EEE 6212
Semiconductor Materials

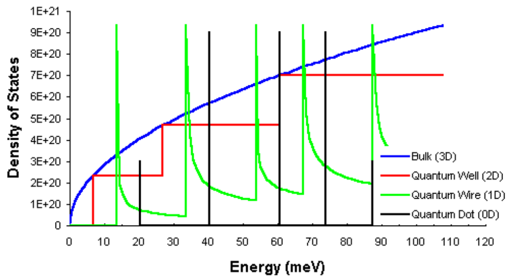
Lecture 28: Nano-Technologies

Lecture 25: Nano-Technologies

- ‘***how to ?***’: fabrication methods for nano-technology
- ‘***what for ?***’: nano-technological devices
- ‘***where ?***’: typical application areas

motivation: review of DOS in 3D, 2D,1D,0D

The stronger the confine ment is, the more the initially continuous DOS splits up into discrete levels. This means a narrower range of wavelengths in optical emission or absorption, which is useful for opto-electronics.



type of confinement

none (3D)

a potential well or quantum well confines particles to movement in (*x,y*) plane (2D)

a quantum wire or nano-rod confines particles to movement along *y*-direction only (1D)

total confinement by quantum dot: particle can no longer move at all (0D)

fabrication methods for nano-technology

primary fabrication methods:

1. **epitaxy**
   a. growth of thin or thick layers
   b. in-situ surface treatment (oxidation, nitridation, annealing)
2. **lithography**
   a. local deposition or etching
   b. metallisation
3. **ion implantation**
   a. doping
   b. intermixing
4. **colloidal chemistry**
   a. formation of nano-rods or nano-particles from suspension
   b. surface functionalisation

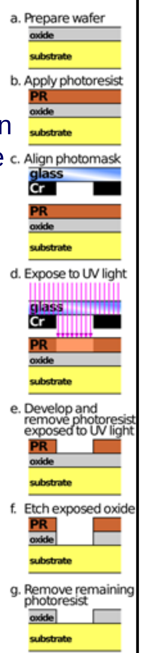
epitaxy

1. epitaxy

a. growth of thin or thick layers
  - molecular beam epitaxy (MBE) from atomic species
  - ***chemical vapour deposition (CVD)*** from molecular species, e.g. reduction of silicon tetrachloride: $SiCl_4+2H_2 \rightarrow Si+4HCl$, or 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 vapour phase epitaxy (MOVPE or MOCVD), particularly for GaN and CdTe based compounds
  - liquid-phase epitaxy

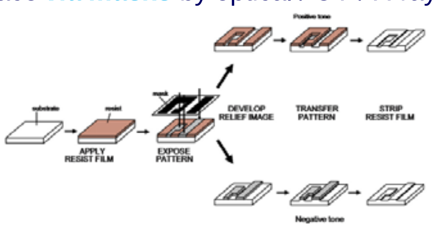
b. in-situ surface treatment
  - ***dry oxidation*** by molecular oxygen (slow): $SiH_4+O_2 \rightarrow SiO_2 +2H_2$
  - ***wet oxidation*** under steam (fast): $Si + 2H_2O \rightarrow SiO_2 +2H_2$
  - ***pyrolytic oxidation*** of alkoxysilanes: $Si(C_2H_5O)_4 + 12O_2 \rightarrow SiO_2 +10 H_2O + 8 CO_2$
  - nitridation with ammonia (NH_3) forms Si_3N_4 diffusion barriers
  - ***rapid thermal annealing***

lithography



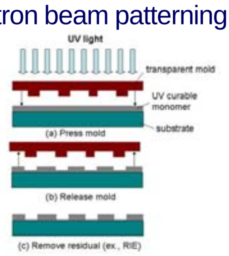
2. lithography

a. local patterning (deposition and etching) of structures on the surface ***via masks*** by optical / UV / X-ray exposure of resist



b. focused ion or electron beam patterning (***direct writing***)

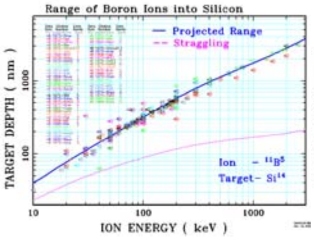
c. nano-imprinting

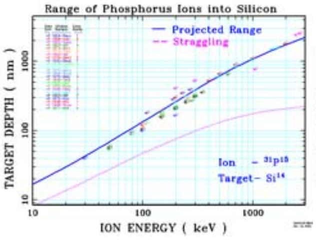


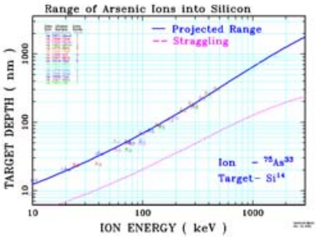
ion implantation

3. ion implantation

a. ***implanting*** 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')







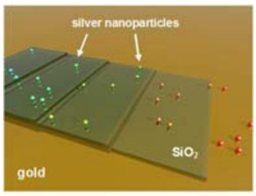
NB: straggling is assumed to the square root of the variance.
data shown are from J.F Ziegler's SRIM code.

