Semiconductor Fundamentals

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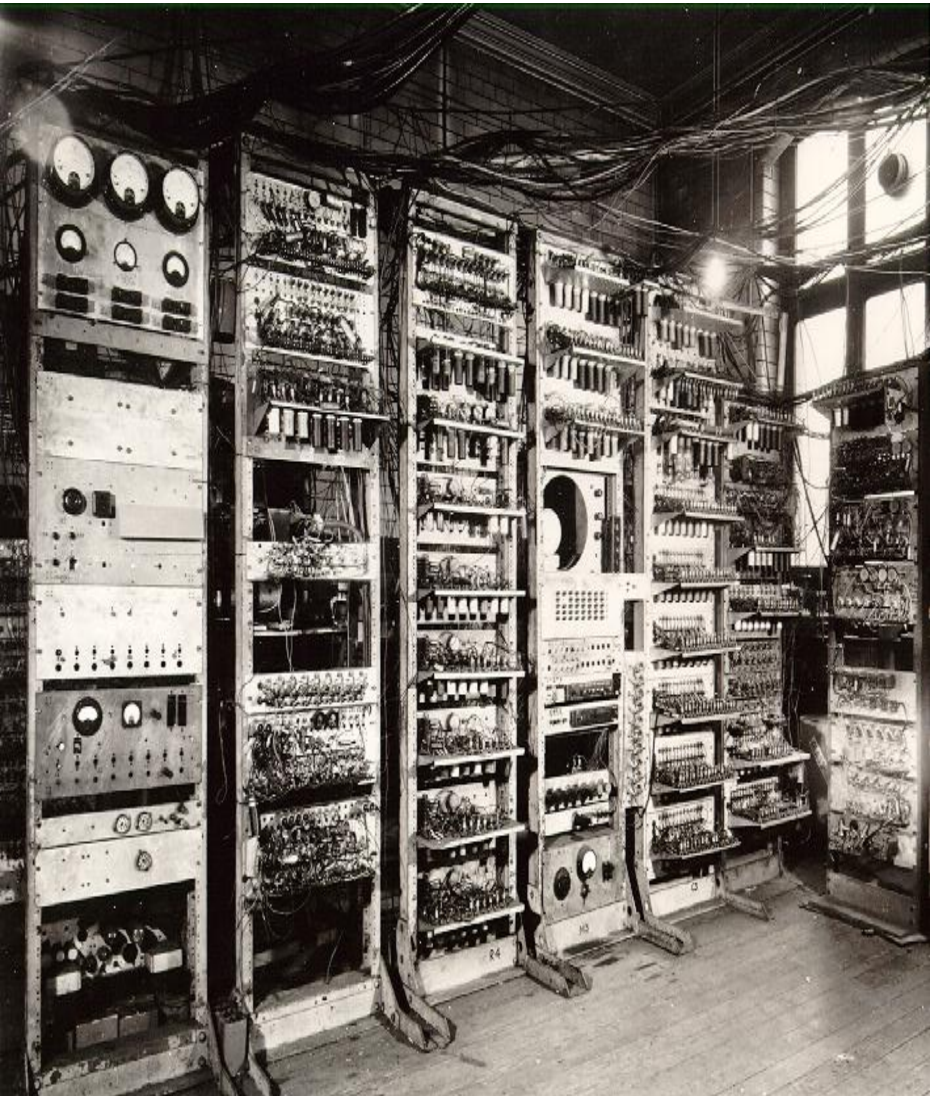
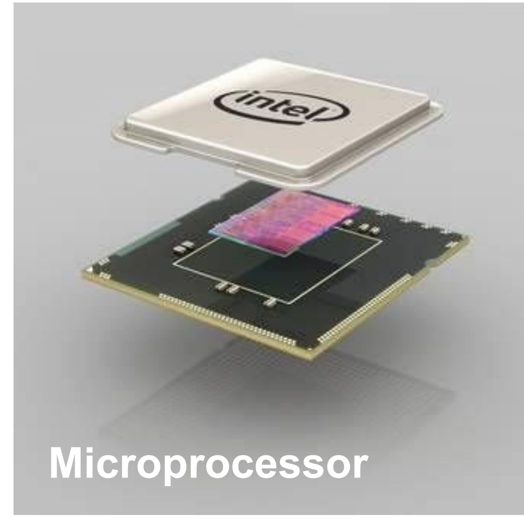
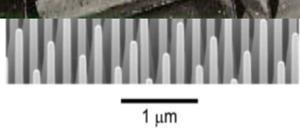
Why use semiconductor?



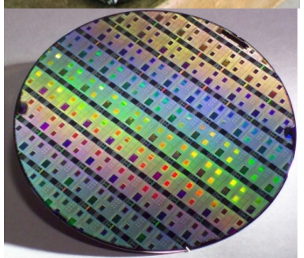


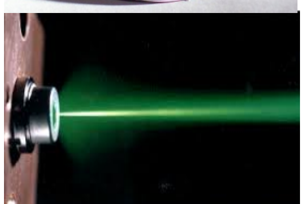
iPad mini

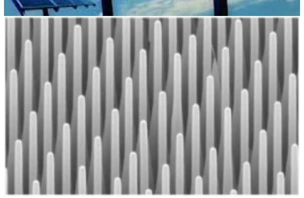
Transistors are used in logic circuits that are compact, low power consumption and affordable.



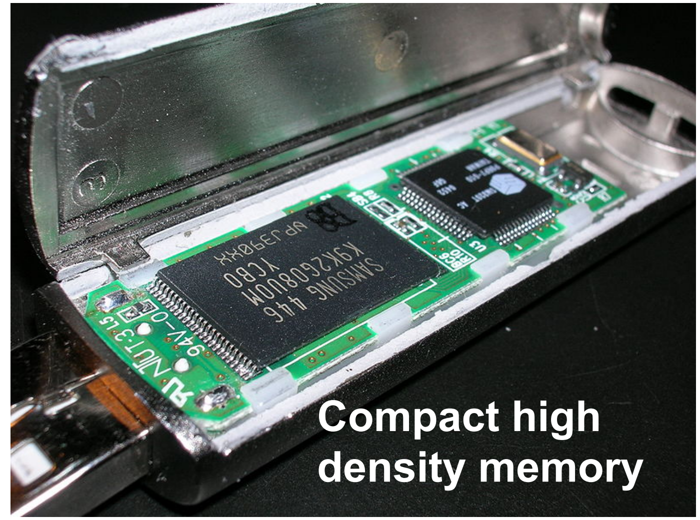
Why use semiconductor?



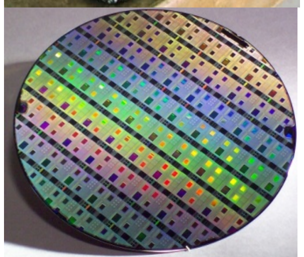


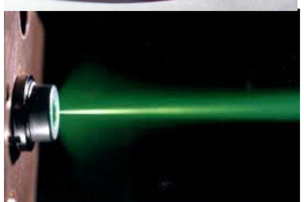


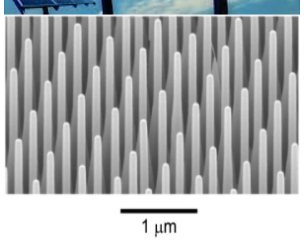
1 μm

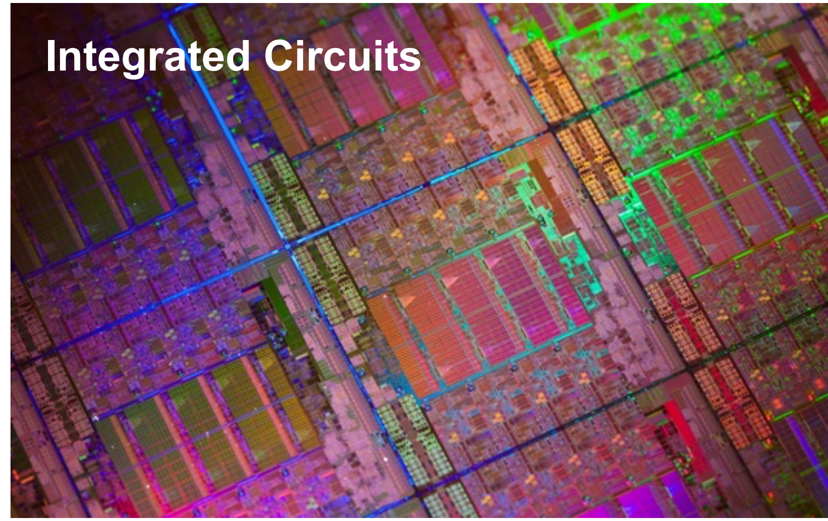


Why use semiconductor?

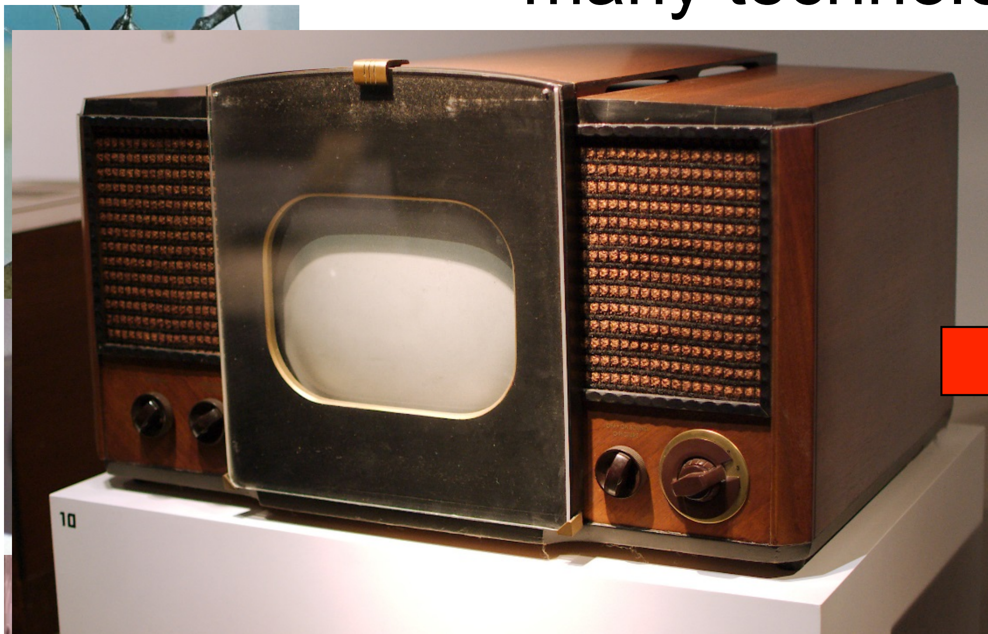


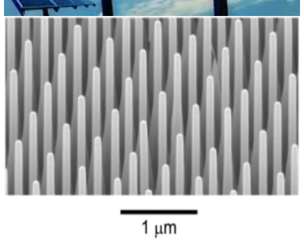






Semiconductor is an important driver of many technologies

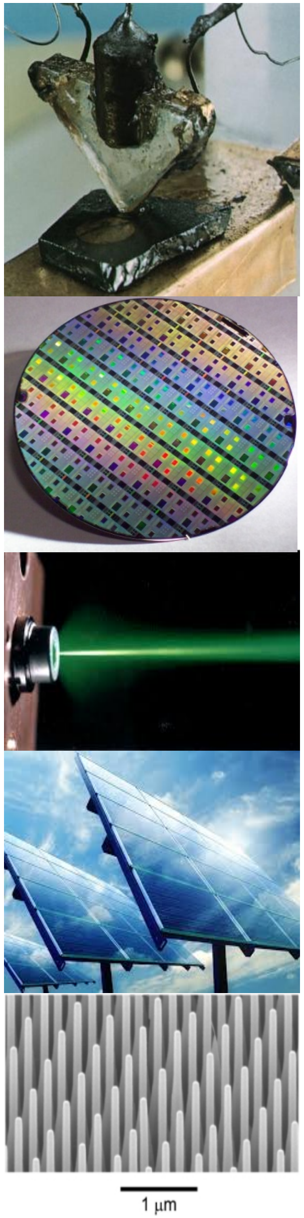




http://www.youtube.com/watch?v=sJehexDPEsE

Flexible display is another exciting example of progress made in semiconductors

Outline



- Basic properties
- Band structure
- Carrier concentration
- Recombination

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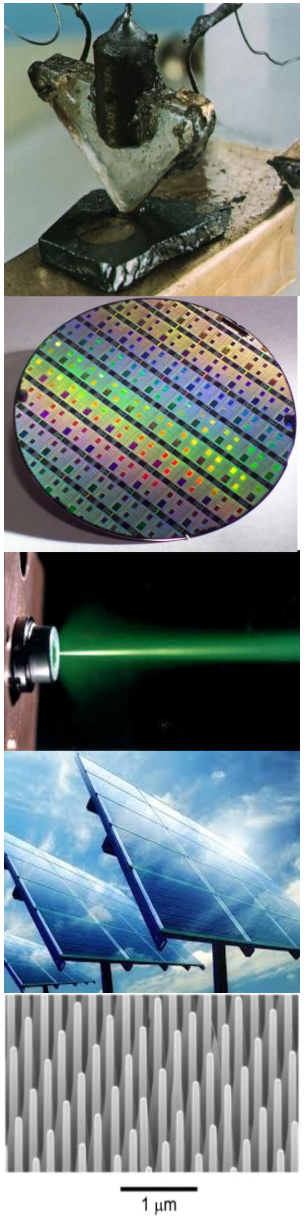

Basic properties of semiconductors

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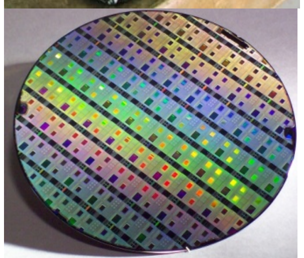
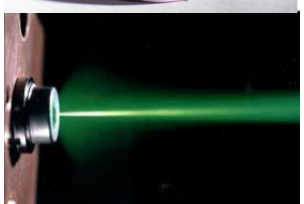
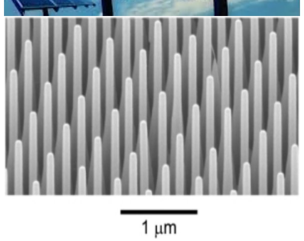
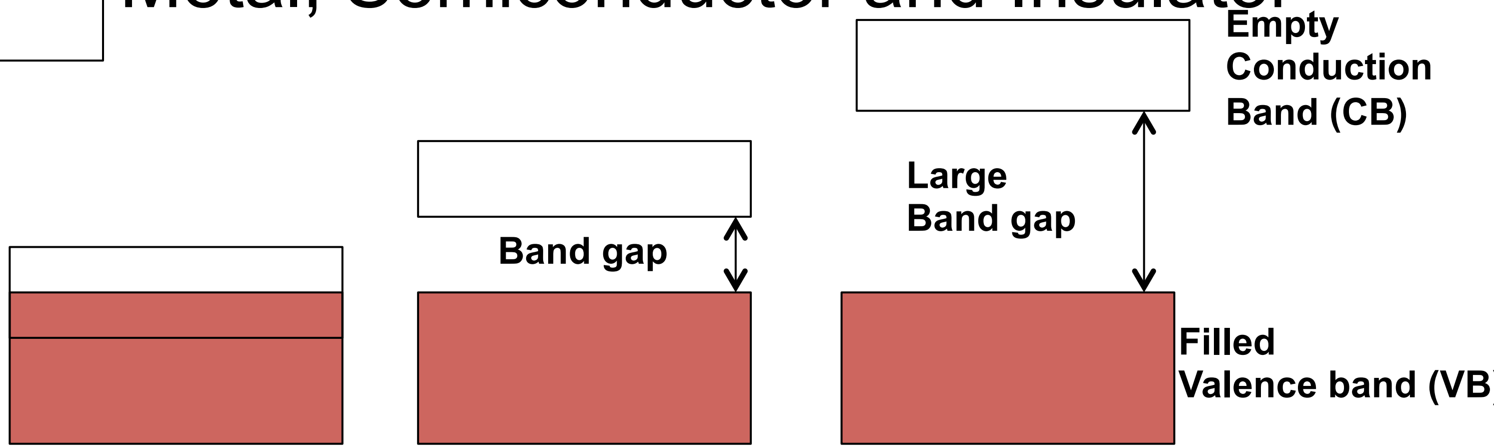
Metal, Semiconductor and Insulator









Metal	Semiconductor	Insulator
•CB and VB overlap. • Electrons move freely under the influence of electric field because there are many available states in the CB. •Good electrical conductor.	•Band gap of meV to a few eV. •At T=0 K, no electron in the CB. •At 300 K, thermal energy kT = 26 meV which is a fraction of the band gap. • Appreciable number of electrons are thermally excited to become free electrons in CB.	•Bandgap is large 9 eV (SiO_2). •Negligible electron in CB. •Cannot achieve good current conduction.

