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EEE337 Semiconductor Electronics
EEE348 Electronics and Devices

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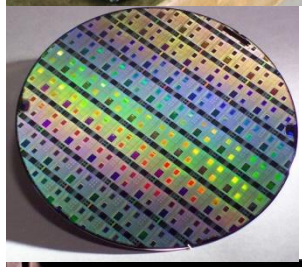
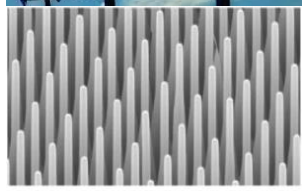
Outline





- Module Background
- Why semiconductor?
- Energy levels in an isolated hydrogen atom
- Band structure

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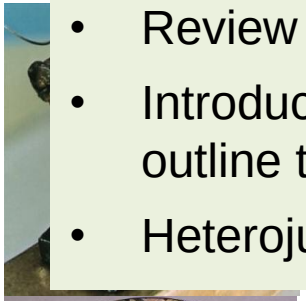
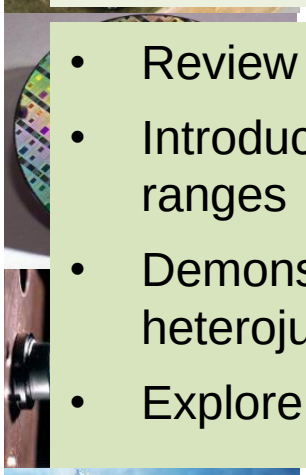
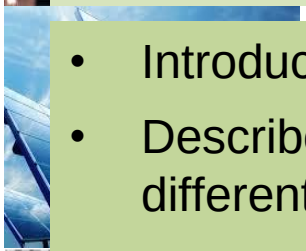
Lecture delivery plan



- Review semiconductor band structure, doping, conduction, junctions
- Introduce the various electronic material systems (Si, Ge, III-V, SiC, GaN) and outline their electronic properties and principal applications
- Heterojunctions



- Review Solar Cell developments
- Introduce optical detector technologies and applications for different wavelength ranges
- Demonstrate performance and functional improvements possible using heterojunctions
- Explore heterostructure optoelectronic devices such as Lasers, LEDs



- Introduce the physics of high speed devices
- Describe how tunneling, Gunn and impact ionisation effects leads to negative differential resistance

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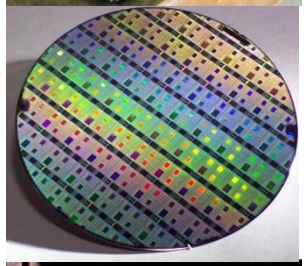
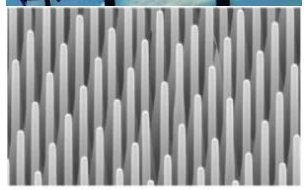
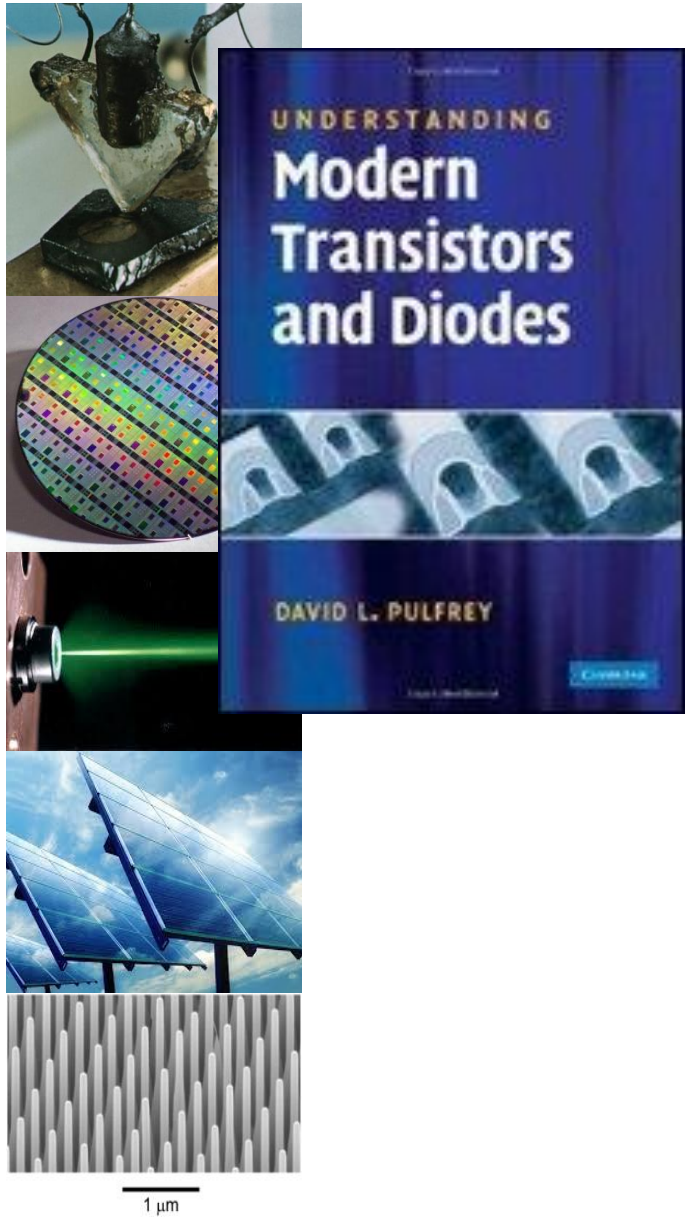
Module details