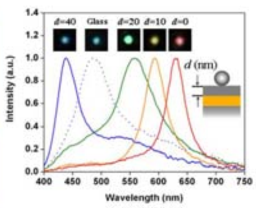
b. intermixing (***disordering***) layers at given depth by ion implantation, e.g. to avoid spinodal decomposition

colloidal chemistry

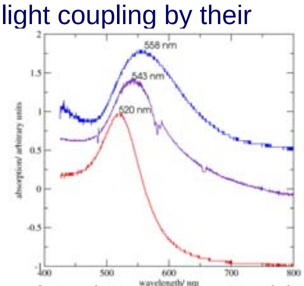
4. colloidal chemistry

a. formation of nano-rods or nano-particles from crystallite growth in suspension
b. surface functionalisation by organic molecules to provide steric hindrance to clustering so the nano-particles stay separate
c. dispersion of gold or silver nano-particles onto (patterned) semiconductor surfaces to improve light coupling by their 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

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nano-technological semiconductor devices

devices:

1. **electronics** (voltage <-> current, charge storage)
   a. ***smaller and faster MOSFETs*** as switches and amplifiers
   b. devices for quantum computing based on single electrons or spins
2. **opto-electronics** (current-> light)
   a. more powerful LEDs
   b. more powerful and longer lasting LASER diodes
   c. integration of LASERs with MOSFETs for optical computing
   d. quantum cascade LASERs for tailoured IR applications
3. **solar cells** (light -> current)
   a. new concepts by incorporating quantum dot or quantum wire structures
   b. improvement of surface coupling by plasmonics
   c. improved sub-wavelength anti-reflective coatings
   d. ***multi-junction solar cells***

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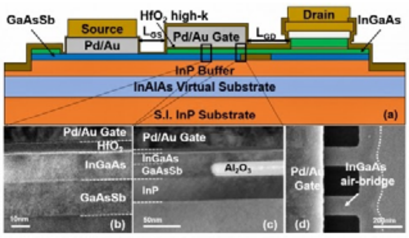
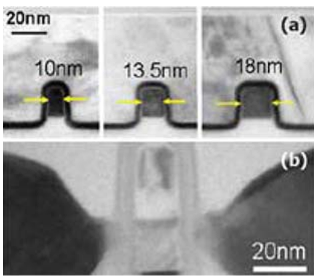
MOSFETs: two recent highlights

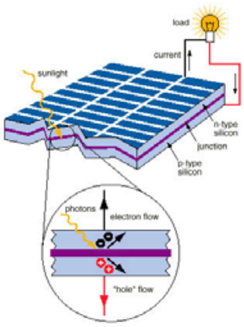


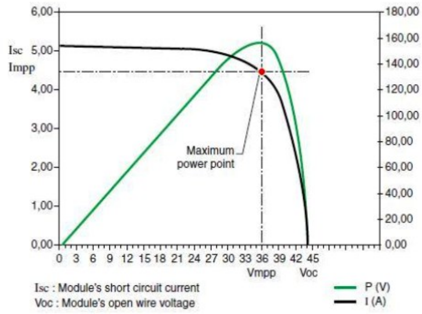
engineers from MIT have fabricated a double quantum well MOS-FET. Solar UK conference, Watford, 6 November 2014



TEM cross-sectional images through the probably smallest MOS-FET made by IBM and GlobalFoundries to date: SiGe channel Tri-gate pFET with H_{fin}=17nm, W_{fin} = 10-18nm (a) and gate length L_g<20 nm (b). Hasemi et al., paper T2-2, Symp. VLSI Technol. and Circuits, Tokyo, 10-14 June 2013

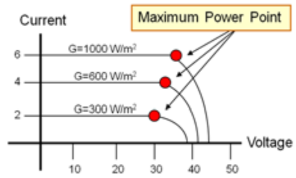
solar cells: principles





principle: pn-junction as solar cell:

- absorption of light, generating electron-hole pairs
- separation of charge carriers by built-in field (~0.55V for 1 Si cell)
- extraction of charge carriers to an external circuit, yielding a current that depends on load impedance



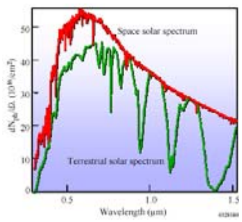
I-V versus Illumination (36 cell string)

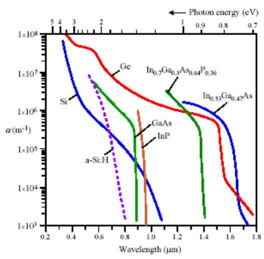
power point tracking: maximise the current × voltage product

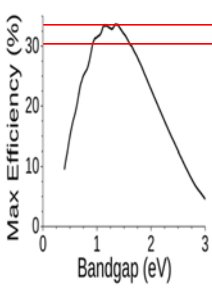
solar cells: efficiency

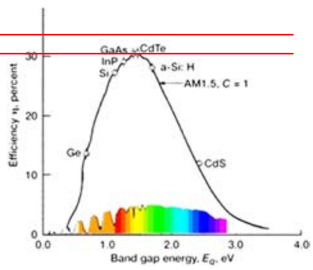
theoretical max. efficiency of single-junction solar cells given by fraction of solar spectrum absorbed: only photons with the energy of the bandgap (E=E_g) are converted with good efficiency. Photons with lower energy are not absorbed at all; those with higher energy ($E \geq E_g$) are reduced to band-gap energy by thermalization of the photogenerated carriers, so fraction ΔE=E–E_g is wasted.