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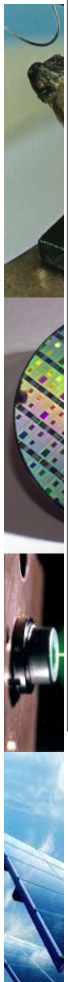
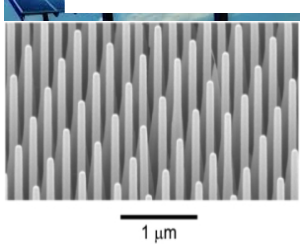
Common Semiconductors



Key: element name / atomic number / symbol / atomic weight (mean relative mass)

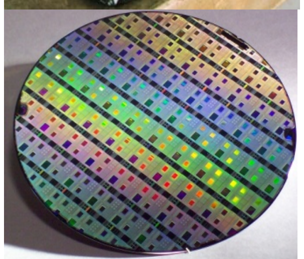
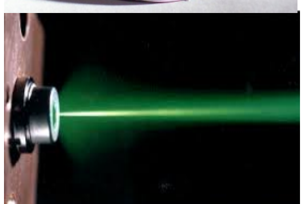
												II	III	IV	V	VI		
hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

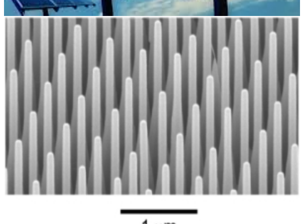
*lanthanoids	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
**actinoids	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

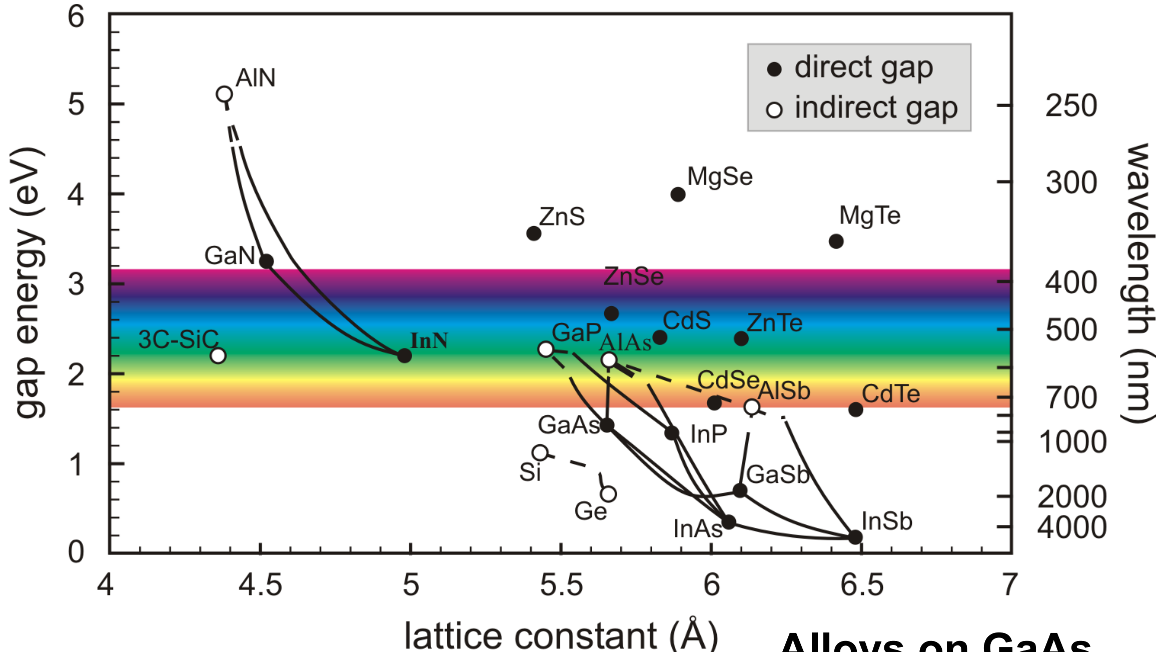


Group IV: Si and Ge
Group III-V: GaAs, InP, GaP, InAs, InSb
Group II-VI: HgCdTe, CdZnTe

Semiconductor Alloys



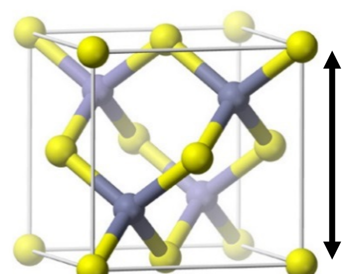


Widely available substrates

IV	**III-V**	**II-VI**
Si	**GaAs**	**CdTe**
Ge	**InP**	**CdSe**
SiC	**InSb**	**ZnSe**
	GaSb	**ZnTe**
	InAs	

Alloys on GaAs

AlGaAs
InGaP
AlInP

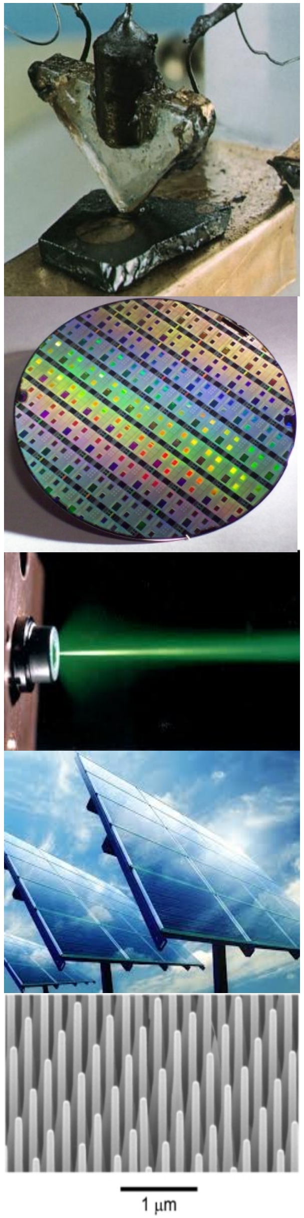


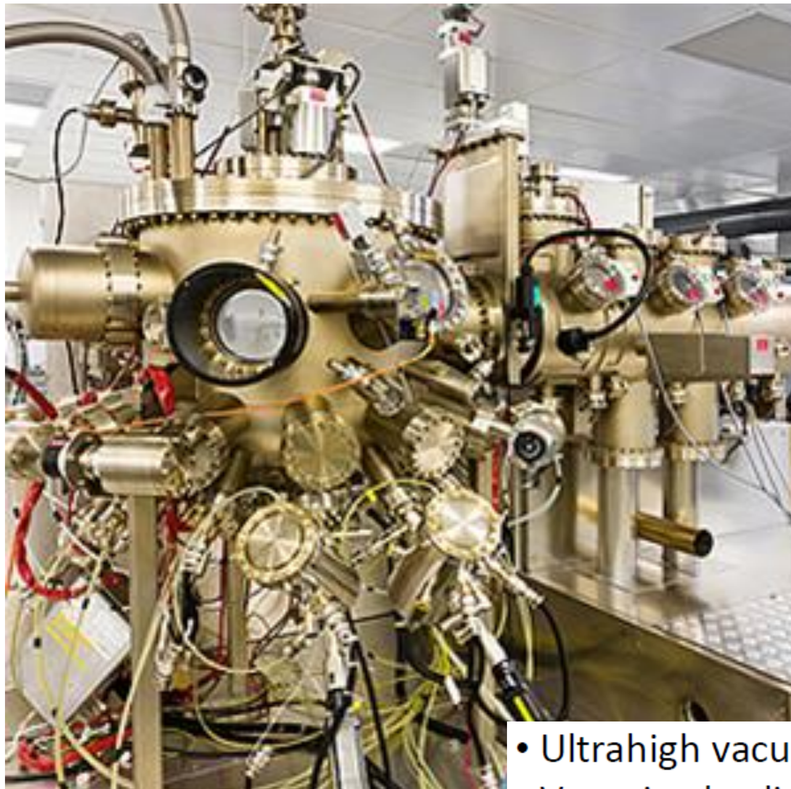
Lattice constant

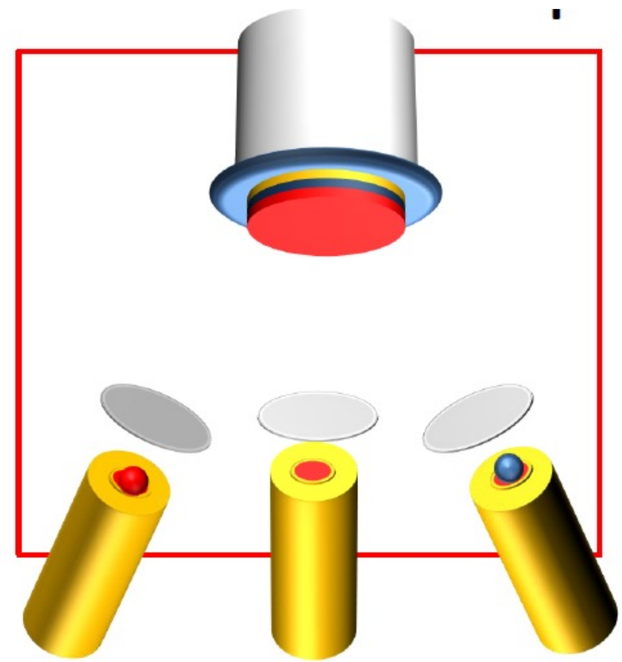
Alloys on InP

InGaAs
InAlAs
GaAsSb
AlAsSb
InGaAsP
InAlGaAs

Ultra high vacuum Molecular Beam Epitaxy (MBE)







- Ultrahigh vacuum conditions (base pressure ~10^{-10}mbar)
- Vaporised solid ultrapure elemental sources
    - Group III: In, Ga, Al
    - Group V: (N), P, As, Sb, Bi
    - Dopants: Si and Be
- Condense onto a heated, rotated substrate

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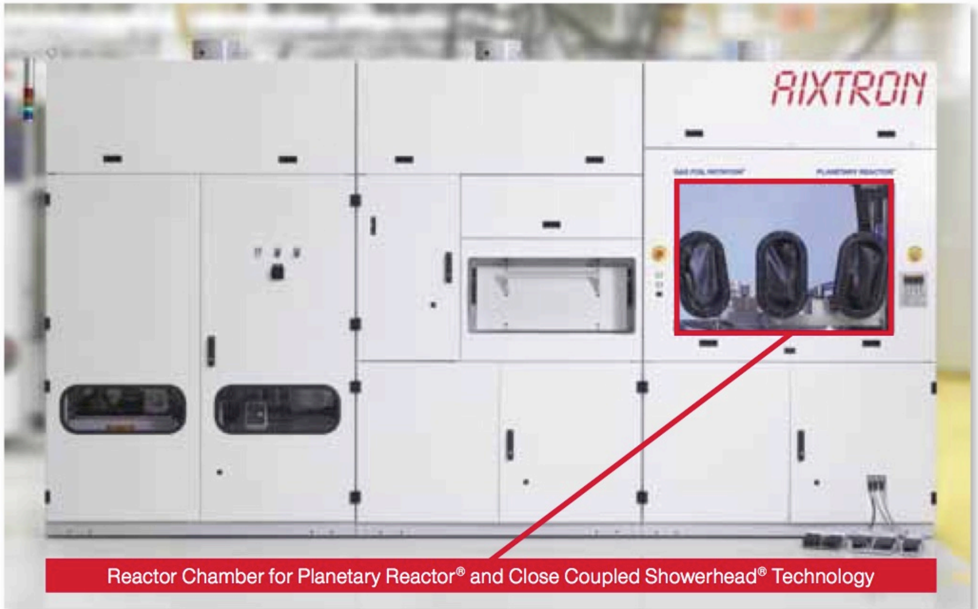
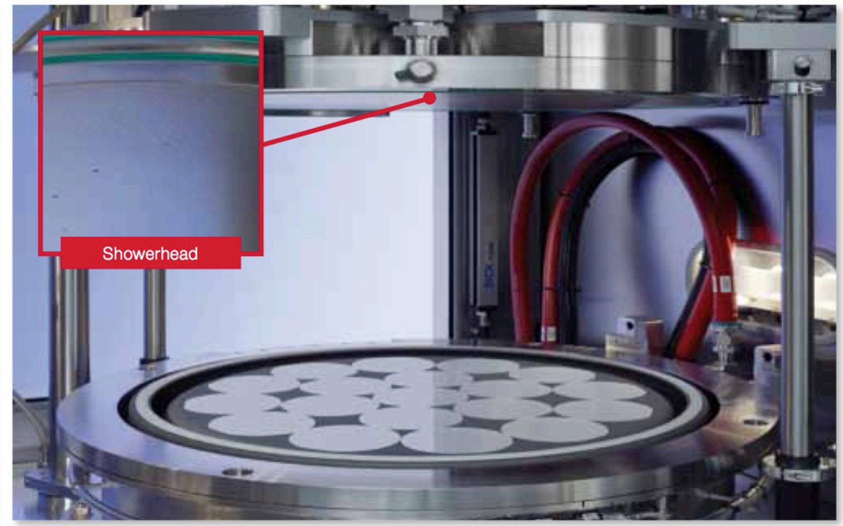
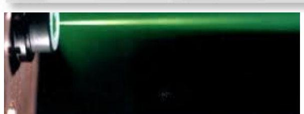
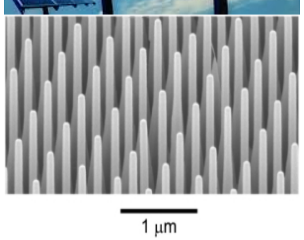
Metal Organic Vapour Epitaxy (MOVPE)









Selected chemicals are vaporised and transported into the reactor together with other gases.
Chemical reactions on a heated substrate produces the semiconductor crystals.