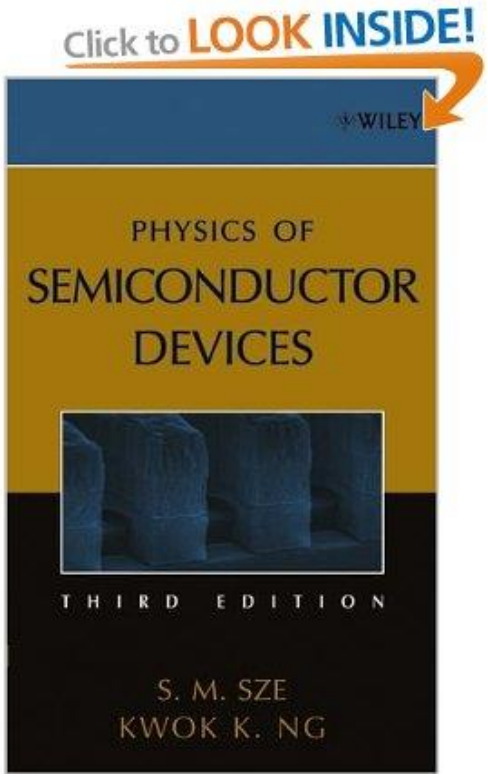
Time Allocation
24 lectures, 12 problem classes, 62 hours independent study.
Recommended Previous Courses
Knowledge equivalent to EEE118, EEE225.
Assessment
3 out of 4 questions on 2 hour examination.

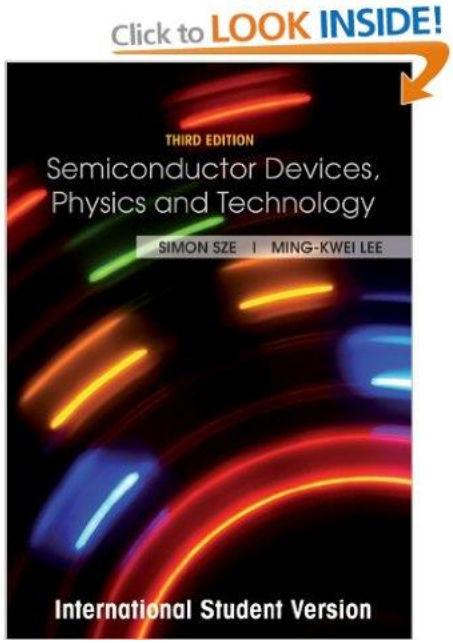
Recommended Books



Ebook:

(Library-Electronic Resources-Ebooks-Ebook supplier information-Dawsonera)





