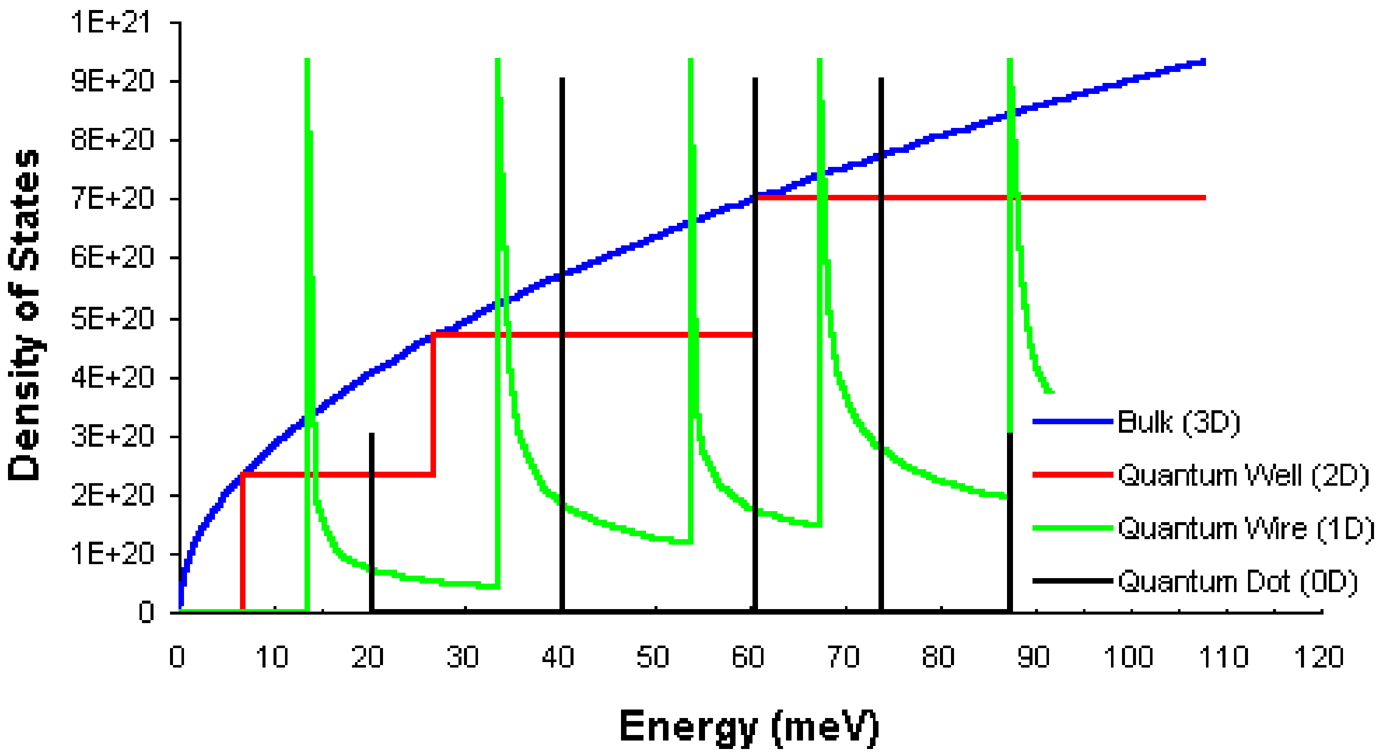
A Quantum Wire or nanorod confines the particles to movement along y-direction only = 1D

Total confinement by a Quantum Dot, the particle can no longer move at all = 0D

DOS overview – 2

The stronger the confinement is, the more the initially continuous DOS splits up into discrete levels

This concentrates the density of states into an ever narrower a range of wavelengths in optical emission or absorption which is useful for optoelectronic devices



http://britneyspears.ac/physics/dos/dos.htm

Making the materials …

1) Bulk

    Growth of crystals, growth of "thick" layers on substrates

2) Quantum Wells

    Formed using materials of different bandgaps (e.g. GaAs/AlGaAs)

    Can also be formed by electrostatic gates and depletion/accumulation of bulk materials (MOSFETs) (3D → 2D)

3) Quantum Wires

    Growth in ridges or grooves giving a local composition variation

    Electrostatic gates to deplete a QW structure (2D → 1D)

    Etching to create narrow channels

    Self assembled nanowire growth

4) Quantum Dots

    Self assembled growth using lattice mismatch (e.g. InAs/GaAs)

    Electrostatic gates to deplete a QW structure (2D → 0D)

    Inorganic synthesis routes – colloidal chemistry of nanocrystals

Fabrication methods

1) Epitaxy
   - Growth of thin or thick layers
   - in-situ surface treatment (oxidation, nitridation, annealing)

2) Lithography
   - Enables localised deposition or etching
   - Metallisation for contacts, gates etc

3) Ion Implantation
   - Broad and selective area doping
   - Intermixing

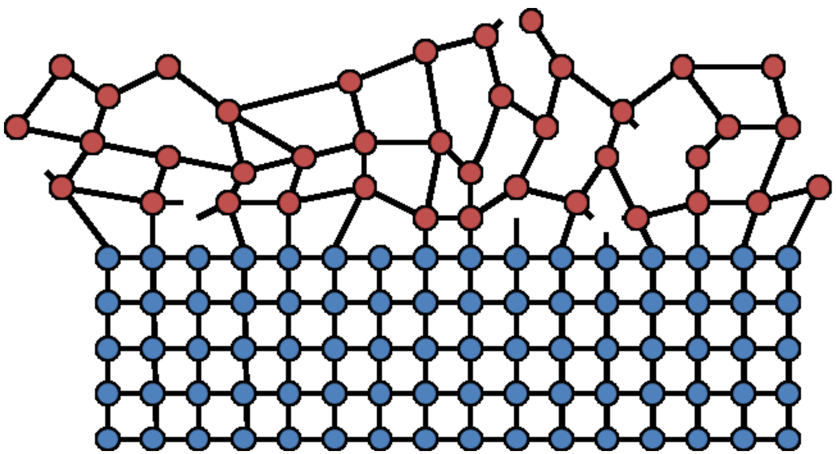
4) Colloidal Chemistry
   - Formation of nano-rods or nano-crystals from suspensions
   - Surface functionalisation

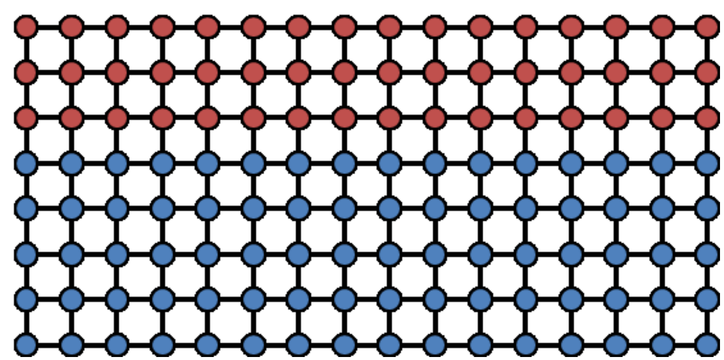
1) Epitaxy

The term *epitaxy* comes from the Greek roots *epi* (ἐπί), meaning "above", and *taxis* (τάξις), meaning "an ordered manner“ → “arranging upon” (Wikipedia)

In short this means that the layer being grown has defined crystal orientation with respect to the substrate