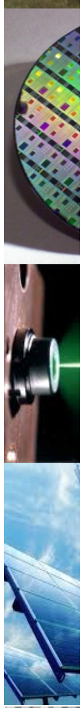
Table 1. Some physical properties of important semiconductor materials

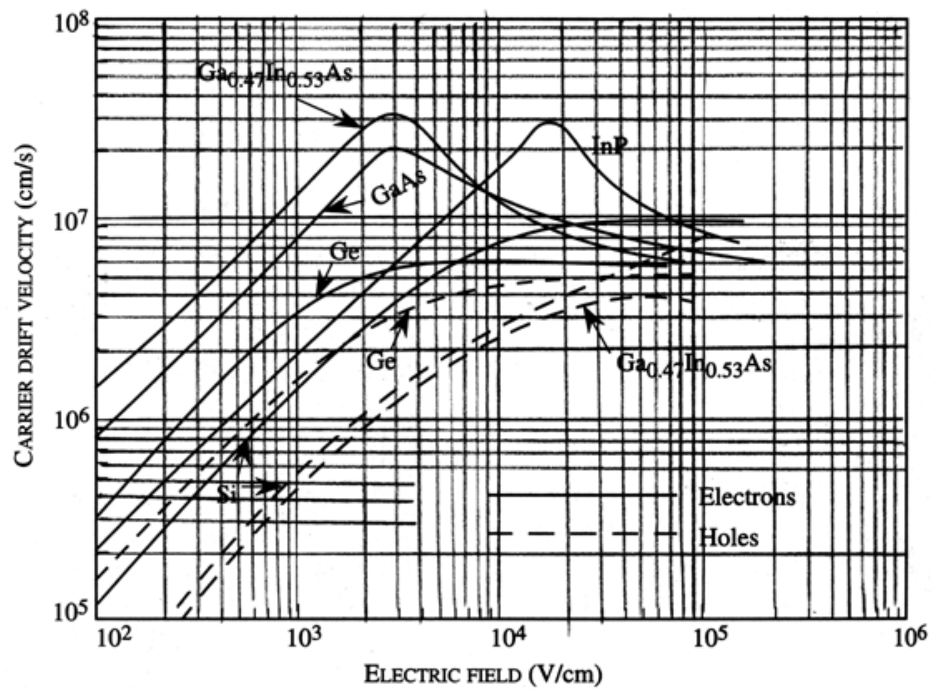
Type of material	*Material*	*Width of energy gap electron volts*		*Carrier mobility at 300°K (cm^2/volt-sec)*		*Crystal-structure type*	*Lattice constant (angstrom units)*	*Melting point (°c)*	*Vapor pressure at melting point (atmospheres)*
		At 300°K	*At 0°K*	*Electrons*	*Holes*				
Element	C (diamond)	5.47	5.51	1,800	1,600	Diamond	3.56679	4027	10^{-9}
	Ge	0.803	0.89	3,900	1,900	Diamond	5.65748	937	
	Si	1.12	1.16	1,500	600	Diamond	5.43086	1420	10^{-6}
	a-Sn		–0.08			Diamond	6.4892		
$A^{IV}B^{IV}$compound	a-SiC	3	3.1	400	50	Zinc blende	4.358	3100	
$A^{III}B^{V}$	AlSb	1.63	1.75	200	420	Zinc blende	6.1355	1050	<0.02
compound	BP	6				Zinc blende	4.538	>1300	>24
	GaN	3.5				Wurtzite	3.186 (*a*=axis)	>1700	>200
							5.176 (*c*=axis)		
	GaSb	0.67	0.80	4,000	1,400	Zinc blende	6.0955	706	$<4\times10^{-4}$
	GaAs	1.43	1.52	8,500	400	Zinc blende	5.6534	1239	1
	GaP	2.24	2.40	110	75	Zinc blende	5.4505	1467	35
	InSb	0.16	0.26	78,000	750	Zinc blende	6.4788	525	$<10^{-5}$
	InAs	0.33	0.46	33,000	460	Zinc blende	6.0585	943	0.33
	InP	1.29	1.34	4,600	150	Zinc blende	5.8688	1060	25
$A^{II}B^{VI}$	CdS	2.42	2.56	300	50	Wurtzite	4.16 (*a*=axis)	1750	
compound							6.756 (*c*=axis)		
	CdSe	1.7	1.85	800		Zinc blende	6.05	1258	
	ZnO	3.2		200		Cubic	4.58	1975	
	ZnS	3.6	3.7	165		Wurtzite	3.82 (*a*=axis)	1700	
							6.26 (*c*=axis)		
	PbS	0.41	0.34	600	700	Cubic	5.935	1103	
compound	PbTe	0.32	0.24	6,000	4,000	Cubic	6.460	917	

Carrier mobility

- Why is carrier mobility an important parameter?

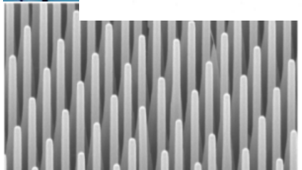
High mobility increases carrier drift velocity





$$\frac{1}{\rho} = \sigma = q(\mu_n n + \mu_p p)$$

High mobility increases conductivity (reduces resistivity)



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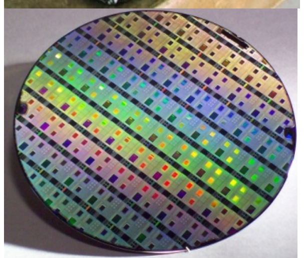
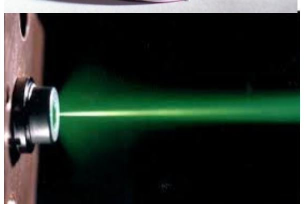
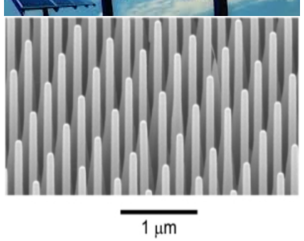
Speed of semiconductor devices



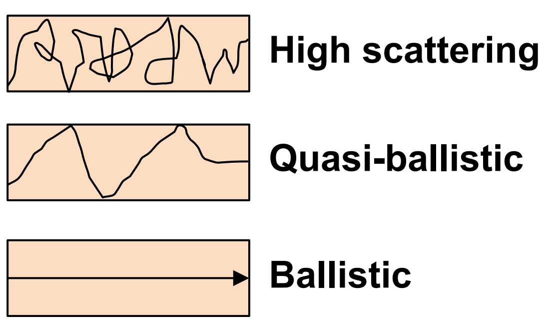




The speed of a semiconductor device fundamentally depends on the carrier transport. Carrier velocity and device size/geometry are the major factors

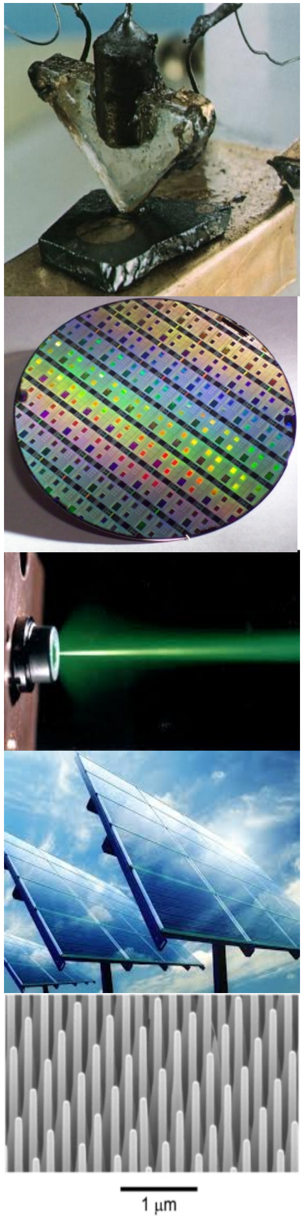
Carrier velocity $v = \mu E$ (*μ = mobility, E = electric field*) $\mu = \dfrac{e\tau}{m}$

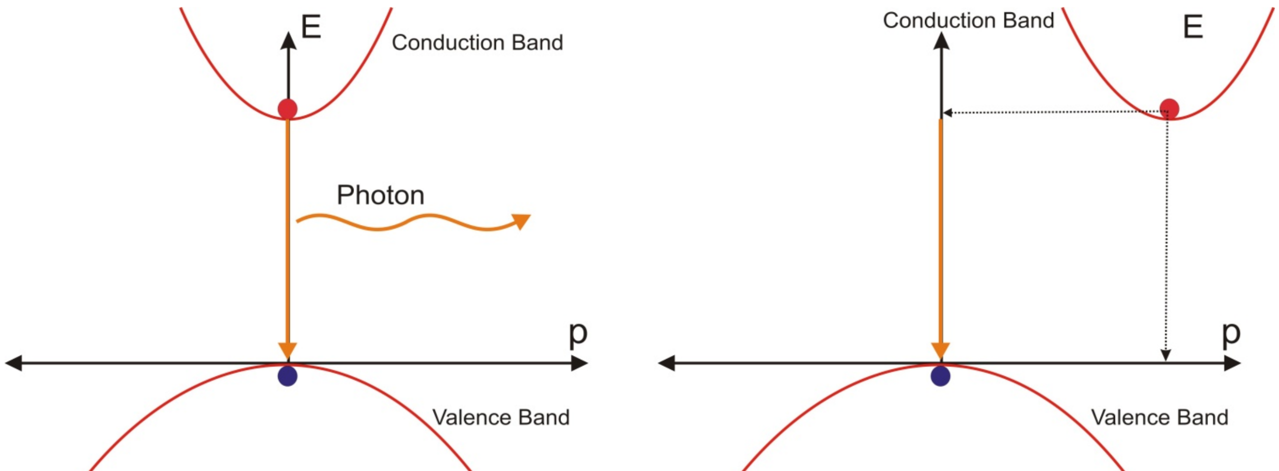
- μ is a material dependent parameter.
- *m can be for electrons or holes, which have very different mass and m-> m*, called the 'effective mass' which is material dependent*
- τ *= carrier lifetime between scattering events (due to imperfections in the semiconductor crystal)*



Materials from Si to graphene have been developed into high speed transistors.
Mobility of 15,000 $cm^2V^{-1}s^{-1}$ demonstrated in graphene (however the theoretical value is 200,000 $cm^2V^{-1}s^{-1}$)

Bandgap

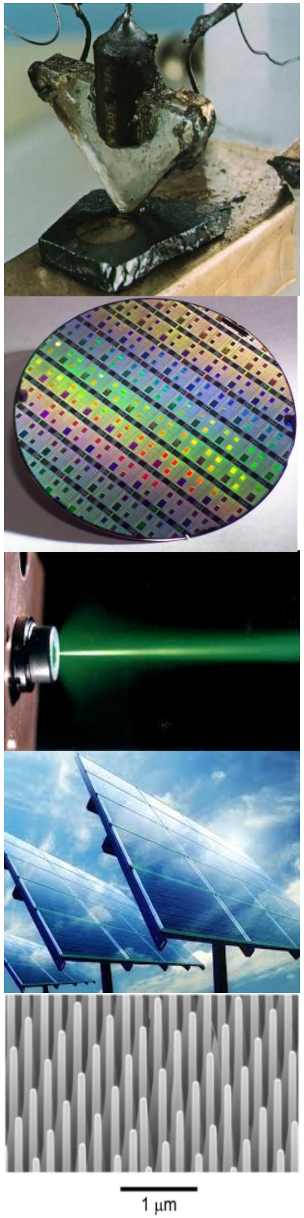




Direct band gap semiconductors (GaAs, InGaAs) are much more efficient light emitter than indirect band gap semiconductors (Si, Ge)

Band gap and recombination process determine the efficiency of optoelectronic devices.

Band gap also controls the carrier concentration (hence current) in electronic devices



How do we design and optimise electronic and optoelectronic devices?

We need the knowledge of band structure and properties of semiconductor.

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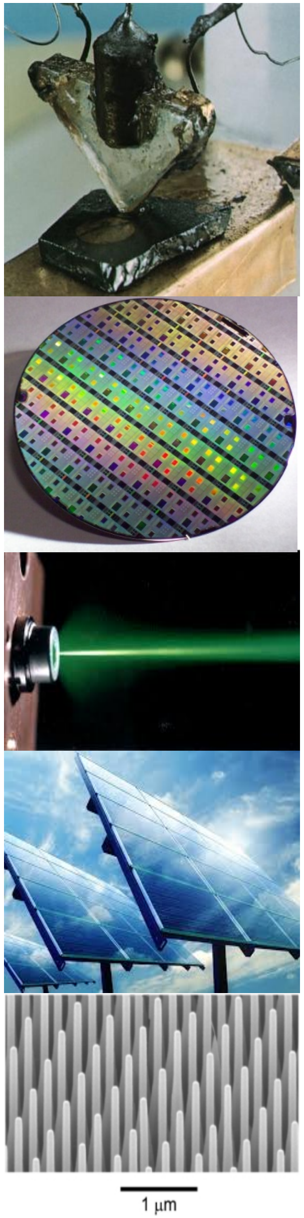
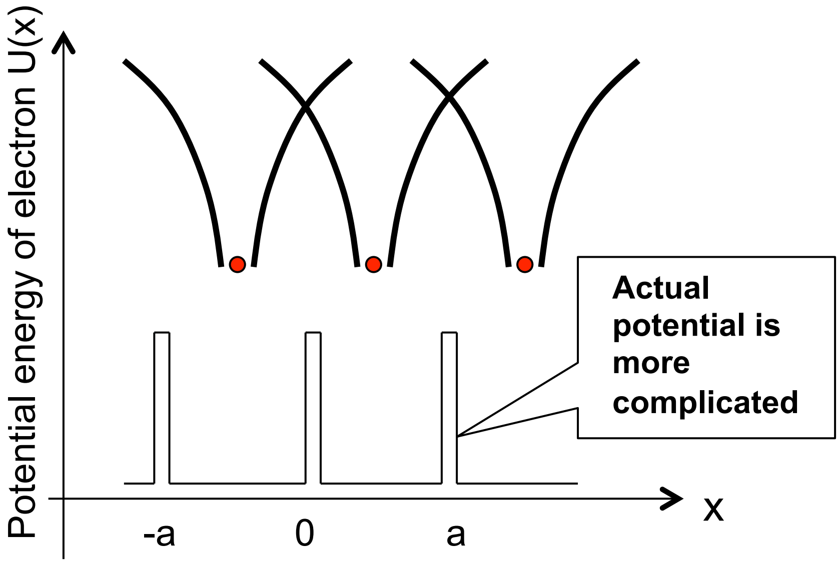
Band structure





To find the allowed energy states, in the crystal we need to treat electron as wave. The equation that produces solutions which are consistent with experiment is the time independent Schrodinger equation.

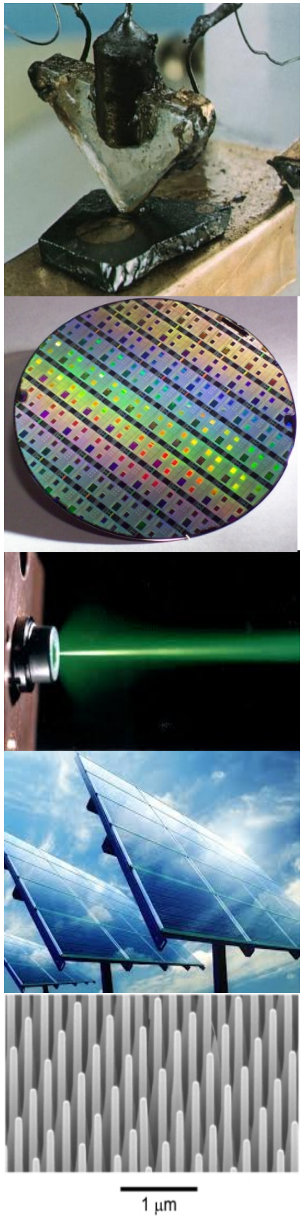
What is Schrodinger equation?