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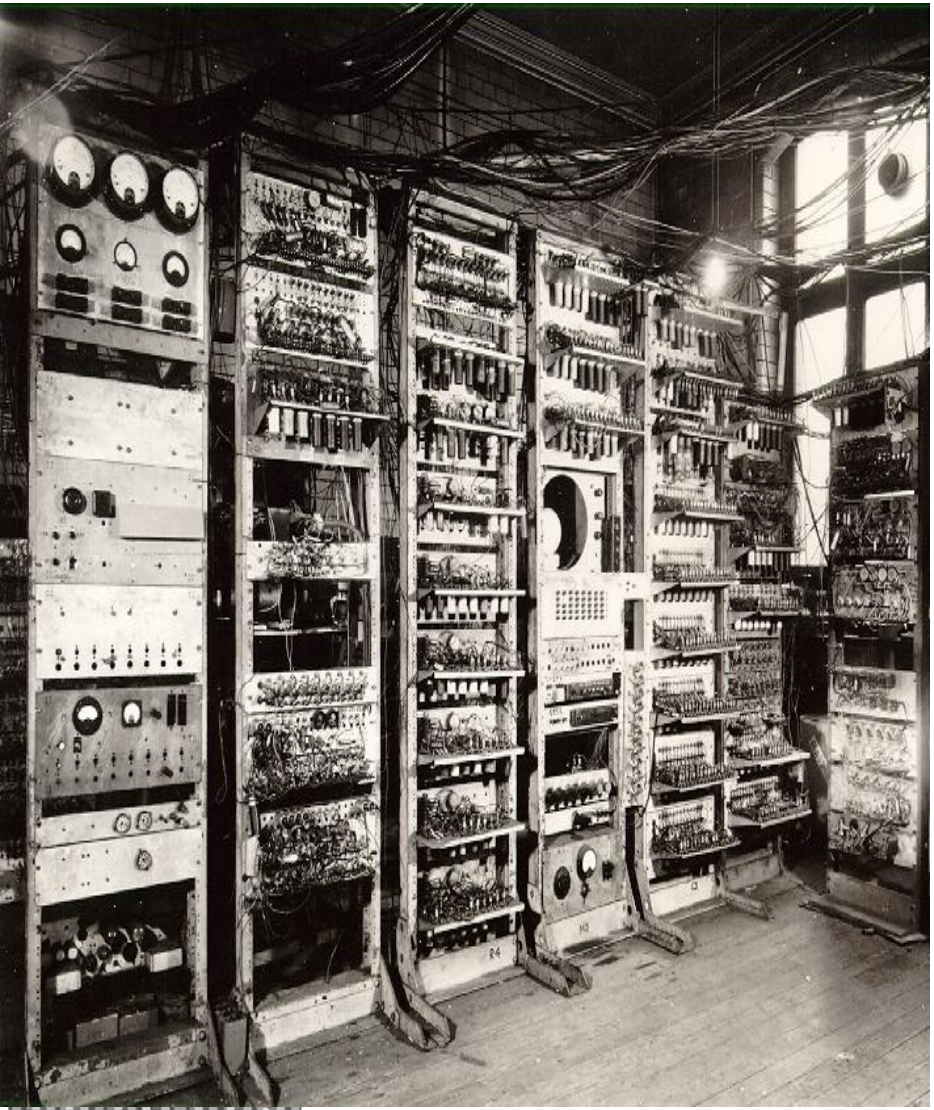
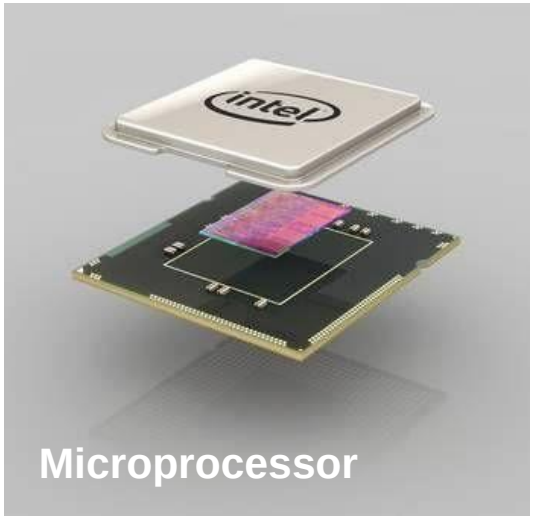
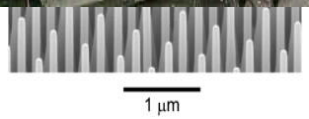
Why use semiconductor?