This differentiates it from a simple “deposition” process

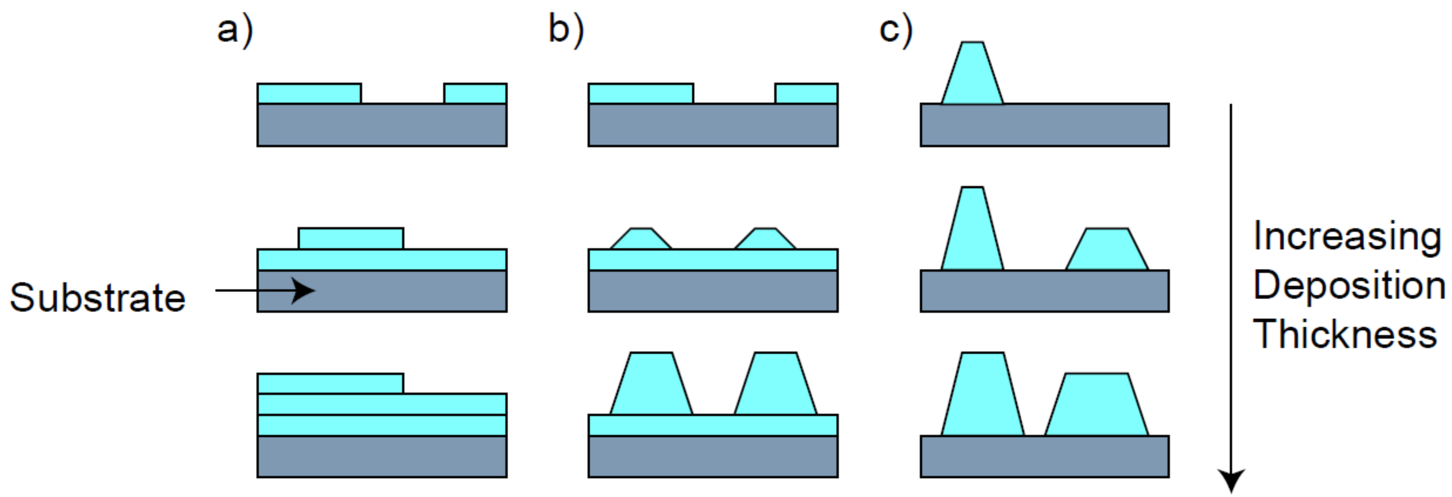




Possible growth modes

Growth generally proceeds by one of three modes

Depends upon the interplay between lattice mismatch and surface energies and growth conditions (kinetics)



a) Layer by Layer growth (Frank van der Merwe)

b) Layer followed by Islanding (Stranski-Krastanov)

c) Islanding (Volmer Weber)

Some deposition techniques

Liquid Phase Epitaxy (LPE)

Crystallisation of material onto a substrate from a molten solution

Molecular Beam Epitaxy (MBE)

Crystallisation of material onto a substrate from one or more beams of evaporated elements/compounds

Chemical Vapour Deposition (CVD)

Crystallisation of material onto a substrate from gas sources via a chemical reaction (e.g. $SiCl_4 + 2H_2 \rightarrow Si + 4HCl$)

Metal-Organic Vapour Phase Epitaxy (MOVPE or MOCVD)

Crystallisation of material onto a substrate from gas sources via chemical reactions where one or more sources are Metal-Organics (e.g. TMAl - $Al_2(CH_3)_6$)

Sputtering, Evaporation/Physical Vapour Deposition (PVD)

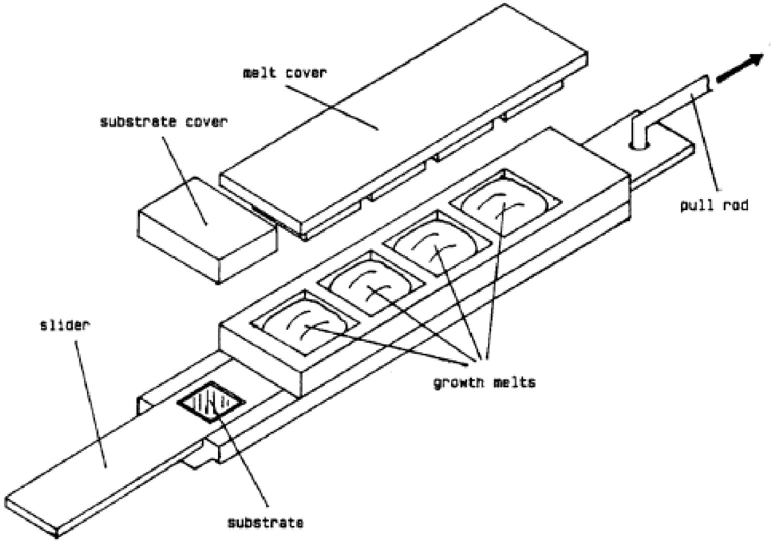
Do not necessarily create crystalline materials

Liquid Phase Epitaxy (LPE)

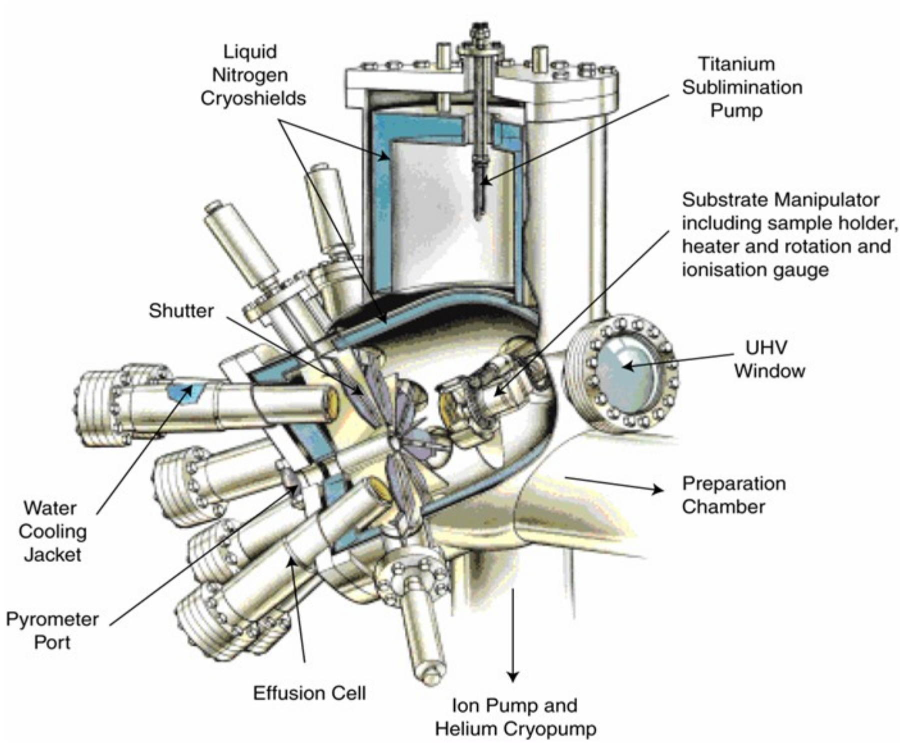
A substrate is brought into contact with a supersaturated melt of the material we wish to deposit and this crystallises on the surface