The total energy (E) is given by the sum of kinetic energy (K) and potential energy (U). So we have K+U =E. From this we can derive a wave equation as

$$(K+U)\Psi(x) = E\Psi(x)$$

$$\frac{\hbar^2}{2m}\frac{d^2\Psi(x)}{dx^2} + U(x)\Psi(x) = E\Psi(x)$$

Band structure

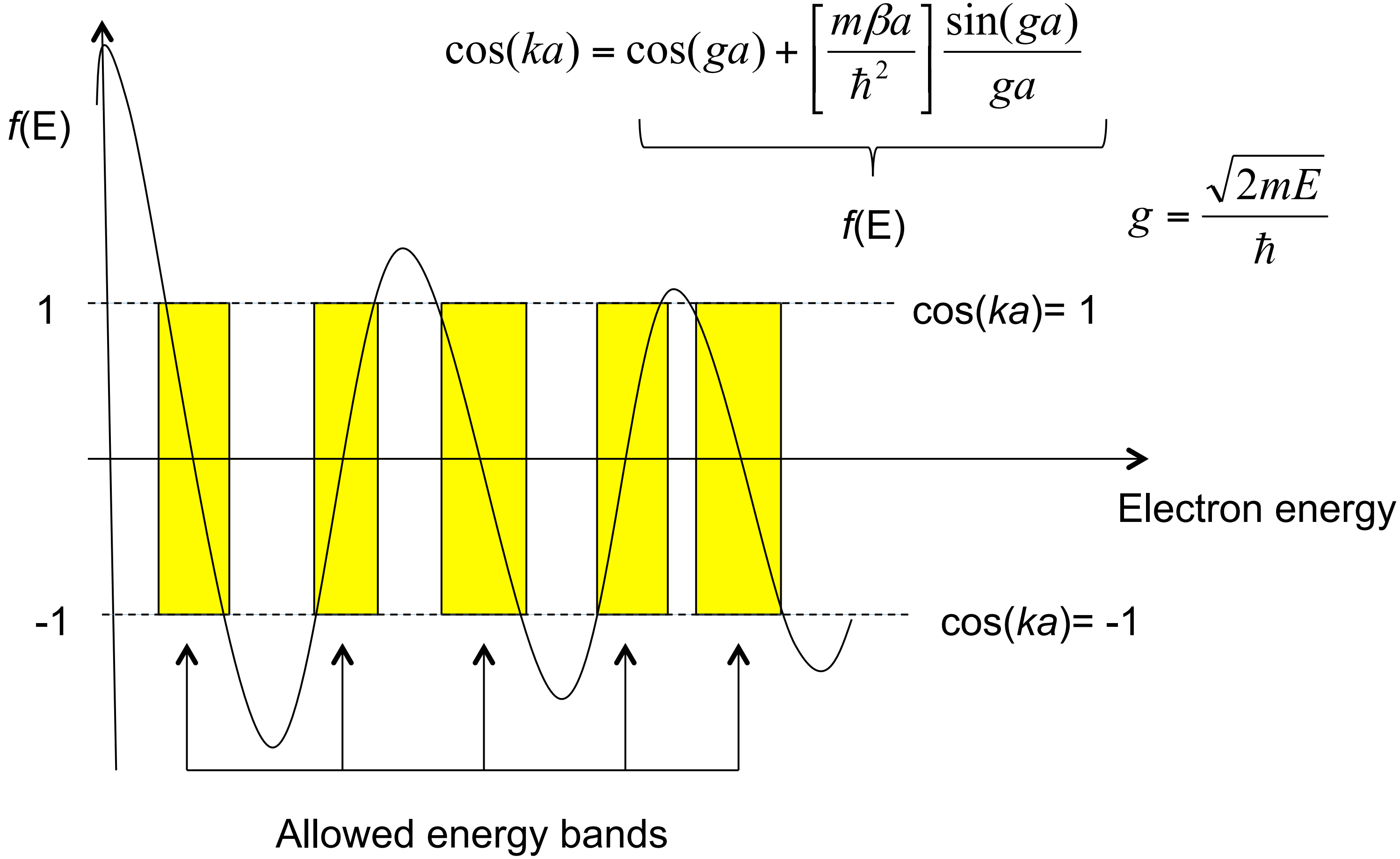


Consider a free electron with U(x) =0 gives $\frac{\hbar^2}{2m}\frac{d^2\Psi(x)}{dx^2} = E\Psi(x)$

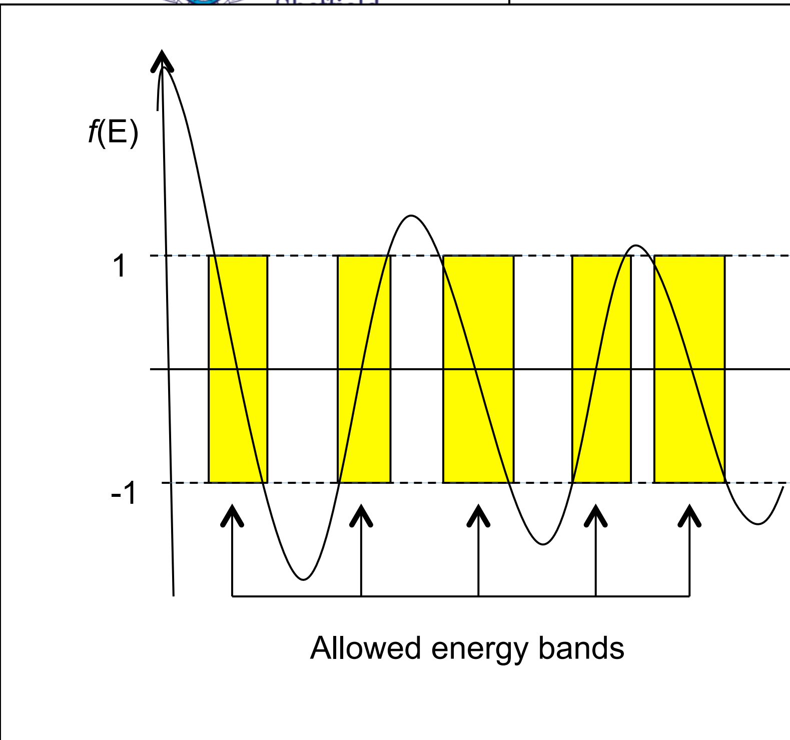
Solving this equation with appropriate boundary conditions produces

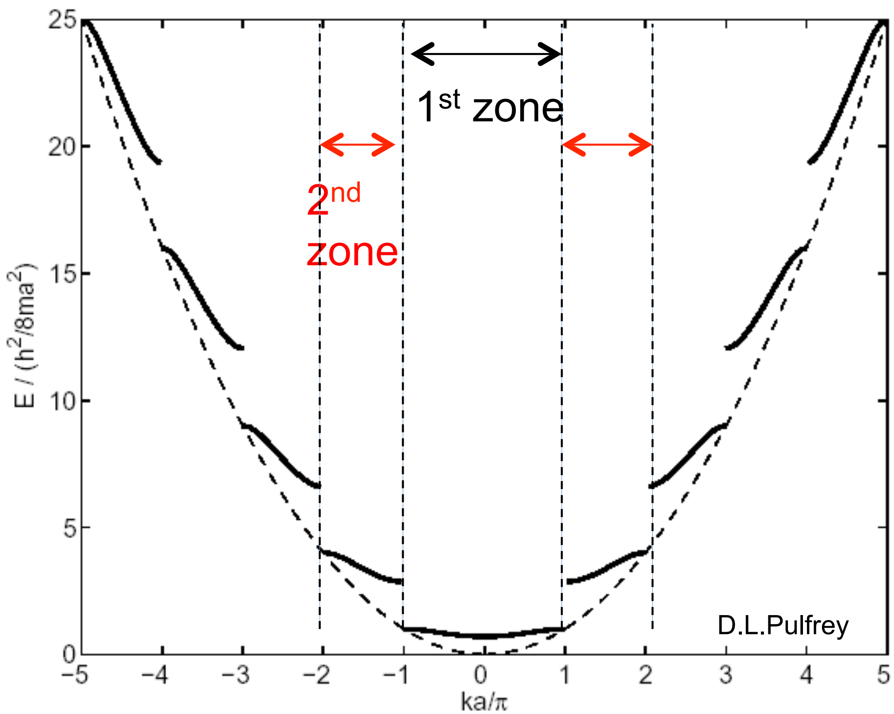
$$\underbrace{\cos(ka) = \cos(ga) + \left[\frac{m\beta a}{\hbar^2}\right]\frac{\sin(ga)}{ga}}_{f(E)}$$

$$g = \frac{\sqrt{2mE}}{\hbar}$$



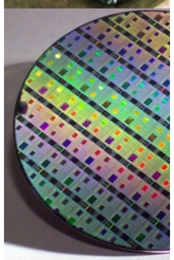
Band structure

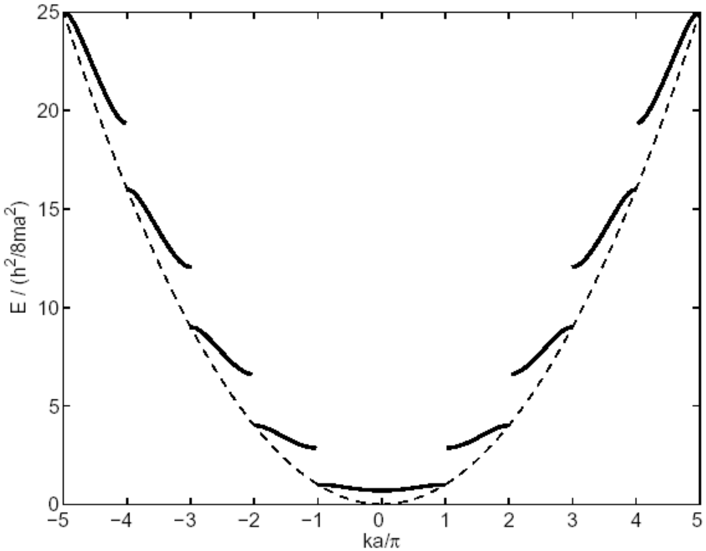




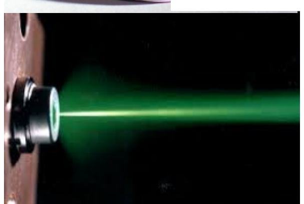
The allowed energy is usually plotted as a function of wavevector k in the extended-zone plot. This can be compressed into a reduced zone plot.

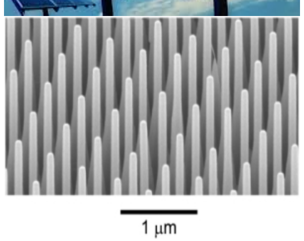
Band structure





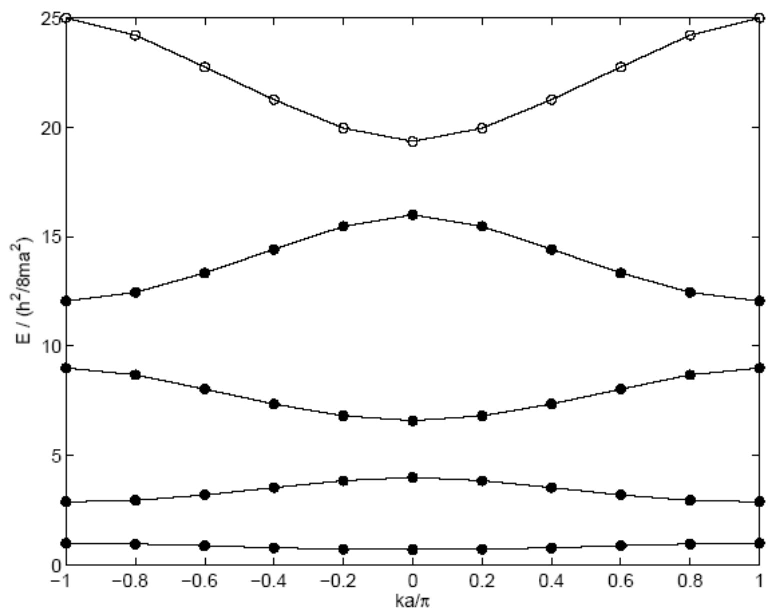
The extended zone is transformed to a reduced-zone called the Brilloun zone. Depending on the number of valence electrons present, the lower bands will be filled with electrons. In the case of Si the first 4 bands are filled with electrons. Hence the bandgap is the energy separation between the 4th and 5th bands.