η^{max}=31-33% for GaAs or CdTe









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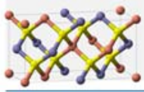
solar cells: structural types

main categories of photovoltaic cells:

1. crystalline silicon (c-Si) solar cells,
2. thin film solar cells (TFSC),
3. multi-junction (MJ) solar cells

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
TSFC	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



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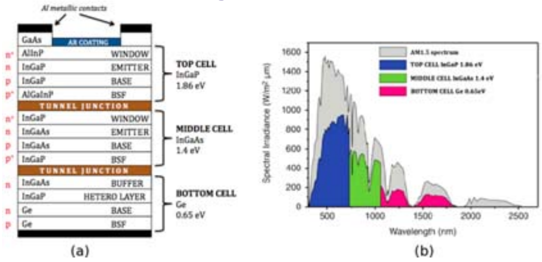
solar cells: thin film solar cells

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

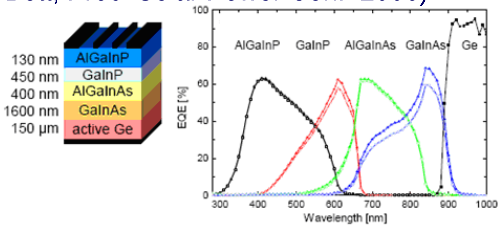
solar cells: multi-junction cells

GaAs based triple junction solar cells,
10kW, powering NASA satellite DAWN, launched Sep. 2007

idea: lowest band-gap material at bottom,
because IR has larger penetration depth!
max. efficiency at high cost!



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)



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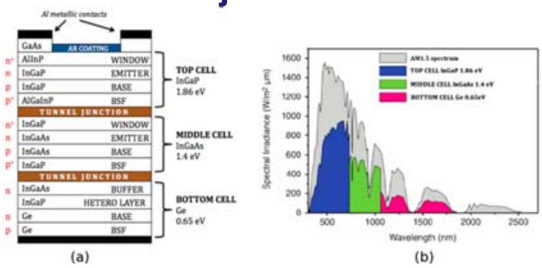
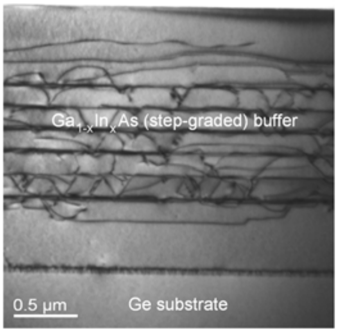
solar cells: multi-junction cells



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

Below left: dislocated buffer between Ge substrate and InGaAs for a multi-junction solar cell (Schöne et al., 18th Microscopy of Semiconducting Materials conference, J.Phys. Conf. Ser. *471* (2013) 012008)



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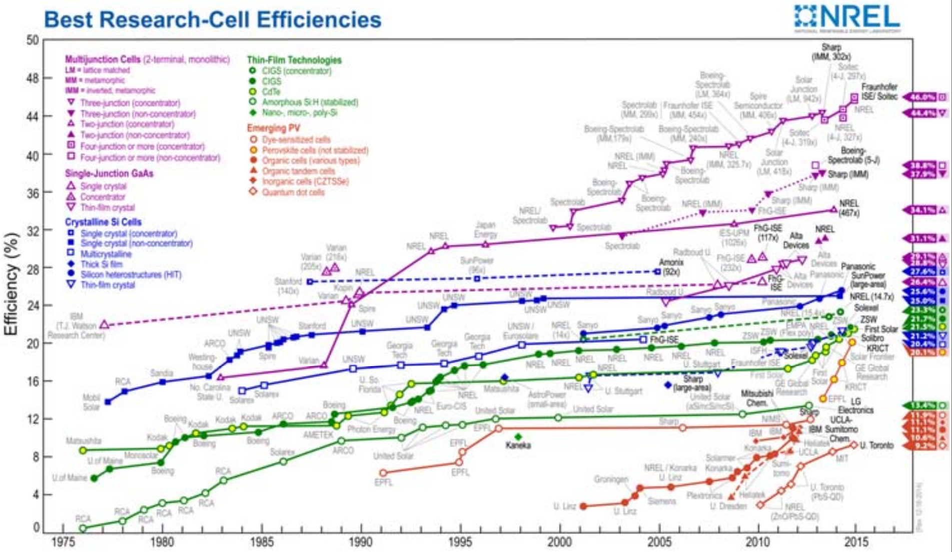
solar cells: comparison of types



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nano-technological applications

application areas:

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