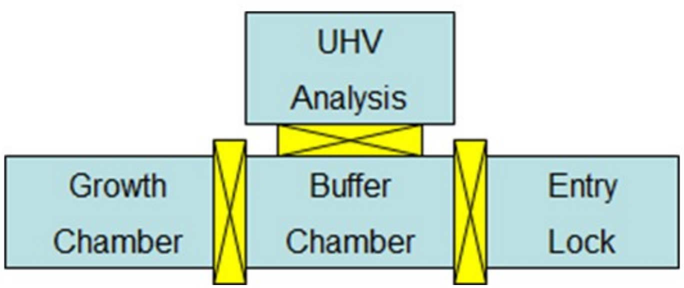
“Sliding boat” technology allows for heterostructure growth by bringing the substrate into contact with different melts at different stages of the growth

Interfaces are not particularly abrupt but growth rates are high making this a cheap and mass production method suitable for devices such as GaP LEDs



Molecular Beam Epitaxy





Ultra High Vacuum deposition technique leading to low impurity levels

Chamber pressure 10^{-11} mbar total

Partial pressure of impurities 10^{-15} mbar

Beams of atoms or molecules produced from heated elemental/compound sources impinge on a heated crystalline substrate

Long mean free path between collisions meaning reactions take place on the substrate surface not in the gas phase $(3m!!)$

Abrupt interfaces possible due to relatively slow growth rate and fast acting mechanical shutters

Wide range of in-situ techniques for monitoring growth (RHEED, STM, AES, XPS etc.)

Applicable to a wide range of materials

Semiconductors – III-V, Si, Si-Ge, II-VI, IV-VI

Metals, Insulators, Organics (OLEDs)

Oxides (ABO_3, High Temperature Superconductors)

Source Materials in III-V MBE

High purity source materials

99.99999% (7Ns) purity or higher

Group IIIs

Gallium, Aluminium, Indium

Group Vs

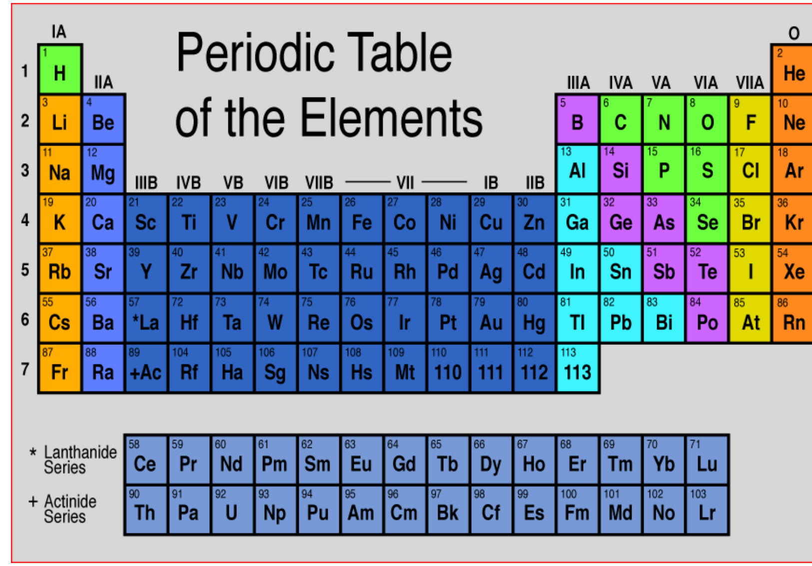
Arsenic, Phosphorous, Antimony,
Nitrogen, Bismuth

Dopants

Beryllium (p), Magnesium (p)
Silicon (n), Carbon(p), Tellurium (n)

Substrates

GaAs, InP, InAs, GaSb, InSb,
Sapphire … GaN, AlN, Ge, Si



http://facstaff.gpc.edu/~pgore/PhysicalScience/Periodic-table.html http://www.wafertech.co.uk/products/source-materials/
http://www.dtisanitary.com.tw/GaAs-Substrate.html, http://cmk.sk/products/gallium-arsenide/

Chemical Vapour Deposition

Generally takes place as a higher pressure than MBE leading to a much smaller mean free path $(30\mu m)$

A carrier gas (N_2, H_2, He) transports the reactant species to the substrate, these may be gases, volatile liquids, sublimable solids or a combination of all

Molecules can interact and react in the gas phase

A wider variety of CVD reactions can take place

Pyrolysis, Reduction, Oxidation, Compound formation, Disproportionation, Reversible Transfer

e.g. reduction of silicon tetrachloride: $SiCl_4 + 2H_2 \rightarrow Si + 4HCl$

decomposition of silane: $SiH_4 \rightarrow Si + 2H_2$

n-doping by PH_3 or AsH_3, p-doping by diborane (B_2H_6)

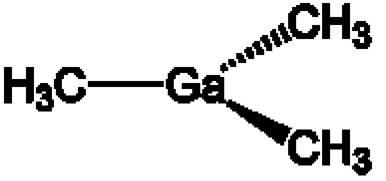
(autodoping by impurities from substrate if growth is too slow!)

Metal-Organic CVD (MOCVD)

Sometimes called Metal-Organic Vapour Phase Epitaxy (MOVPE)

Uses a mixture of gas sources and volatile metal-organics

TMGa = Trimethylgallium



e.g. Silane + Ammonia + TMGa ➔ GaN:Si

Offers higher growth rates than MBE and is sometimes considered (incorrectly) as the only viable production technique

Used for a wide range of materials from InP based telecoms devices through GaN and CdTe

Potential issues with hazardous gas sources used

https://en.wikipedia.org/wiki/Trimethylgallium

In-situ surface treatment

Dry Oxidation by molecular oxygen (slow)

$$SiH_4 + O_2 \rightarrow SiO_2 + 2H_2$$

Wet Oxidation under steam (fast)

$$Si + 2H_2O \rightarrow SiO_2 + 2H_2$$

Pyrolytic Oxidation of alkoxysilanes

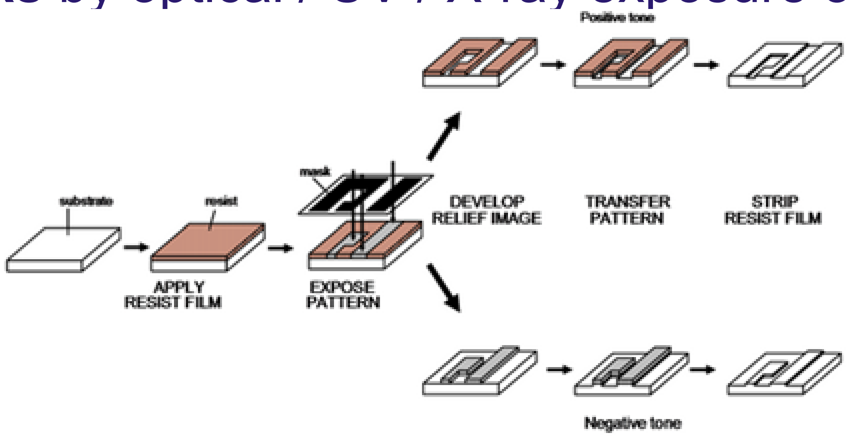
$$Si(C_2H_5O)_4 + 12O_2 \rightarrow SiO_2 + 10H_2O + 8CO_2$$