Empty states

Filled with electrons



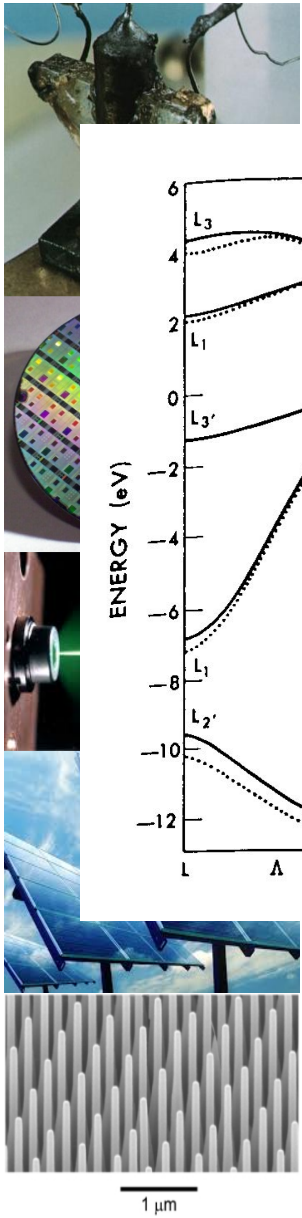
Conduction band

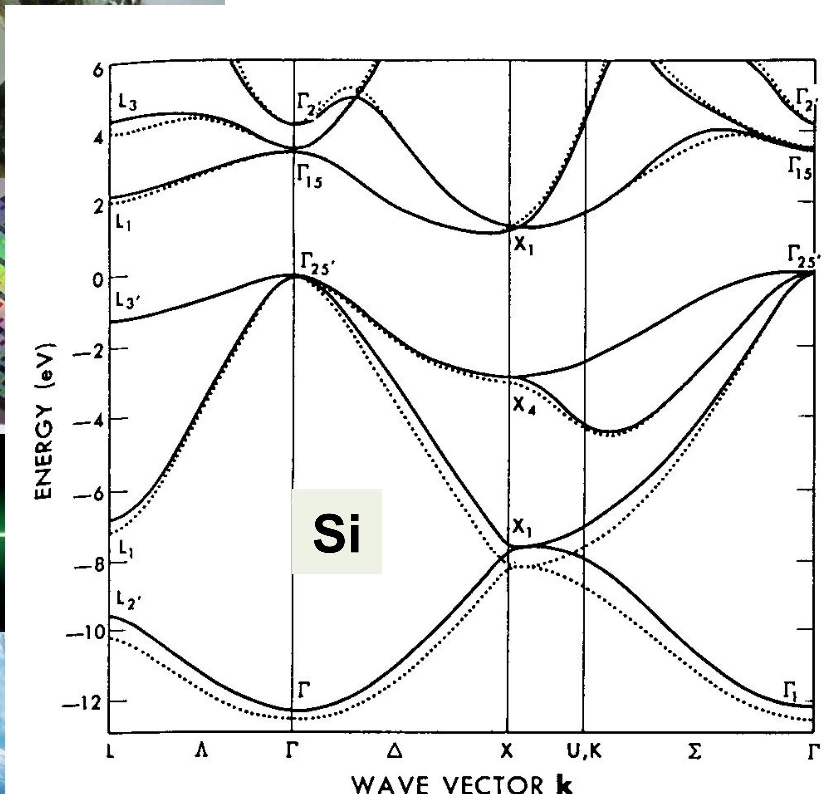
Valence band

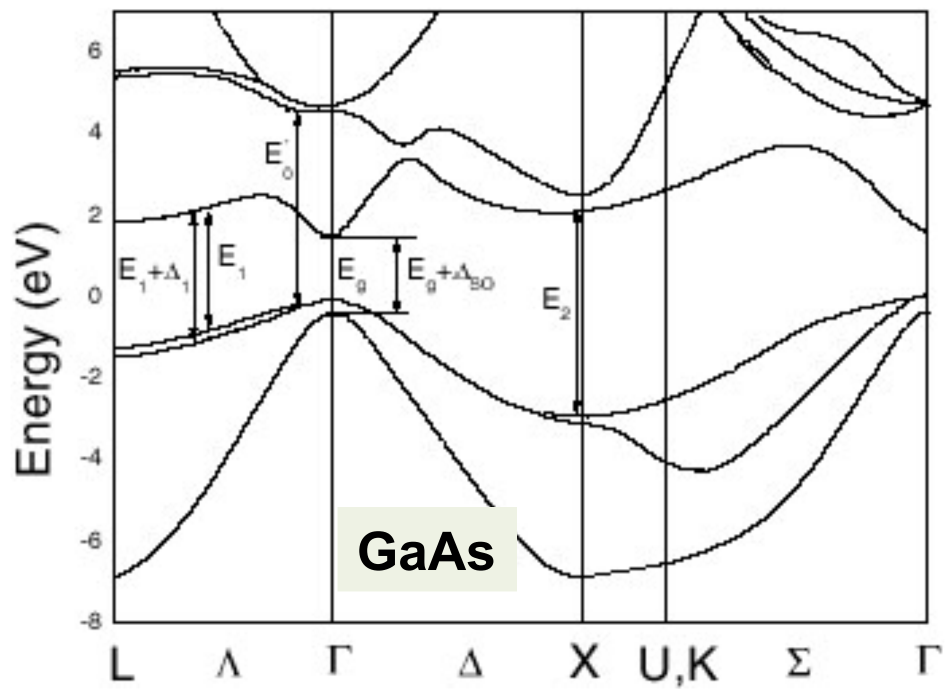
D.L.Pulfrey

C H Tan

Band structure

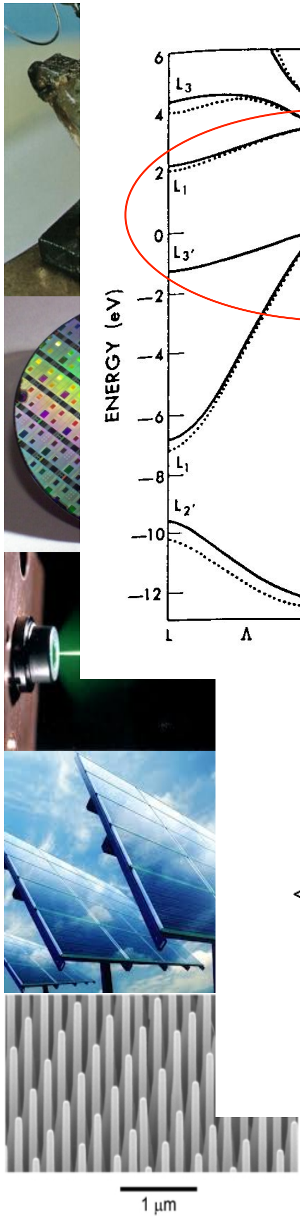


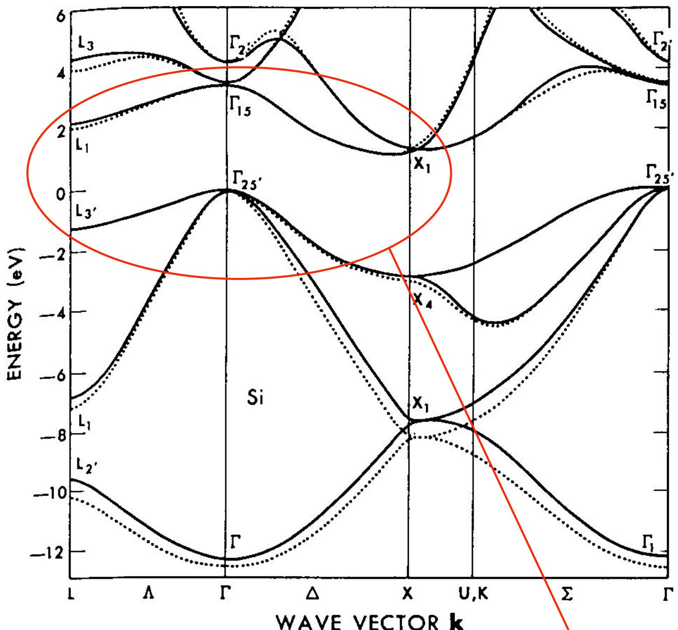


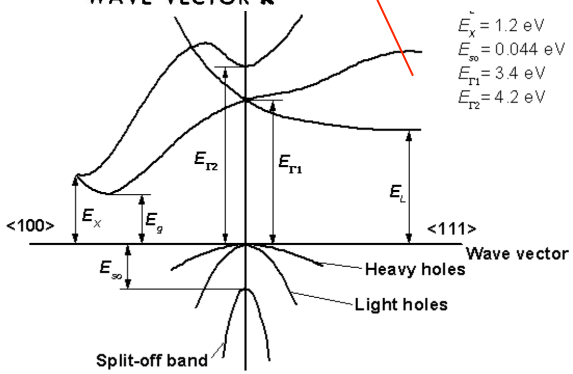


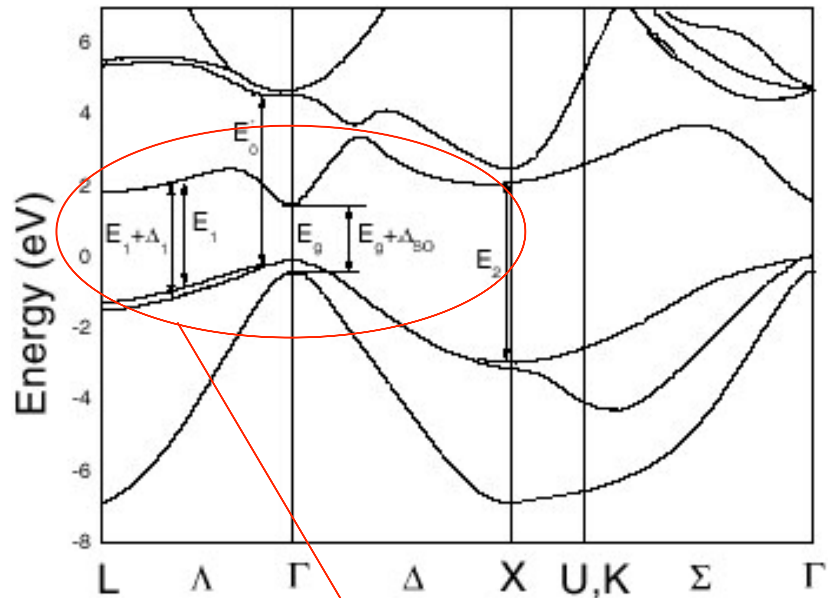
The valence bands are relatively similar they are related to the similar bonding coordination of diamond and zinc blende. The conduction bands are more different as the electrons are “freer” than the valence electrons.

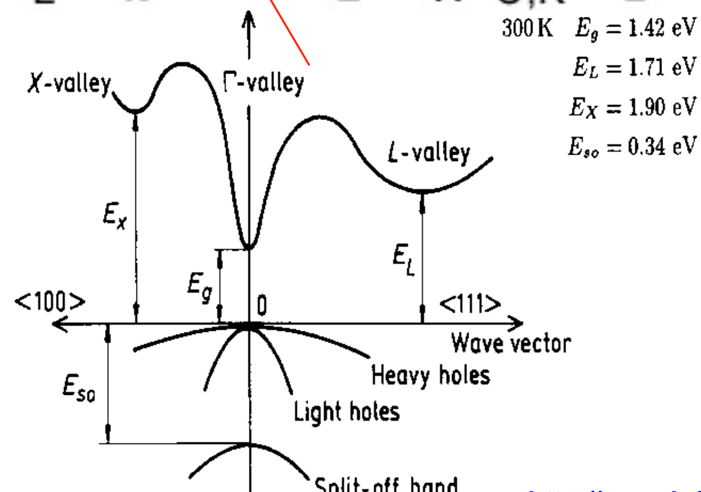
Band structure







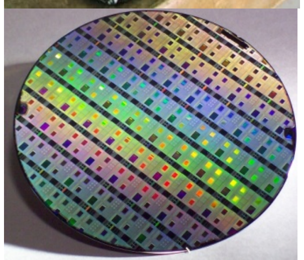
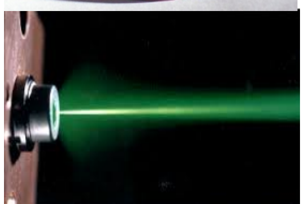


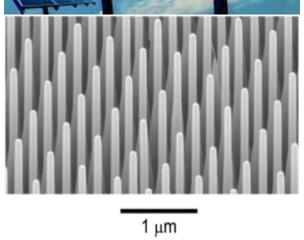


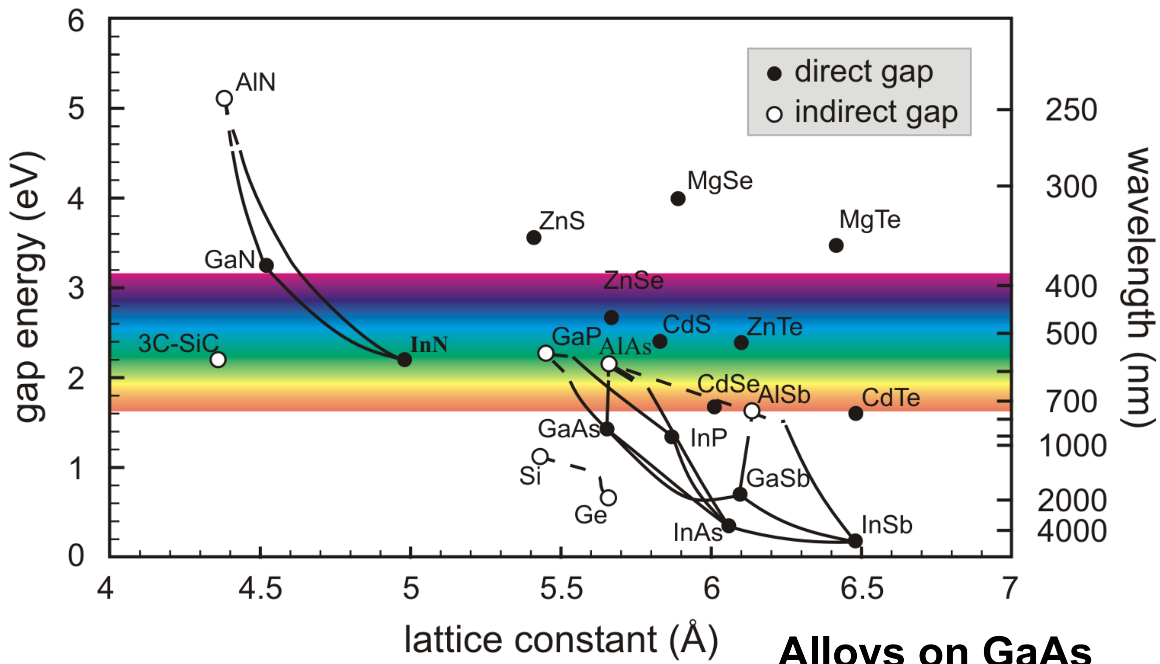
http://www.ioffe.ru/SVA/NSM/

These look very different to the two band schematic earlier

Semiconductor Alloys





Widely available substrates

IV	III-V	II-VI
Si	GaAs	CdTe
Ge	InP	CdSe
SiC	InSb	ZnSe
	GaSb	ZnTe
	InAs	

Alloys on GaAs

AlGaAs
InGaP
AlInP

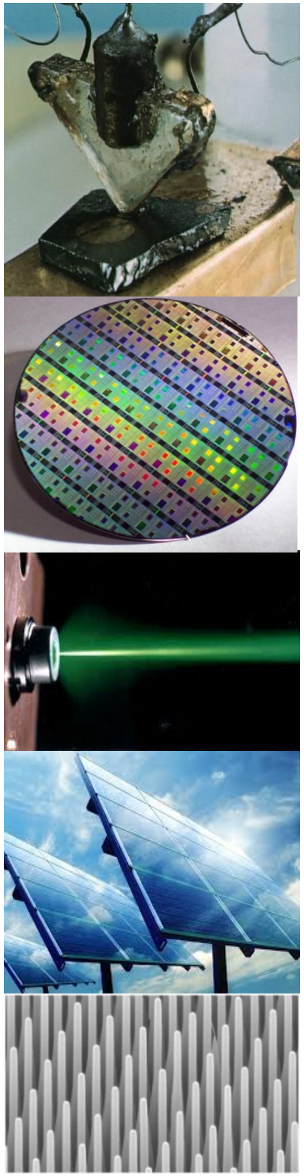
Alloys on InP

InGaAs
InAlAs
GaAsSb
AlAsSb
InGaAsP
InAlGaAs

Lattice matched semiconductors form heterostructures that can be used in many electronic devices

The University Of Sheffield.

Semiconductor alloys



1 µm

To a first order approximation the alloy properties can be determined from the properties of the two materials (semiconductor *A* and *B*) combined.

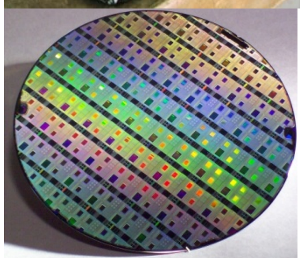
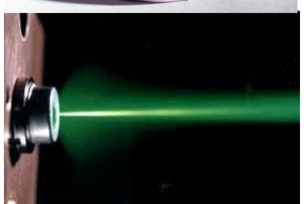
$$E_{alloy}(k) = xE_A(k) + (1-x)E_B(k)$$ Band structure

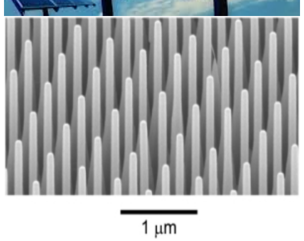
$$a_{alloy} = xa_A + (1-x)a_B$$ Lattice constant

$$\frac{1}{m^*_{alloy}} = \frac{x}{m^*_A} + \frac{(1-x)}{m^*_B}$$ Effective mass

Band gap, mobility, resistivity, breakdown voltage, emission (and detection) wavelength, mechanical hardness and thermal conductivity are some of the properties that can be optimised by carefully selecting the semiconductor used.

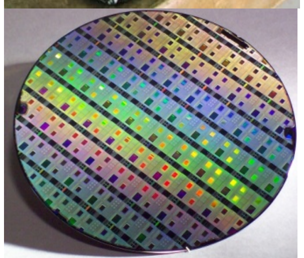
Semiconductor properties

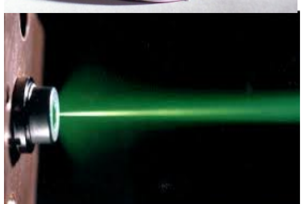




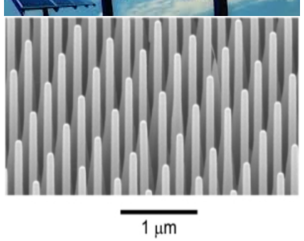


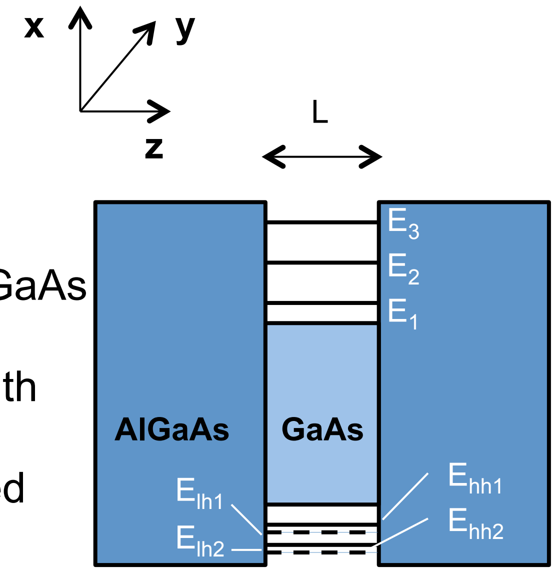
In addition to this **BULK** semiconductors, many properties can be modified using heterostructures and nanotechnology (quantum well, quantum dot, nanowire).

Quantum wells





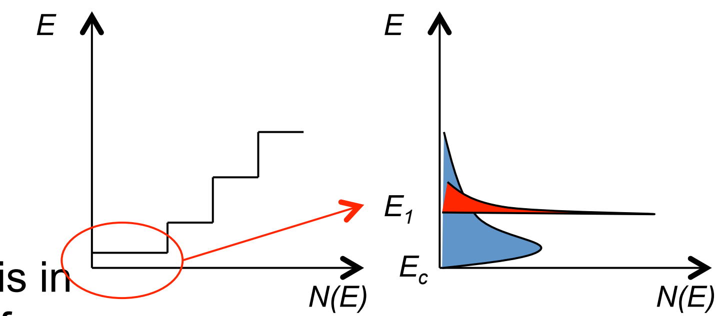




Why is quantum well useful?

- The quantum well is formed when the width of GaAs layer is reduced to 10-20 nm.
- Width is comparable to the de Broglie wavelength $\lambda_{Broglie}=h/p$.
- Assuming an infinite barrier height, the quantised energy level is constant and is given by

$$E_n = \frac{1}{2m^*}\left(\frac{\pi\hbar n}{L}\right)^2$$

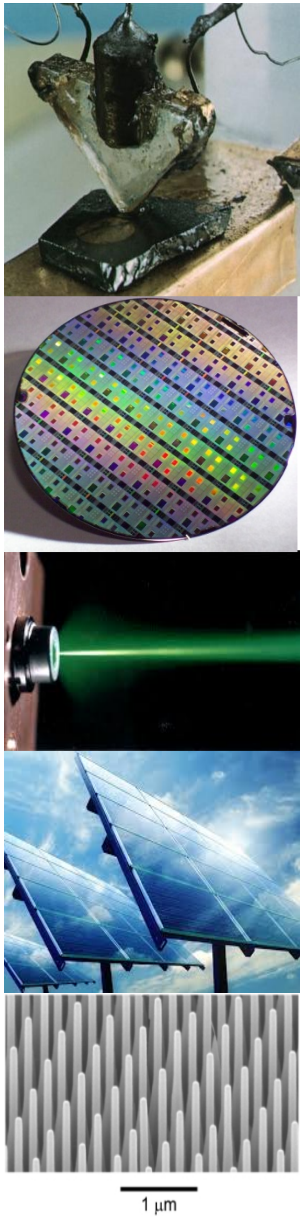


In each sub-band (E_1,E_2, E_3) the electron is in a 2-D world. Because of this the density of states also have a 2-D behaviour.

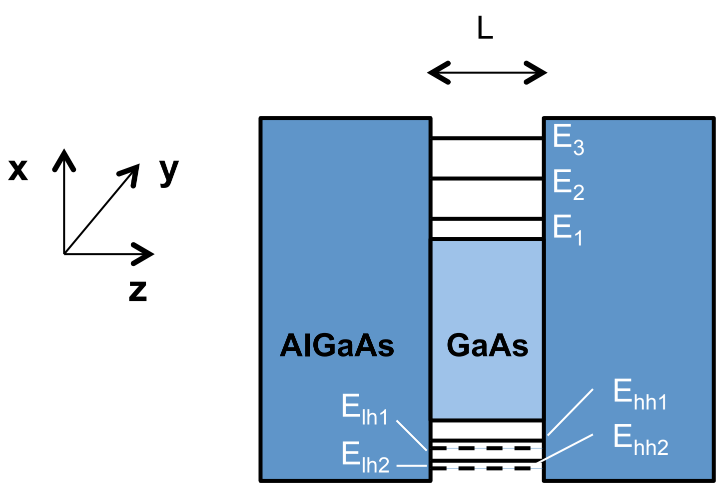
The parabolic form of conduction band density of states has been replaced by "staircase" form

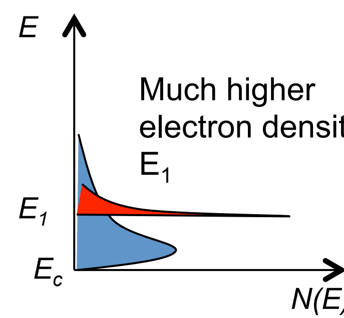
$$N(E)dE = \frac{4\pi m^*}{h^2}\sum_i H(E - E_i)dE$$

Quantum well LED

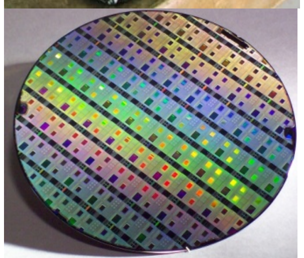
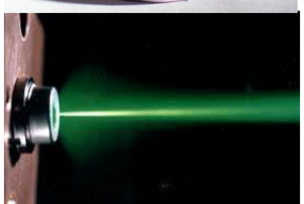


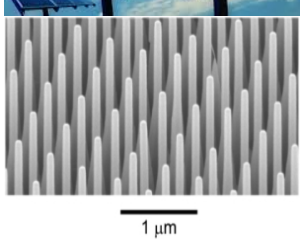
There is a group of electrons at E_1 and a group of holes at E_{hh1} available to initiate radiative recombination. Population in version is much easier to achieve in quantum well due to the higher density of states at E_1. Improvements offered by quantum well LEDs over DH LEDs include much **lower threshold current, high output power and high speed**.



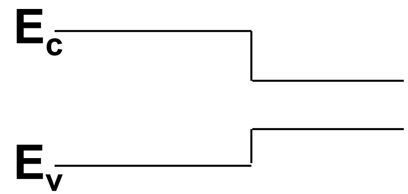


Quantum wells

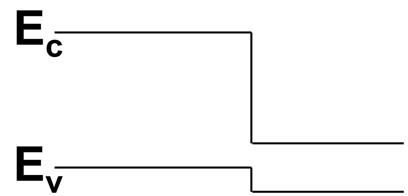






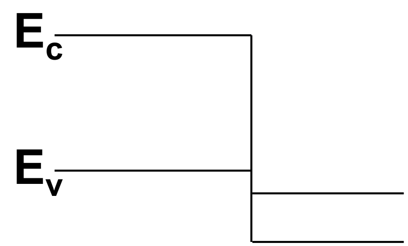
Type I heterojunction

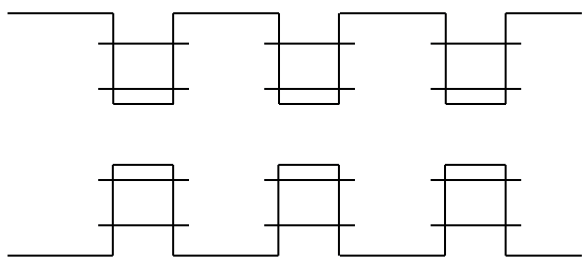


Type II heterojunction

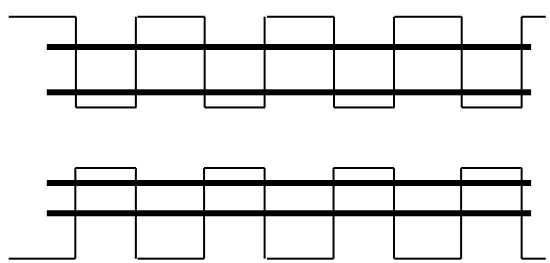


Type III heterojunction





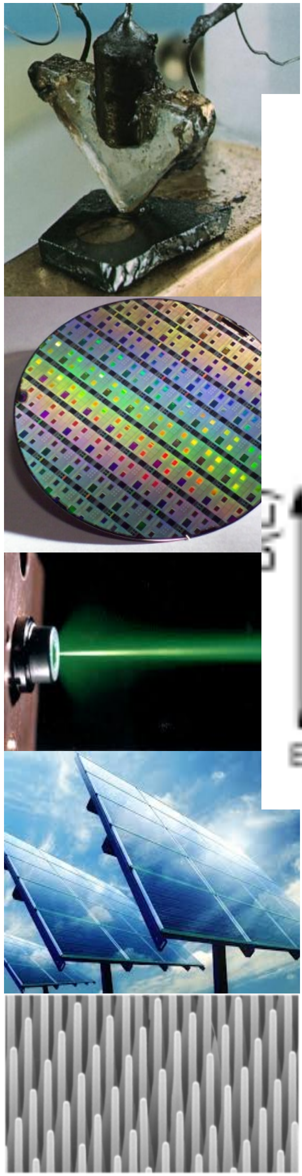
Quantum well

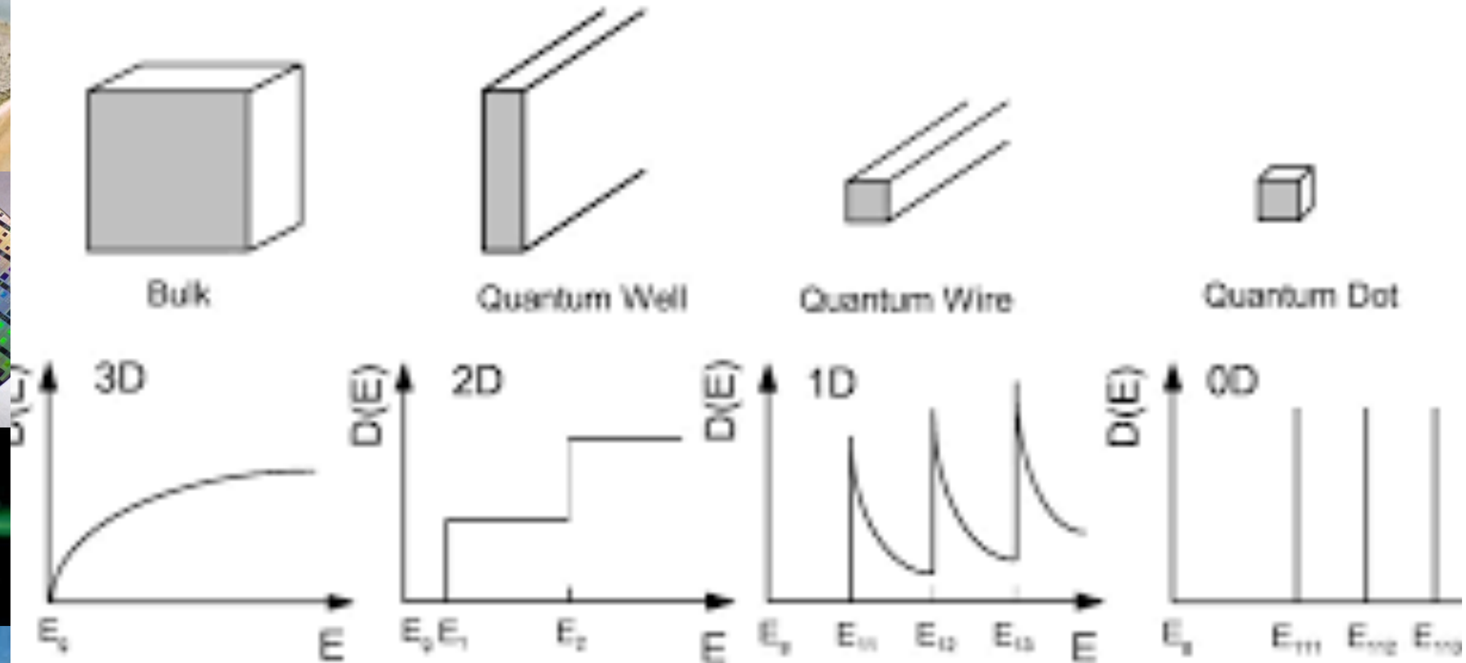


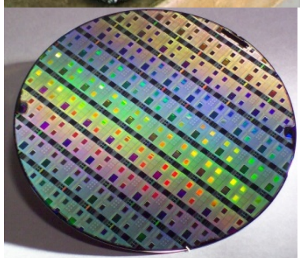
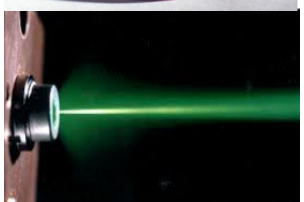
Superlattice

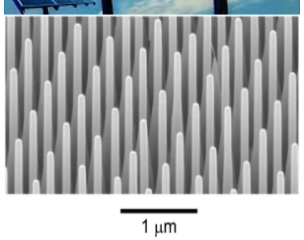
C H Tan

Density of states modification


1 µm





Carrier concentration

C H Tan

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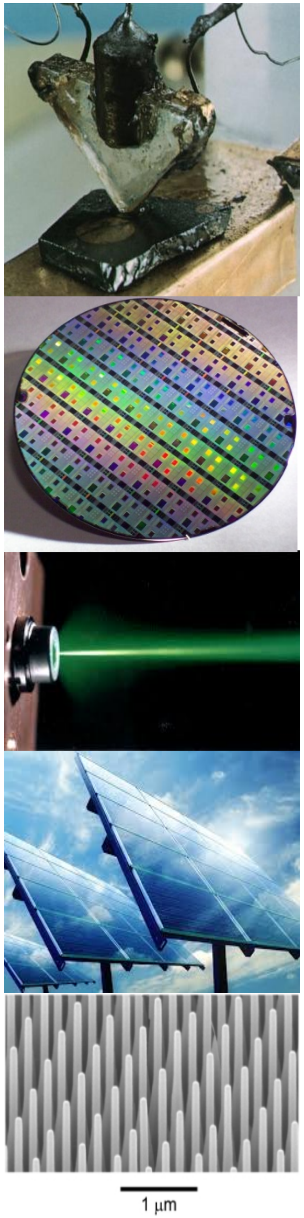
What make semiconductor conducts?



At equilibrium (i.e no external excitations such as light, pressure or electric field), the electron concentration in the conduction band is

$$n = \int_0^{E_{top}} N(E)\,f(E)\,dE \qquad N(E) = 4\pi\left(\frac{2m}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}}$$

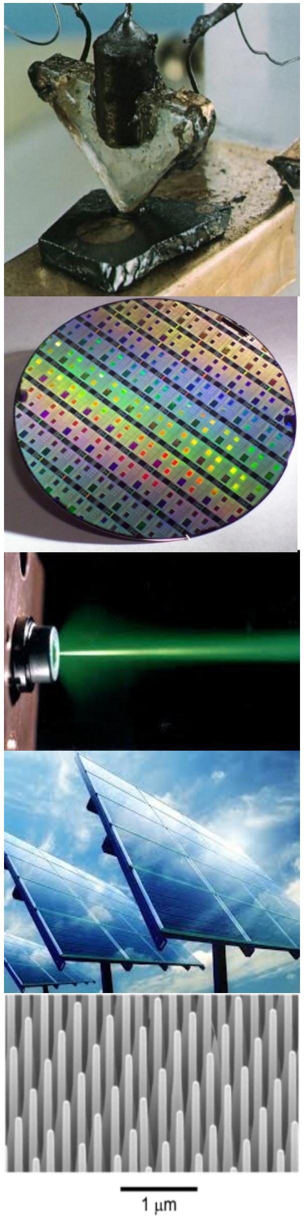
N(*E*)* is the density of states (i.e, the density of allowed energy states per energy range per volume and *F*(*E*) is the Fermi-Dirac distribution given by

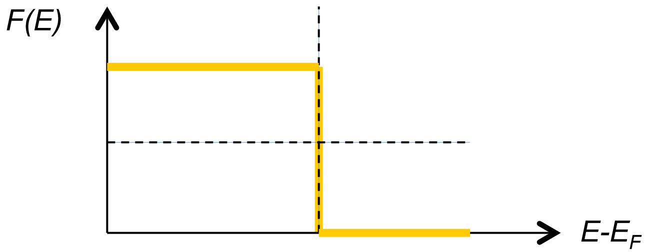
http://jas.eng.buffalo.edu/education/semicon/fermi/functionAndStates/functionAndStates.html

$$f(E) = \frac{1}{1+\exp\left(\dfrac{E-E_F}{kT}\right)}$$

E_F is the Fermi level corresponding to the probability of electron occupancy of 0.5.

Carrier concentration





$$f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

It can be shown (p.31-32, Sze and Lee) that the electron density (for non-degenerate semiconductors) is given by

$$n = N_C \exp\left[-\left(\frac{E_C - E_F}{kT}\right)\right]$$

Hole density is given by

$$p = N_V \exp\left[-\left(\frac{E_F - E_V}{kT}\right)\right]$$

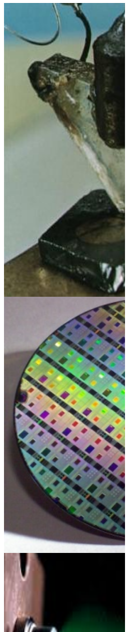
$$n_i = \sqrt{np} = \sqrt{N_C N_V} \exp\left(-\frac{E_g}{2kT}\right)$$

$$E_g = E_C - E_V$$

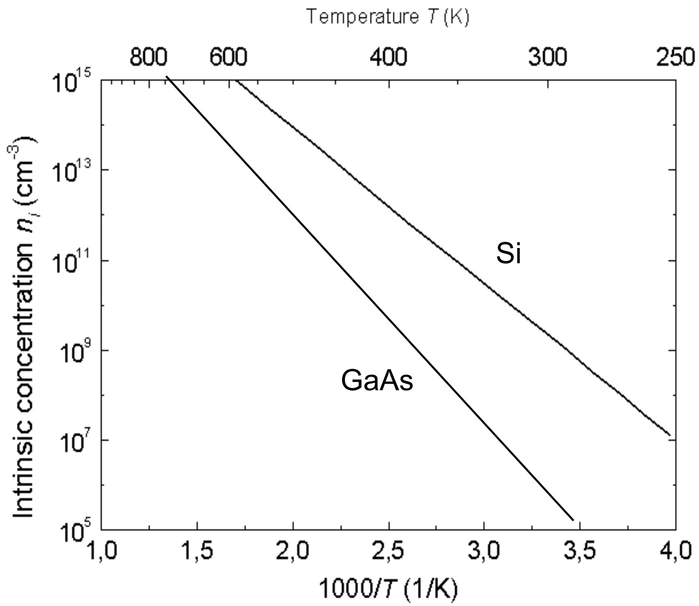
n_i determines the leakage current flowing in a photodiode and transistor and the short circuit current in solar cell.