Nitridation with ammonia (NH_3) forms Si_3N_4 diffusion barriers

Rapid Thermal Annealing

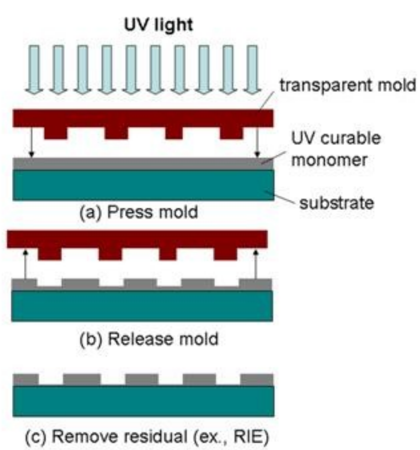
2) Lithography

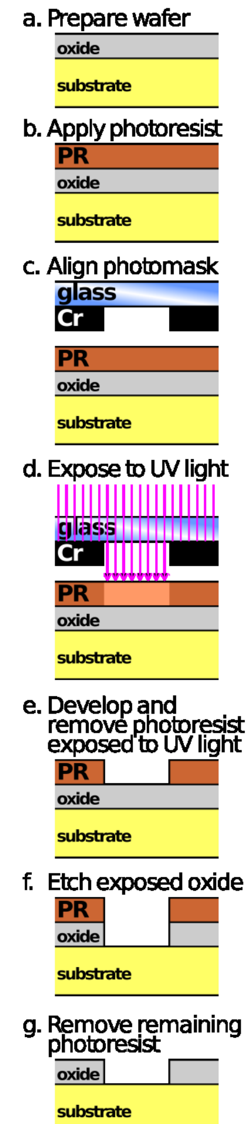
Local patterning (deposition or etching) of structures on the surface **via masks** by optical / UV / X-ray exposure of resist



Focused ion or electron beam patterning (**direct writing**)

Nano-imprinting





The University Of Sheffield.

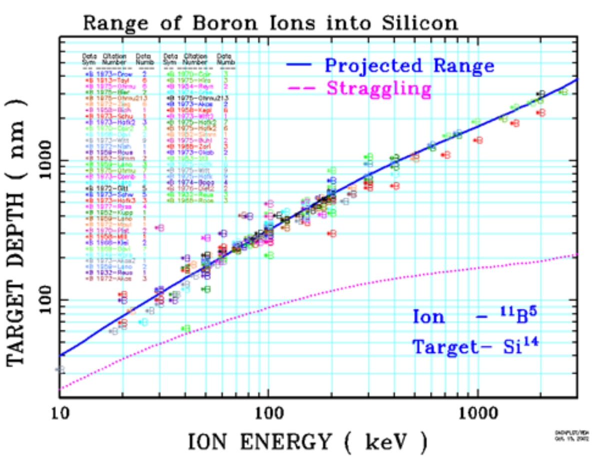
3) Ion Implantation

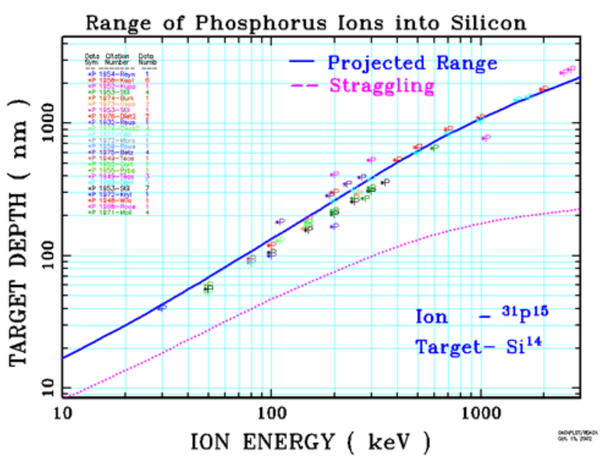
Implant high energy ions through a mask filter to a certain depth given by ion penetration range

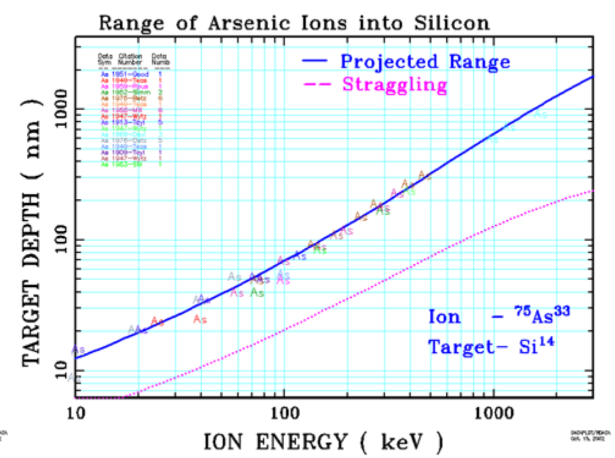
Followed by annealing to bring interstitial atoms onto lattice sites (electrical activation)

“Straggling” is assumed to be the square root of the variance (data from J.F. Ziegler’s SRIM code)

Also can be used for intermixing (**disordering**) layers at a given depth by ion implantation







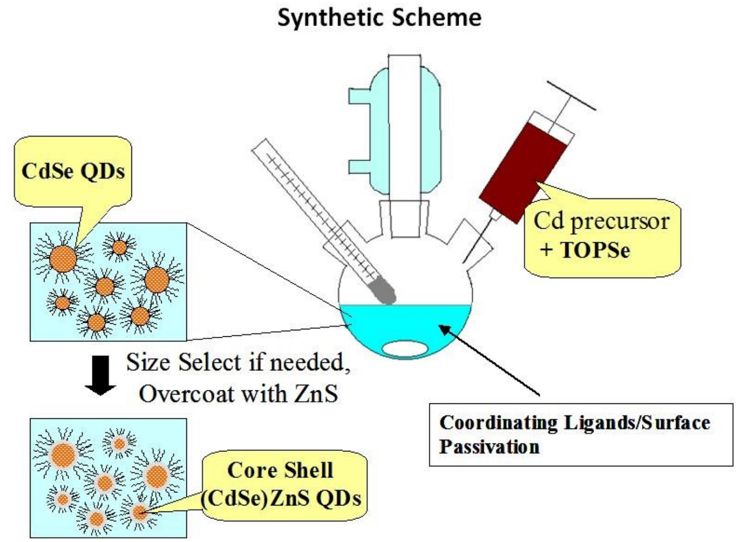
4) Colloidal Chemistry

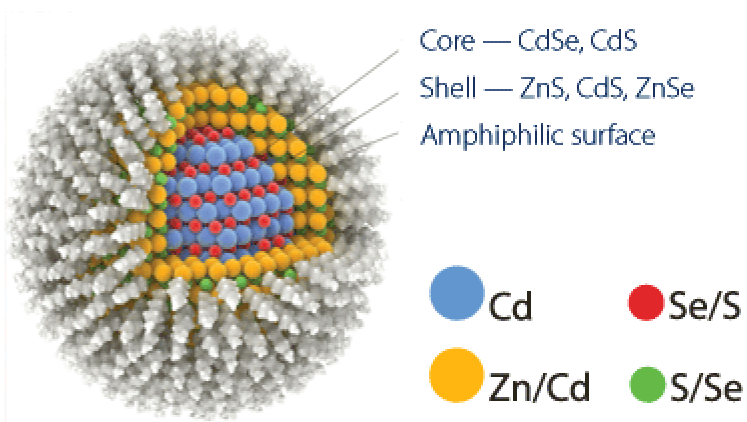
Formation of nano-rods or nano-particles from crystallite growth in suspension

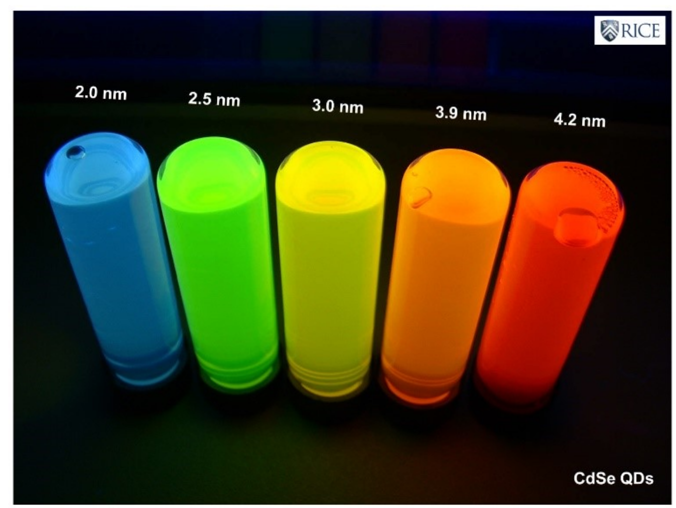
Size of nano-particles affects their properties, they are Quantum Dots…

Watch them being made at

https://www.youtube.com/watch?v=bKLdkjV6Mbc







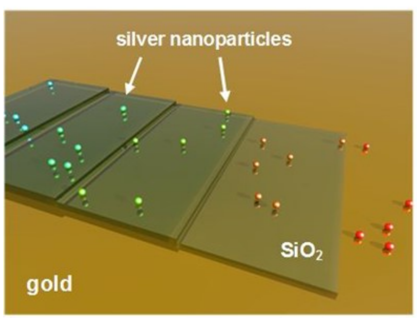
http://en.rusnano.com/press-centre/news/88604 , http://nanocluster.mit.edu/research.php
https://upload.wikimedia.org/wikipedia/commons/9/90/CdSe_Quantum_Dots.jpg

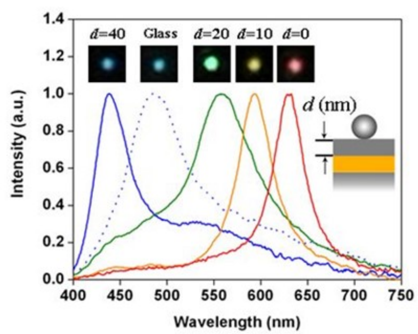
The University Of Sheffield.

4) Colloidal Chemistry

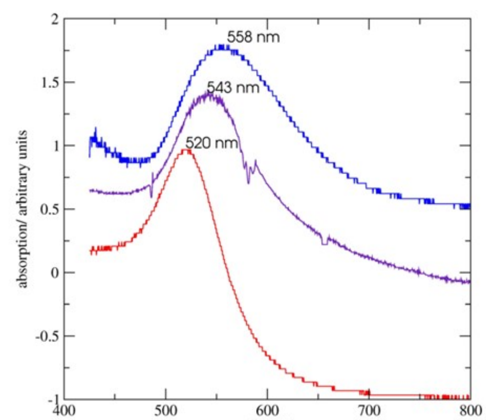
Surface functionalisation by organic molecules to provide steric hinderance to clustering so that nano-particles remain separated

Dispersion of gold or silver nano-particles onto (patterned) semiconductor surfaces to improve light coupling via surface plasmons





surface plasmons of Ag particles as function of thickness of SiO_2 interlayer to Au film

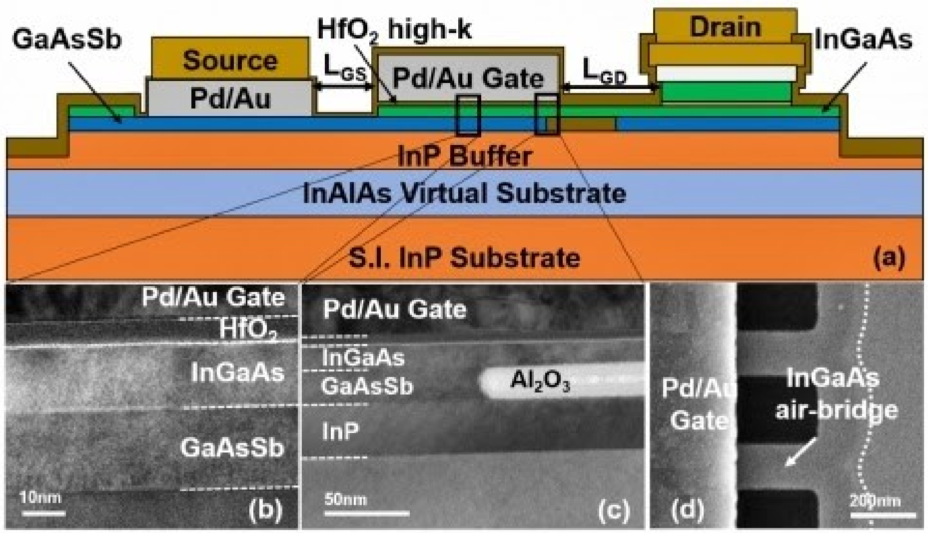


surface plasmons of Au particles as function of their diameters of 14 (red), 75 and 86nm

Nano-technological semiconductor devices

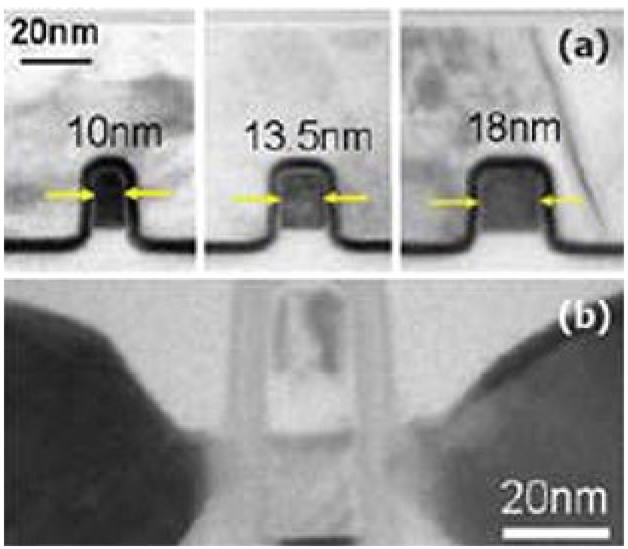
1) Electronics (voltage ←→ current, charge storage)
   - Smaller and faster MOSFETs as switches and amplifiers
   - Devices for quantum computing based on single electrons or spins
2) Opto-Electronics (current → light)
   - More powerful LEDs
   - More powerful and longer lasting LASER diodes
   - Integration of LASERs with MOSFETs for optical computing (III-V on Silicon)
   - Quantum Cascade Lasers for tailored IR applications
3) Solar Cells (light → current)
   - New concepts incorporating quantum dot or quantum wire structures
   - Improvement of surface coupling by plasmonics
   - Improved sub-wavelength anti-reflective coatings
   - Multi-junction solar cells

MOSFETs: two recent highlights



Engineers from MIT are claiming to have fabricated the first tunnel FET with a double quantum well InGaAs/GaAsSb structure

Solar UK Conference, Watford (2014)



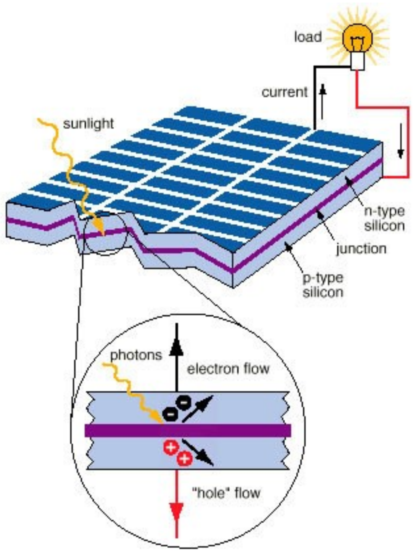
TEM cross-sectional images through probably the smallest MOSFET made by IBM and GlobalFoundries to date (2013!)