Increasing the carrier concentration

http://jas.eng.buffalo.edu/education/semicon/fermi/bandAndLevel/fermi.html



1 µm



Factors influencing the carrier concentration

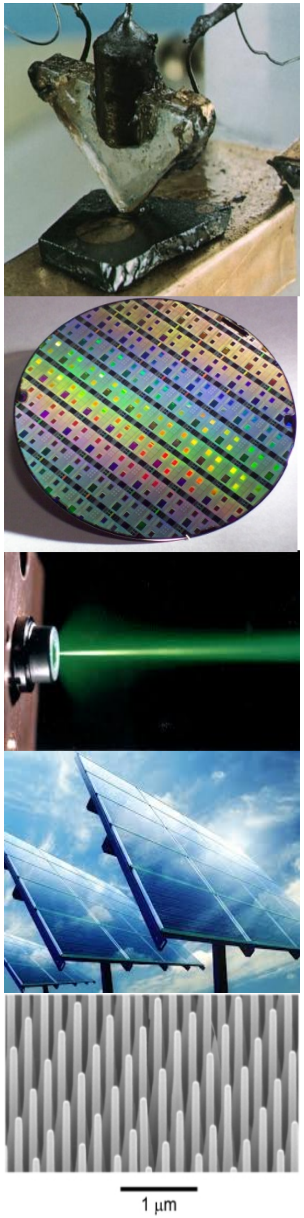
- **Temperature**
- **Chemical**
- **Optical**
- **Electrical**

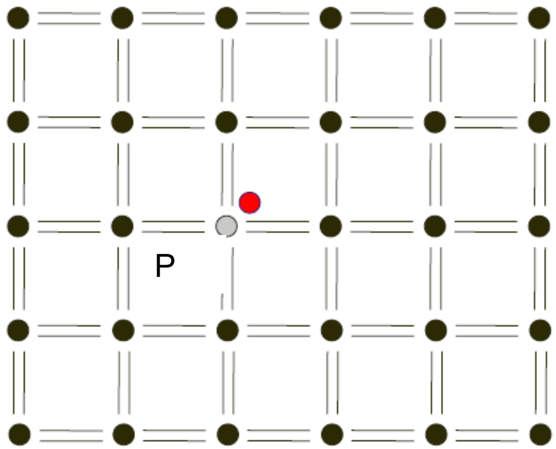
$$n_i = \sqrt{N_C N_V}\exp\left(-\frac{E_g}{2kT}\right)$$

The intrinsic carrier concentration is $n_i = 9.65\times10^{9}$ cm^{-3} (Si) but in metals the electron concentration is ~10^{22} cm^{-3}.

It can be seen that even at high temperature the number of electrons remains significantly lower than in metals, hence Si remains as a semiconductor (hence we can manipulate the current flow to make electronic devices).

Chemical generation (Doping)



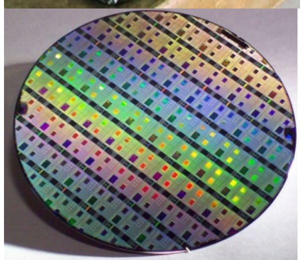


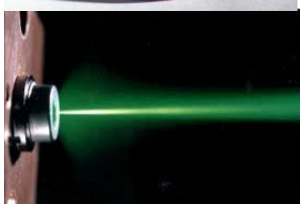
- Boron and Phosporus are important in Si
- Low ionization energy ~ 45meV and similar atomic mass to Si
- Incorporated without too much disruption to the Si crystal.

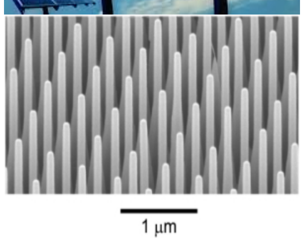
Hence at room temperature there is a high proportional of ionised carriers.

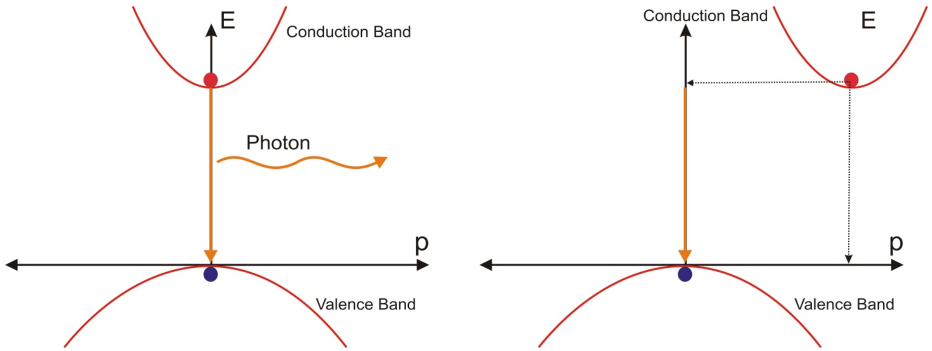
The dopant atoms are usually incorporated during epitaxial growth, ion implantation or high temperature diffusion.

Photon (optical generation)

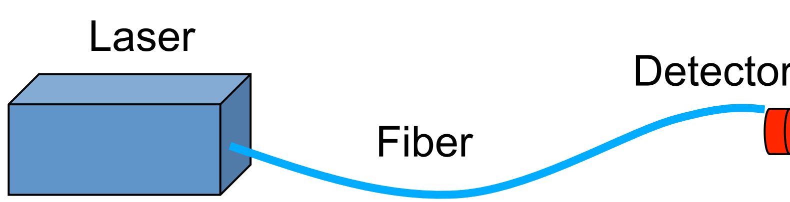








- Conservation of energy and momentum is necessary.
- Indirect semiconductors, the absorption of an optical photon also involves phonons to satisfy the momentum conservation.
- A direct band gap semiconductor has a higher optical absorption coefficient (i,e requires a thinner layer to convert all the incident light into electron-hole pairs).



Optically powered circuit

http://www.jdsu.com/en-us/power-over-fiber/Products/Pages/photonic-power-discover-how-it-works.aspx

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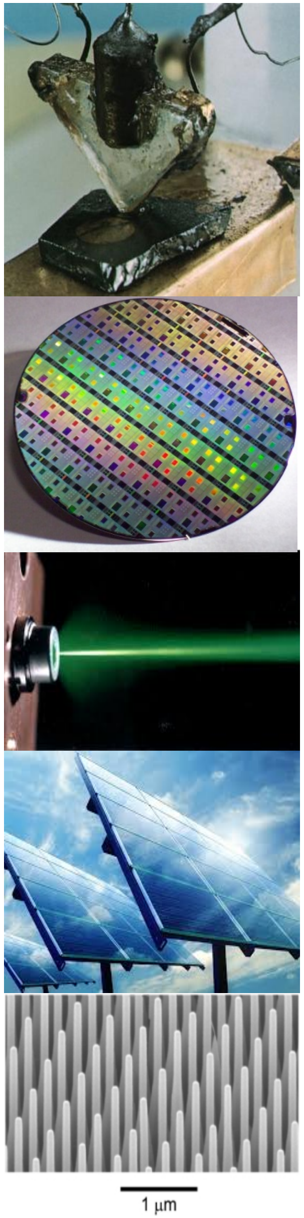
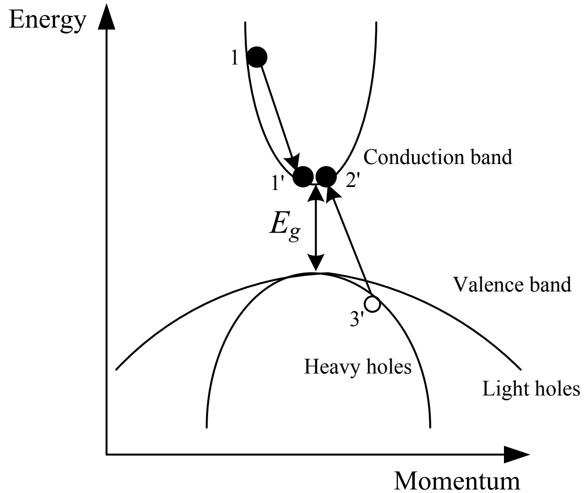
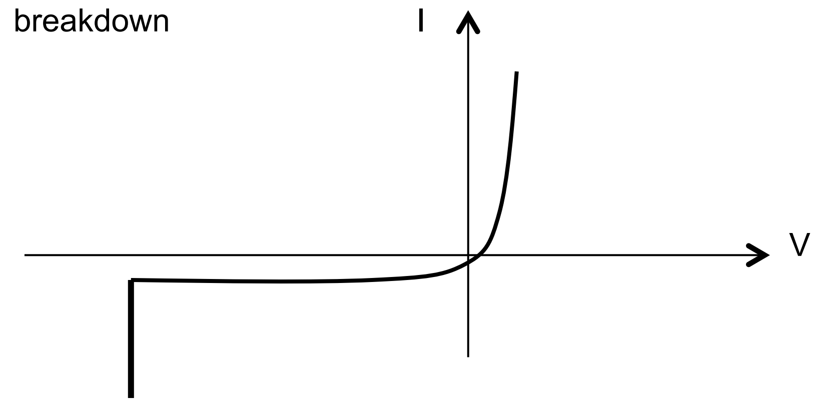
Electrical generation

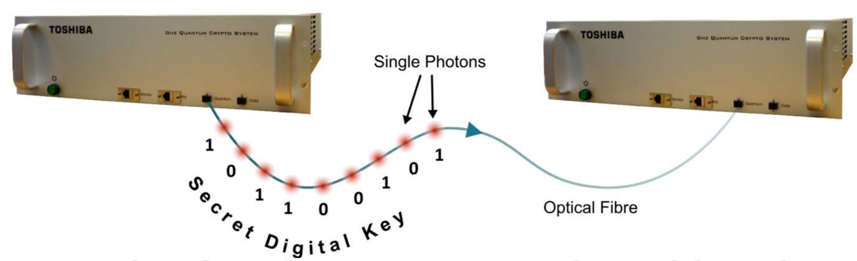






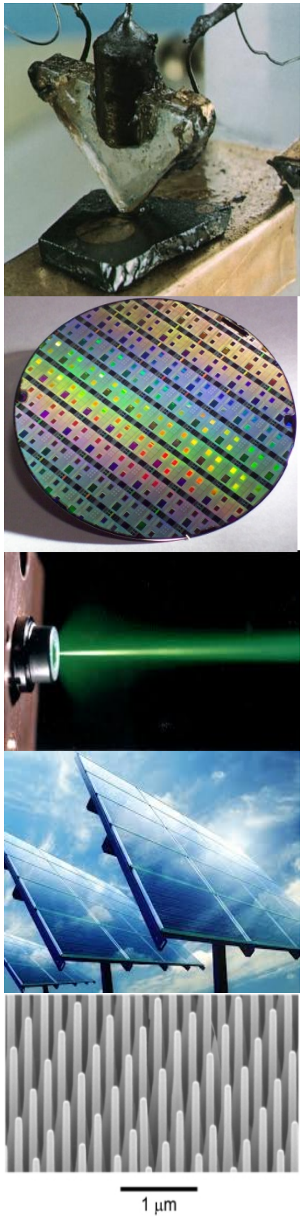
Extremely high security data transmission using single photon

Secret Digital Key Exchange Using Quantum Key Distribution



- This impact ionization process is utilized to provide internal gain in avalanche photodiodes that are routinely used in optical fiber network and quantum key distribution .

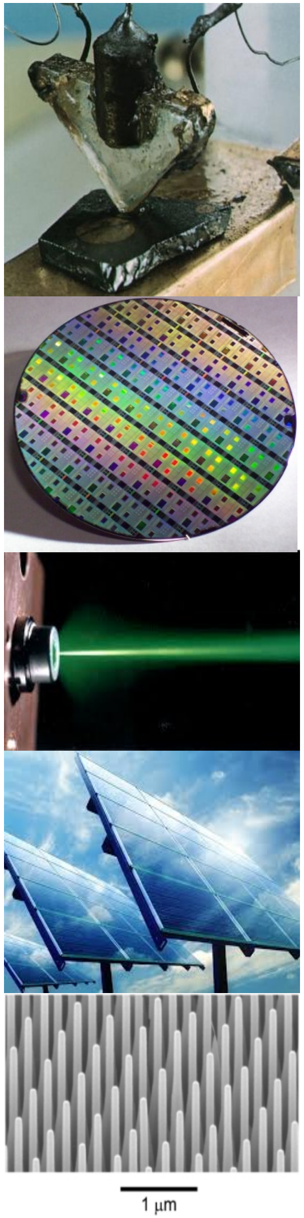
The University Of Sheffield.



Recombination

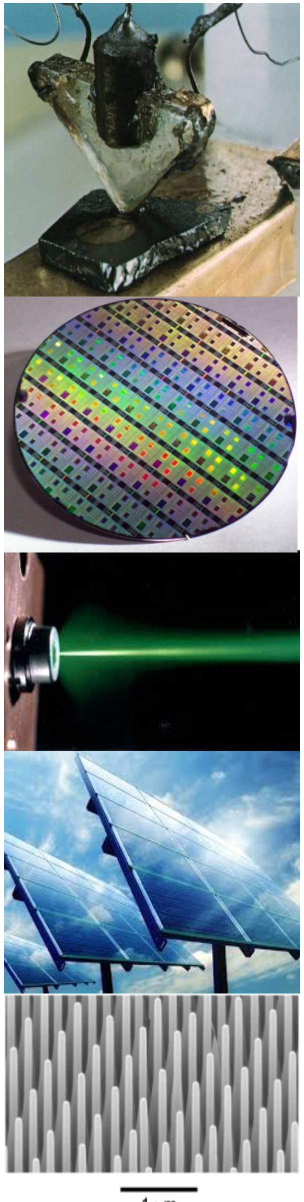
C H Tan

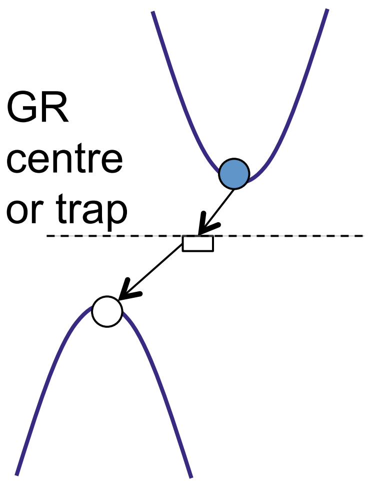
Recombination



- Generation-recombination centre recombination
- Band to band (radiative) recombination
- Auger recombination
- Surface recombination

Generation-recombination (GR) centre

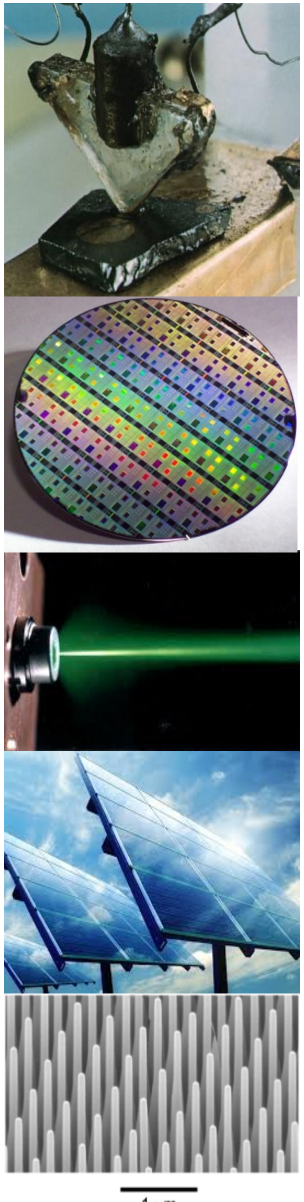




- Semiconductor crystals are not perfect.
- Missing atoms, faults in atom stacking and presence of impurity atom.
- These defects introduce energy levels in the energy gap.
- Distributed across the bandgap, allowing recombination process to take place “step by step”.

The so called mid gap trap is most effective recombination centre as it can capture both hole and electron. The GR centre recombination is also sometimes known as **Shockley-Read-Hall (SRH)** recombination.

Generation-recombination (GR) centre

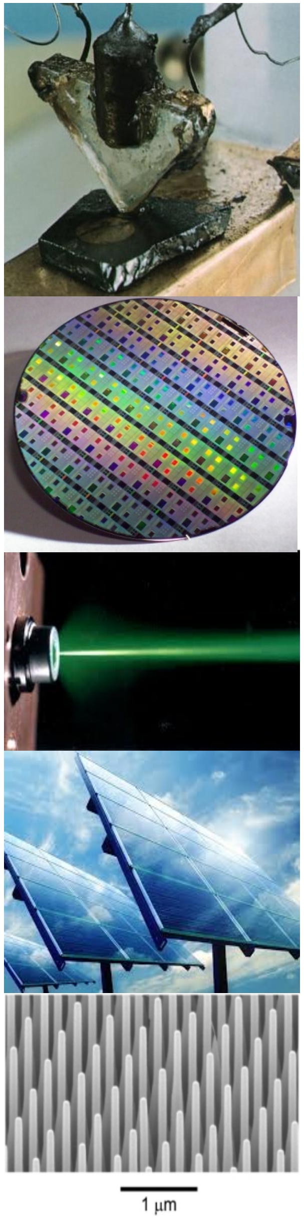


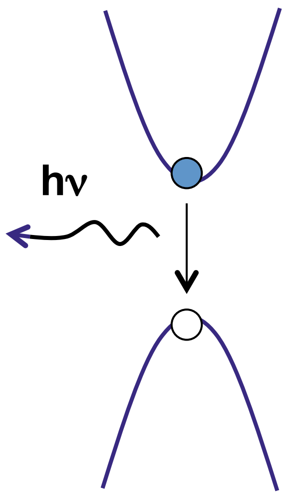
- We note that the recombination process depends on electron, hole and trap density.
- However the main rate limiting factor is the capture of the minority carrier in the material.
- For instance in a p-type material,

$$R_{GR} = rN_T n = An$$

r is a temperature dependent constant, N_T is the trap density and *A* is the trap-dependent recombination coefficient with a unit of s^{-1}.

Radiative recombination





The energy lost when an electron in CB recombines with a hole in VB is converted to a photon.

Phonons are not involved. Hence the probability of creating a photon is much higher than energy dissipation through phonons in direct bandgap material like GaAs.

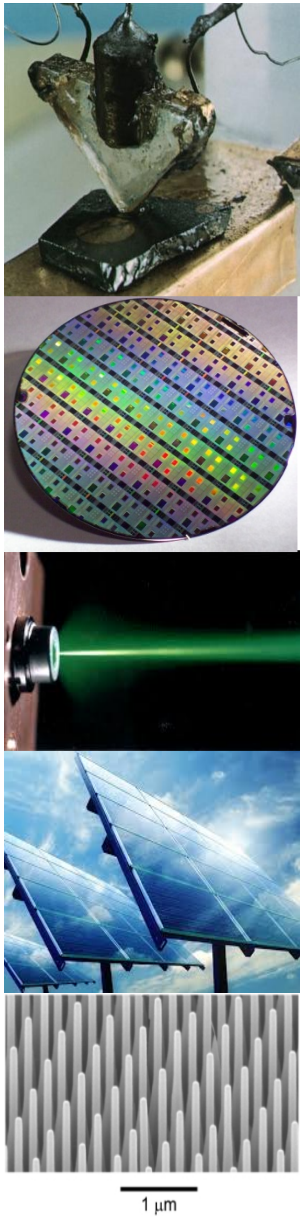
Not surprisingly lasers are made from direct bandgap semiconductors such as GaAs and GaN.

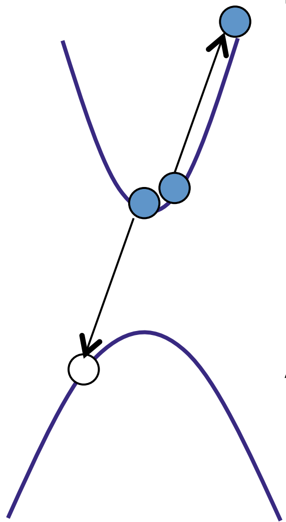
The recombination rate is given by

$$R_{rad} = Bnp$$

where *B* is the radiative recombination coefficient, *n* and *p* are the electron and hole concentrations, respectively. For GaAs B~ $10^{-10}cm^3s^{-1}$ and Si ~ $10^{-14}cm^3s^{-1}$. Radiative recombination is weak in indirect bandgap materials because of the need to converse momentum by involving phonons.

Auger recombination





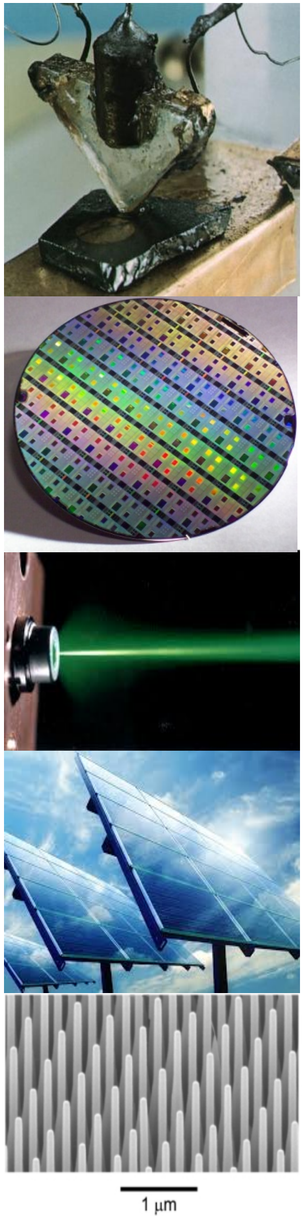
This process is the inverse impact ionization. The energy and momentum produced by the electron-hole recombination resulted in a hot electron (or hole). The hot electron will subsequently dissipate the energy as heat via phonon emission.

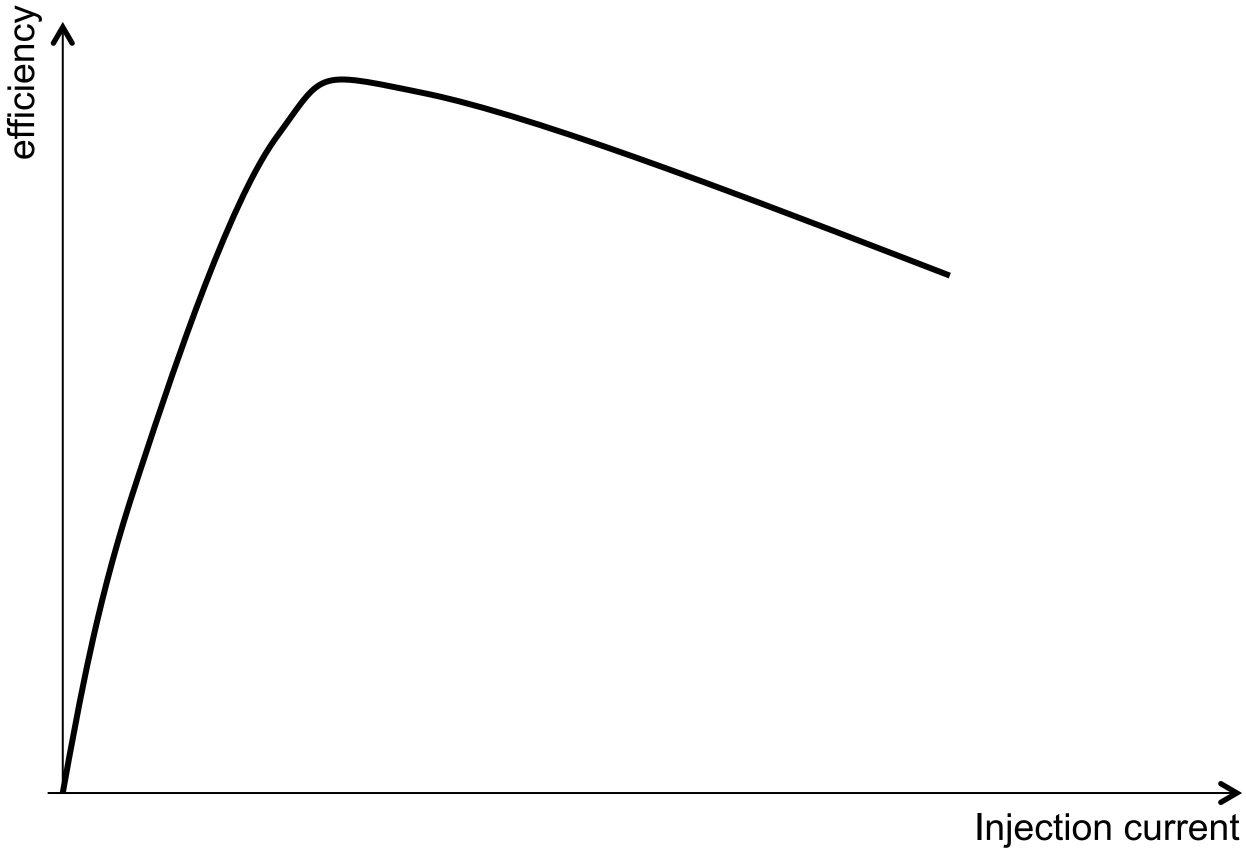
Auger recombination is very important in emitter of solar cell, space-charge region of LEDs and base of HBTs. Because it involves electron and hole, the rate is given by

$$R_{Aug} = Cn^2 p + Dp^2 n$$

C and D are Auger recombination coefficients in cm^6s^{-1}.

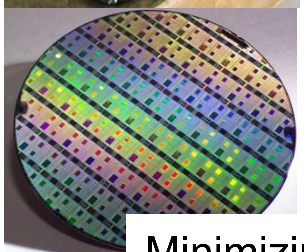
Efficiency in LEDs

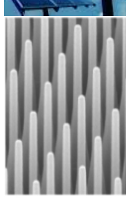


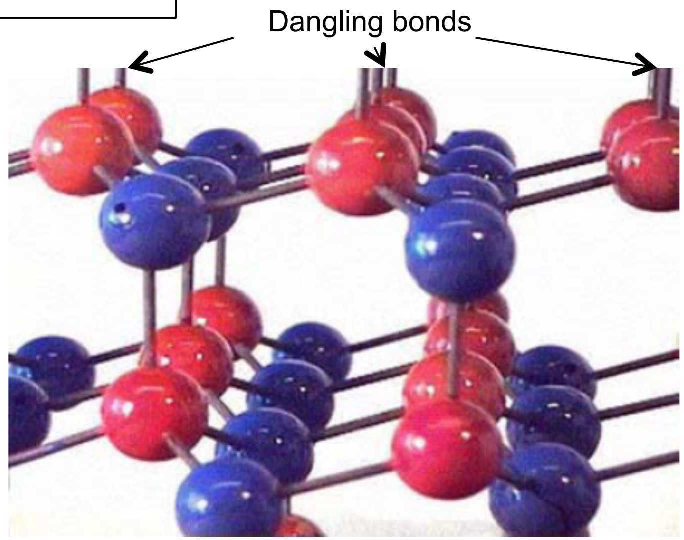


Consider a low defect density pin LED. The quantum emission is dependent on the recombination process. The process that explains the so-called droop effect is not completely verified. Many different contributions (including Auger) have been discussed.

Surface recombination







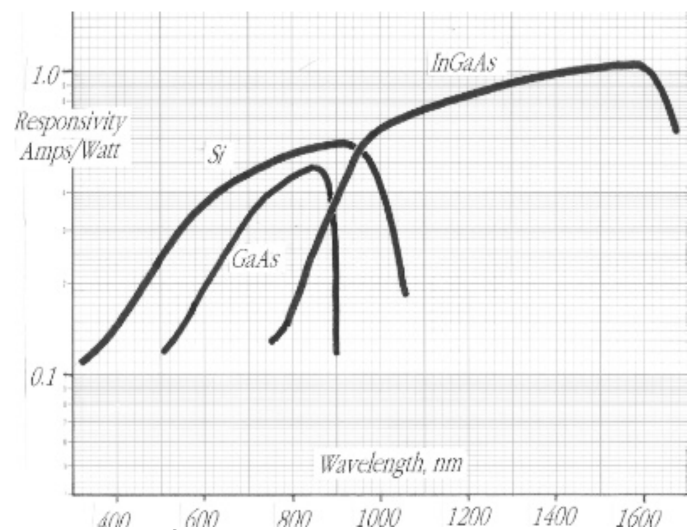
The abrupt discontinuities at the surface dangling bonds that create a large number of localized energy states or generation-recombination centres.

Minimizing surface recombination is the key success of SiO_2/Si that makes

Si such a great material for MOSFET.

In solar cell and photodetectors it is extremely important to ensure that carriers generated by light absorption do not recombine at the surface.

Hence the surface recombination limits the quantum efficiency of solar cell and photodetectors at short wavelengths.



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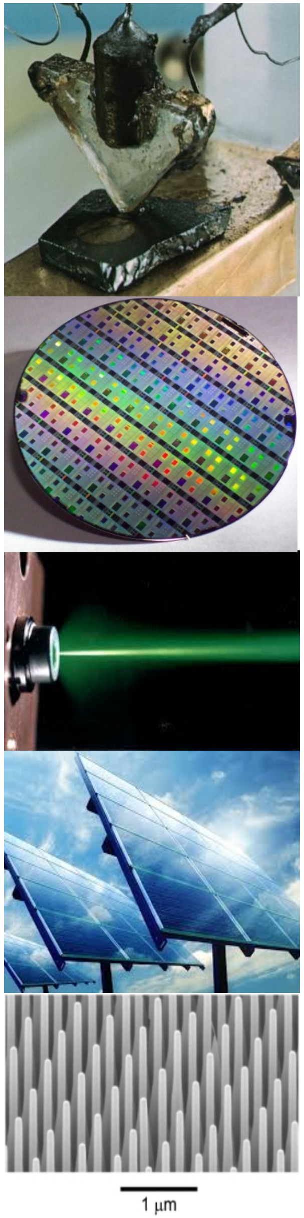
Surface recombination



The surface recombination rate is given by

Hole concentration at the surface

Hole concentration in n-type

$$R_{surf} = v_{th}\sigma_p N_{st}(p_s - p_{no})$$

Thermal velocity

Constant describing the effectiveness of the recombination centres

Surface recombination centre concentration

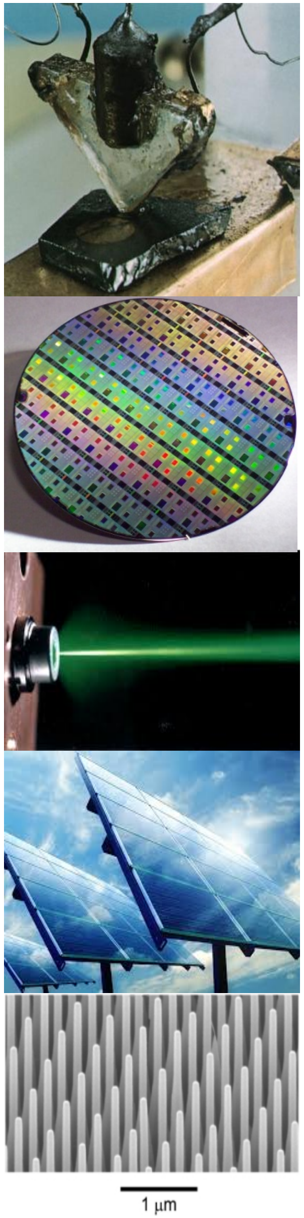
The surface recombination velocity is given by

$$S_{lr} = v_{th}\sigma_p N_{st}$$

In addition to limiting the quantum efficiency surface recombination is also a primary source of generation-recombination leakage currents in photodiodes and transistors.

Therefore successful termination of dangling bond is important for solar cell, photodiodes and transistors.

Summary



- To modify bandstructures, semiconductor alloys, heterostructures, nanostructures and strain engineering are commonly adopted.
- Features of bandstructure are optimised to control density of states, effective mass, scattering mechanisms etc..
- For each application, the carrier concentration in the key parameter that defines semiconductor. External factors that can generate carriers are temperature, chemical, optical and electrical.
- Controlling recombination process is equally important, e.g: SRH, Radiative, Auger and Surface recombinations.