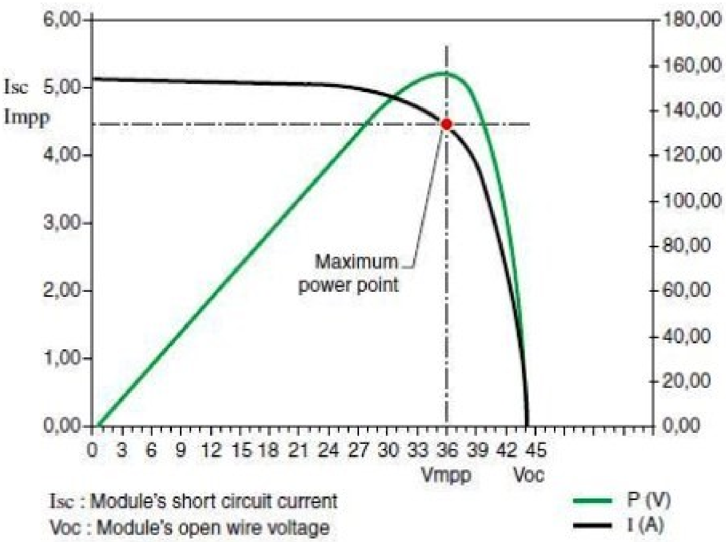
SiGe Tri-gate pFET with

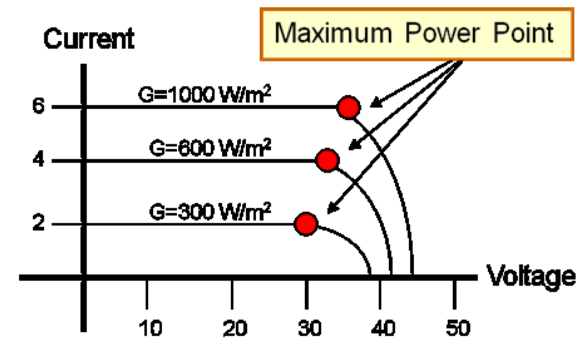
H=17nm, W=10-18nm, gate Length<20nm

(Hasemi et al, Symp. VLSI Technol. And Circuits, Tokyo (2013))

Solar Cells: principles







I-V versus Illumination (36 cell string)

Principle: pn-junction as a solar cell

Absorption of light, generating electron-hole pairs

Separation of charge carriers by the built-in field (~0.55V for a single Silicon cell)

Extraction of charge carriers to an external circuit, yielding a current that depends on load impedance

***power point tracking*: maximise the current × voltage product**

Solar Cells: Efficiency

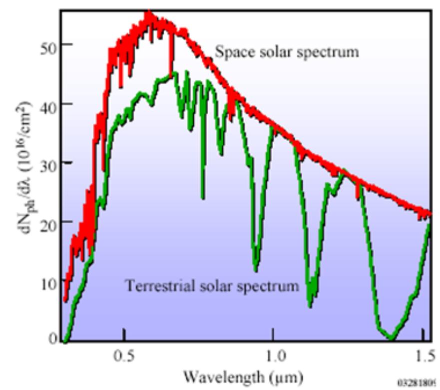
Theoretical max. efficiency of single-junction solar cells given by fraction of solar spectrum absorbed:

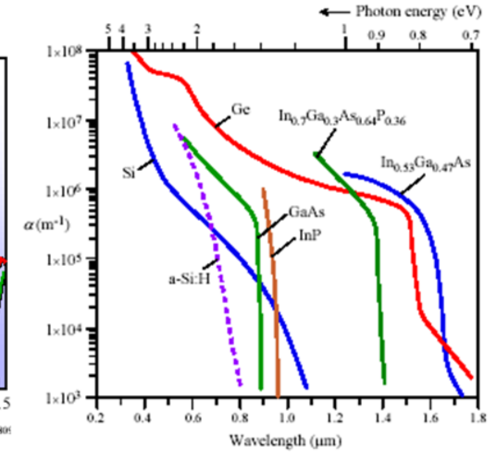
Only photons with the energy of the bandgap $(E = E_g)$ are converted with good efficiency.

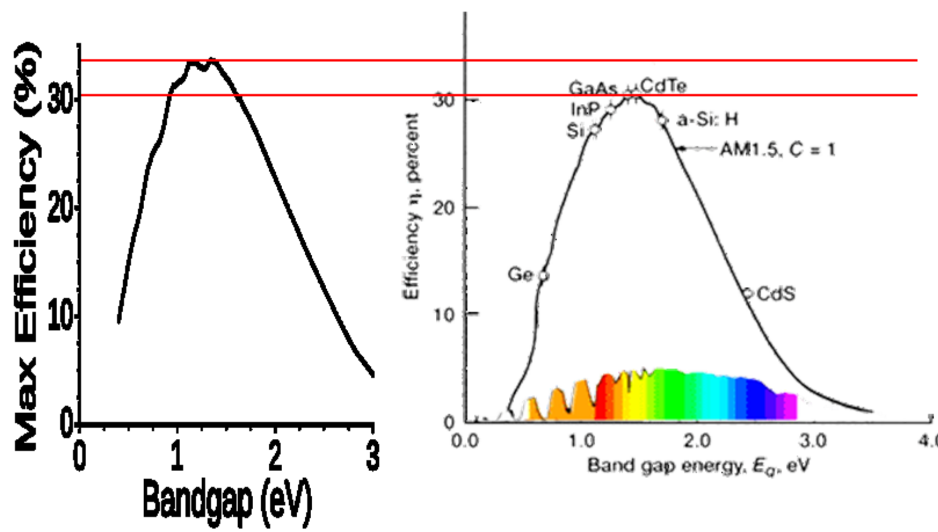
Photons with lower energy are not absorbed at all.

Those with higher energy $(E \geq E_g)$ are reduced to band-gap energy by thermalization of the photogenerated carriers, so fraction $\Delta E = E - E_g$ is wasted.

$\eta^{\max} = 31 - 33\%$ for GaAs or CdTe





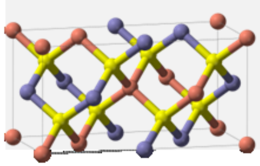


Solar Cells: Types

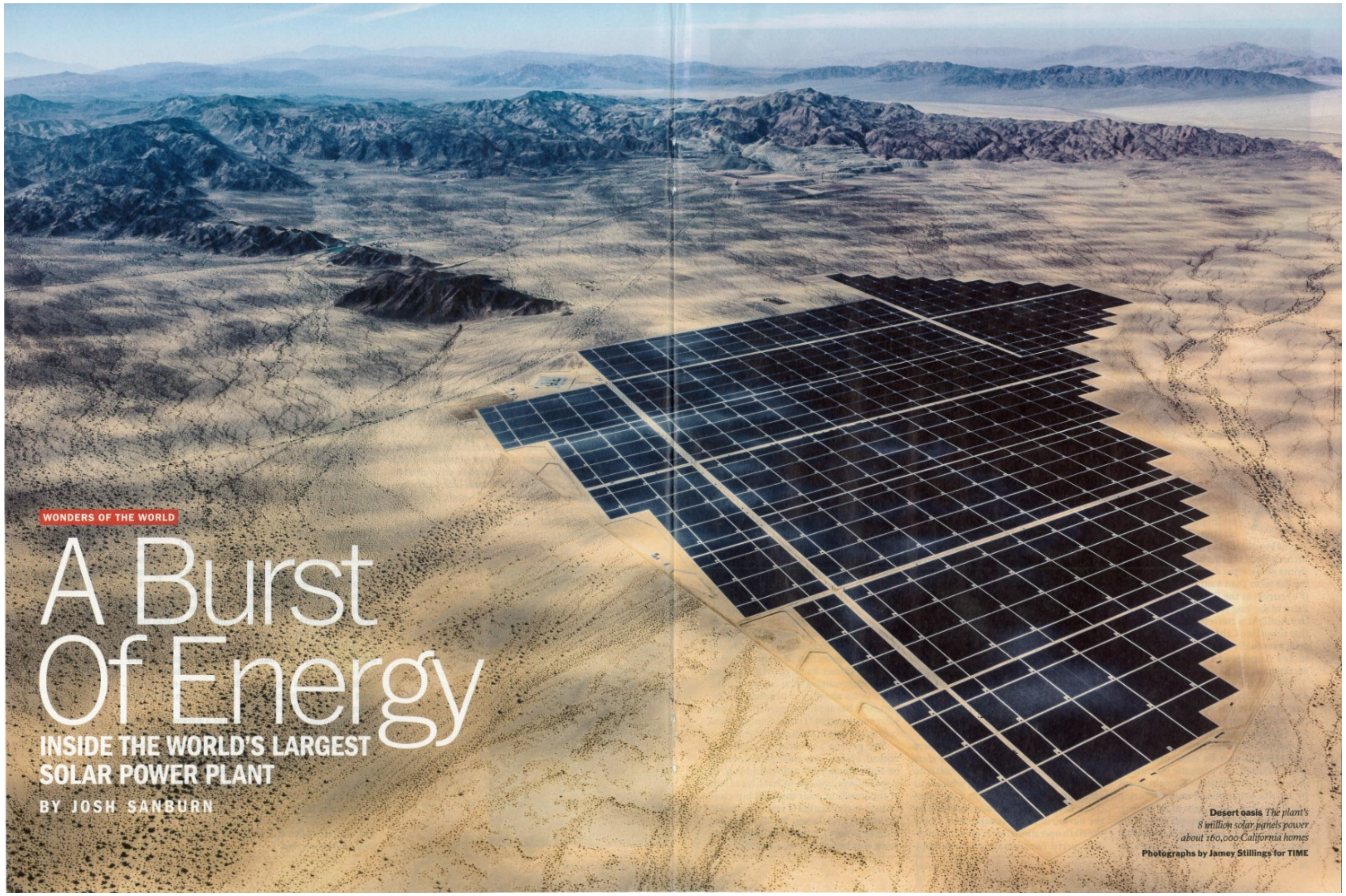
Main categories of photovoltaic cells

1) Crystalline Silicon (c-Si) solar cells
2) Thin Film Solar Cells (TFSC)
3) Multi-junction Solar Cells (MTJ)

category	technology	η (%)	V_{OC} (V)	I_{SC} (A)	W/m²	t (µm)
c-Si	mono-cryst.	24.7	0.5	0.8	63	100
	poly-cryst.	20.3	0.615	8.35	~200	200
TFSC	amorphous Si	11.1	6.3	0.0089	33	1
	CdTe	16.5	0.86	0.029	~100	5
	$CuIn_xGa_{(1-x)}Se_2$ (CIGS)	19.5	–	–	–	1
multi-junction cells	III/V's on Ge	40.7	2.6	1.81	476	140

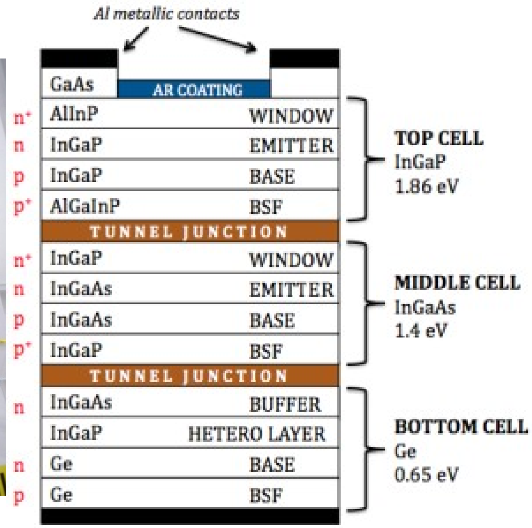


Solar Cells: Thin Film Solar Cells

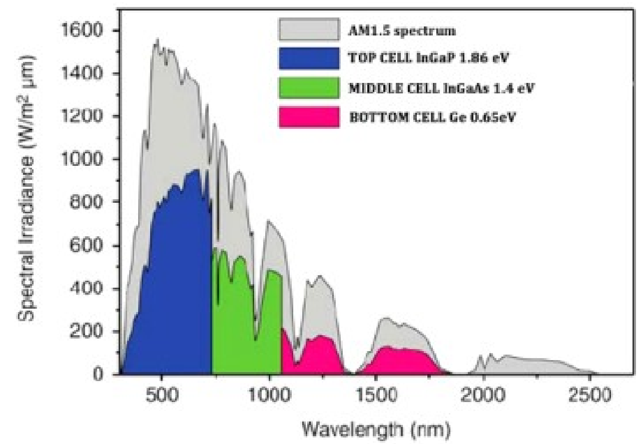


Desert Sunlight, CA, USA: the largest solar photovoltaic installation in the world (as of March 2015): 8 million **thin-film CdTe based** solar cells on 3800 acres , 550MW, powering 160 000 average homes

Solar Cells: Multi-Junction



(a)



(b)

GaAs based triple junction solar cells,

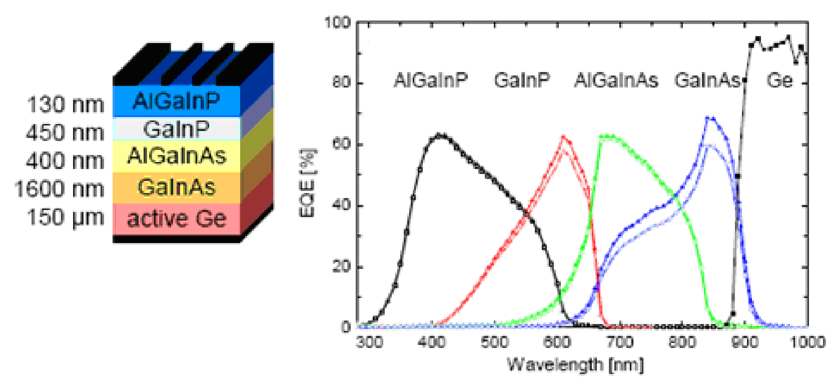
10kW, powering NASA satellite DAWN, launched Sep. 2007

above: layout of triple junction solar cell for $\eta^{max} \approx 50\%$ (from U Strathclyde)

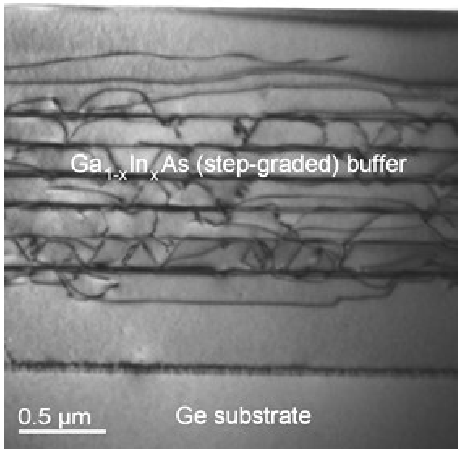
below: layout of 5-layer solar cell (from AW Bett, Proc. Solar Power Conf. 2006)

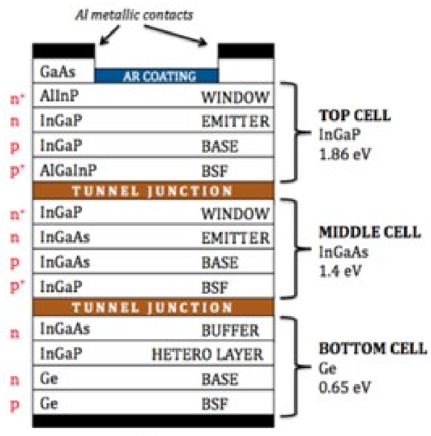
idea: lowest band-gap material at bottom, because IR has larger penetration depth!

max. efficiency at high cost!



Solar Cells: Multi-Junction





(a)

Materials challenges to solve:

Lattice mismatched materials give rise to dislocation formation at the interfaces

Need graded regions and dislocation filters which is more complex and means thicker devices

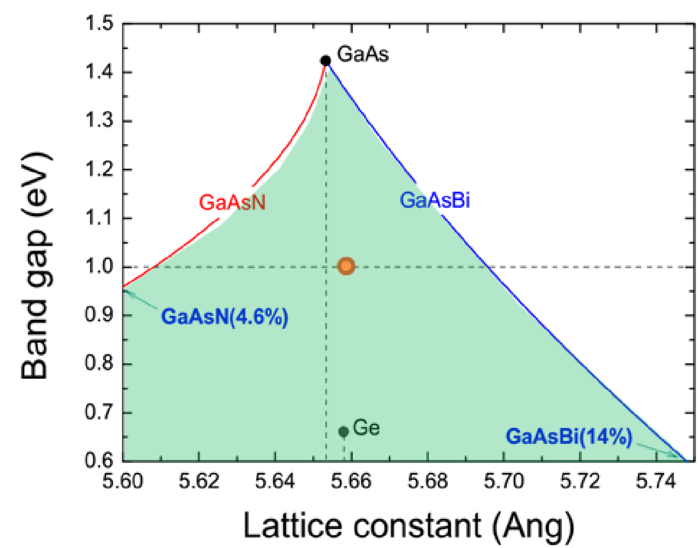
Reuse of expensive substrates to reduce total cost of cell fabrication

Search for new (lattice matched) candidate materials

The addition of small amounts of Nitrogen or Bismuth to GaAs dramatically changes the band structure

GaAsBiN could provide a 1.0eV material lattice matched to GaAs or Ge

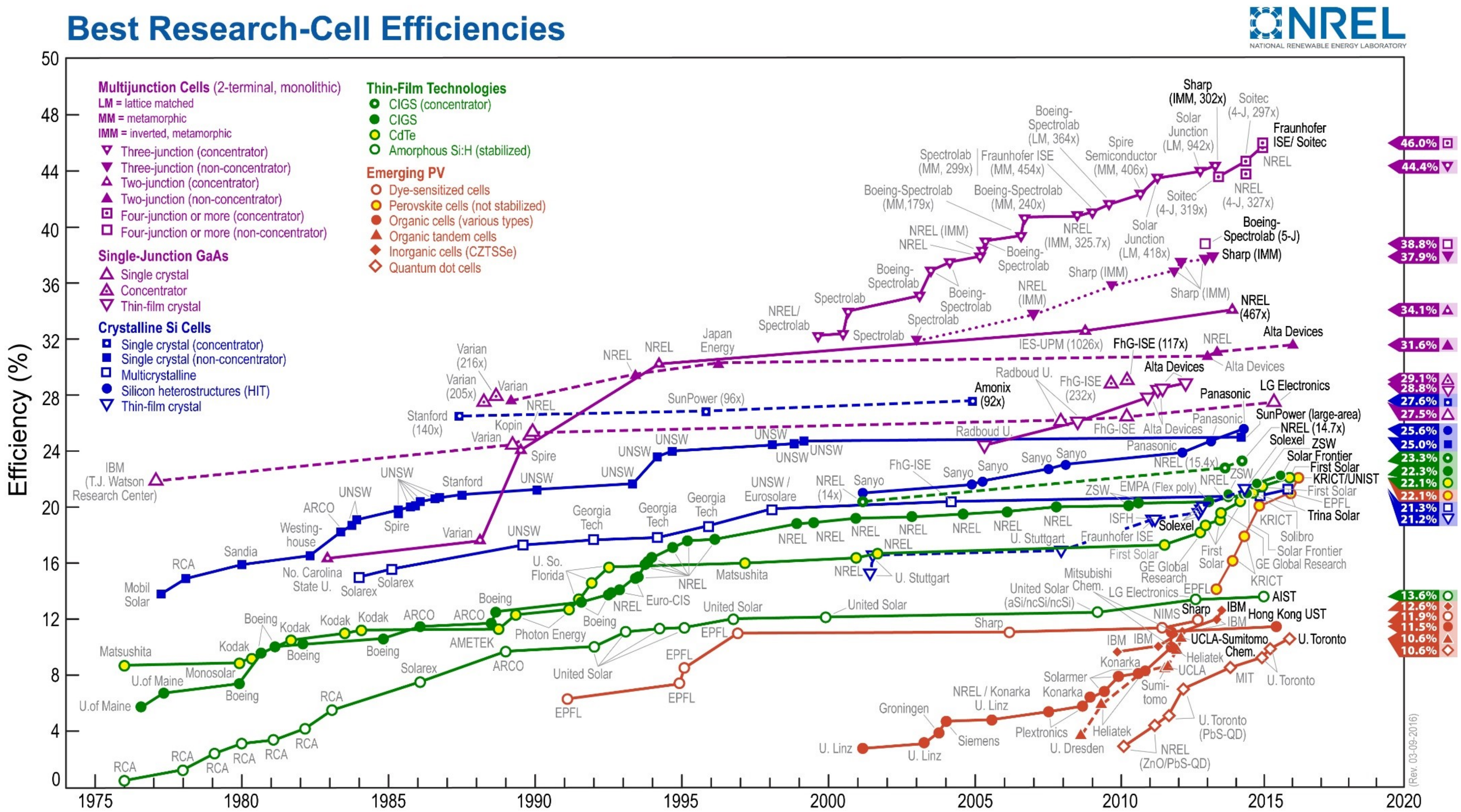
Offers the potential for an InGaP/GaAs/GaAsBiN/Ge 4-junction solar cell with no strained layers



Sweeney, S.J., K. Hild, and J. Shirong. *2013 IEEE 39th*. 2013.

Schöne et al., 18th MSM, J.Phys. Conf. Ser. *471* (2013) 012008

Solar Cells: Comparison of Types



http://www.nrel.gov/ncpv/

Nano-technological applications

1. **physics**
   a. improved data storage
   b. quantum computing schemes
2. **chemistry**
   a. more efficient catalysts
   b. water and dirt-repellent surfaces (‘lotus effect’)
3. **medicine**
   a. colour coded quantum dots for in-vivo imaging of living organisms in 3D
   b. colour coded quantum dots for DNA testing
   c. improved healthcare and cancer treatments by quantum dot assisted drug delivery
4. **other**
   a. invisible watermarking of goods and banknotes
   b. forensics, e.g. nano-particles in gunshot residue

This list is by no means exhaustive!!