iPad mini

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



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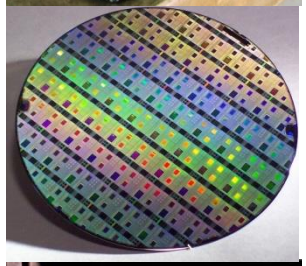
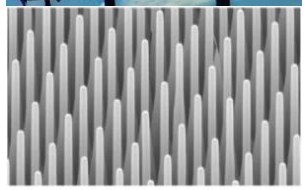
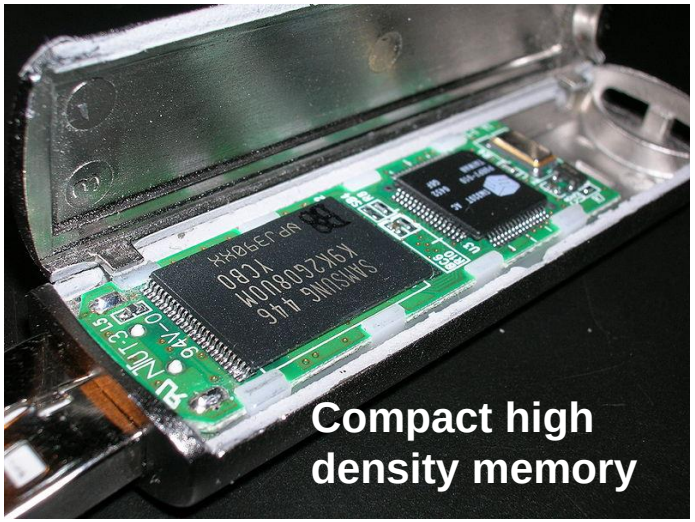
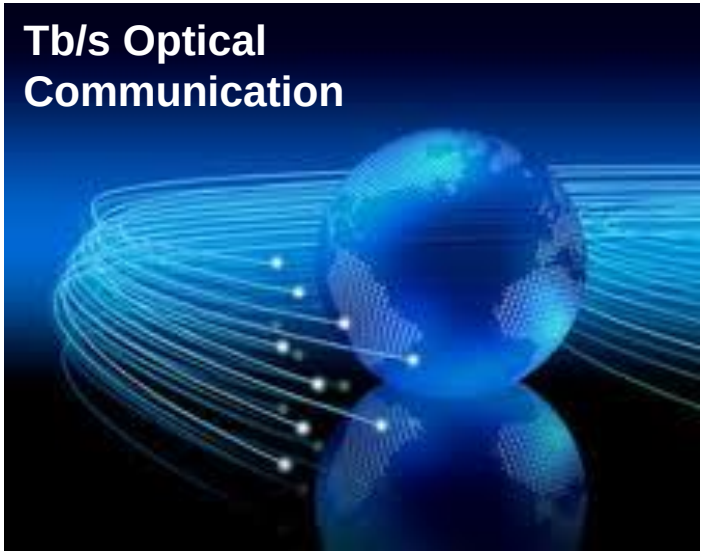
Why use semiconductor?









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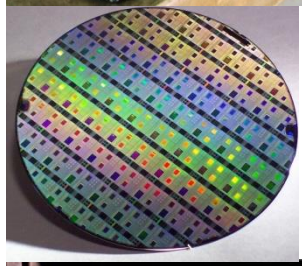
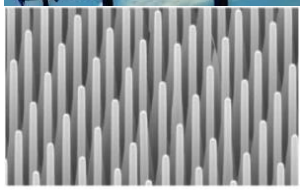
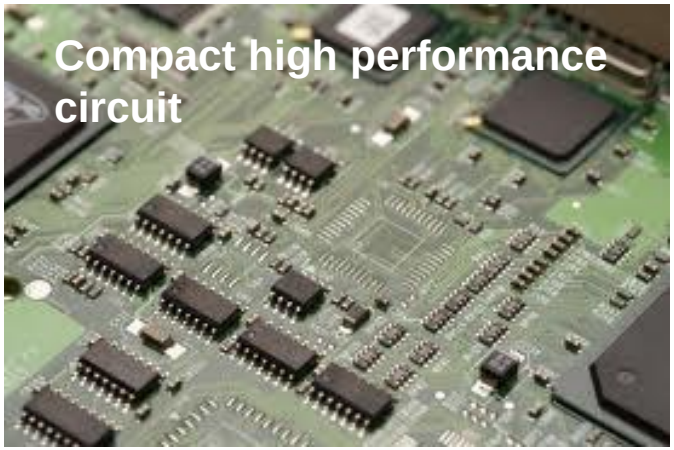
Why use semiconductor?







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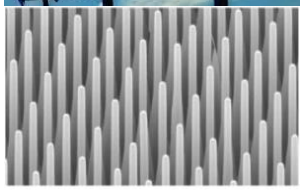
Semiconductor is an important driver of many technologies



Flexible display is another exciting example of progress made in semiconductors

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

https://www.youtube.com/watch?v=AxbHpXE4VM0

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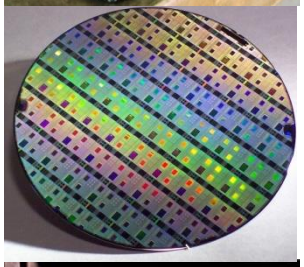

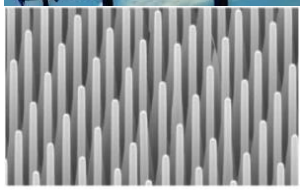

Revision: Basic properties of semiconductors

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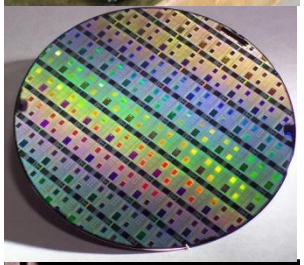
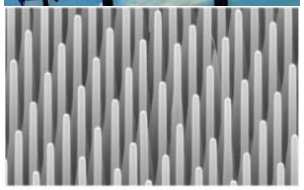
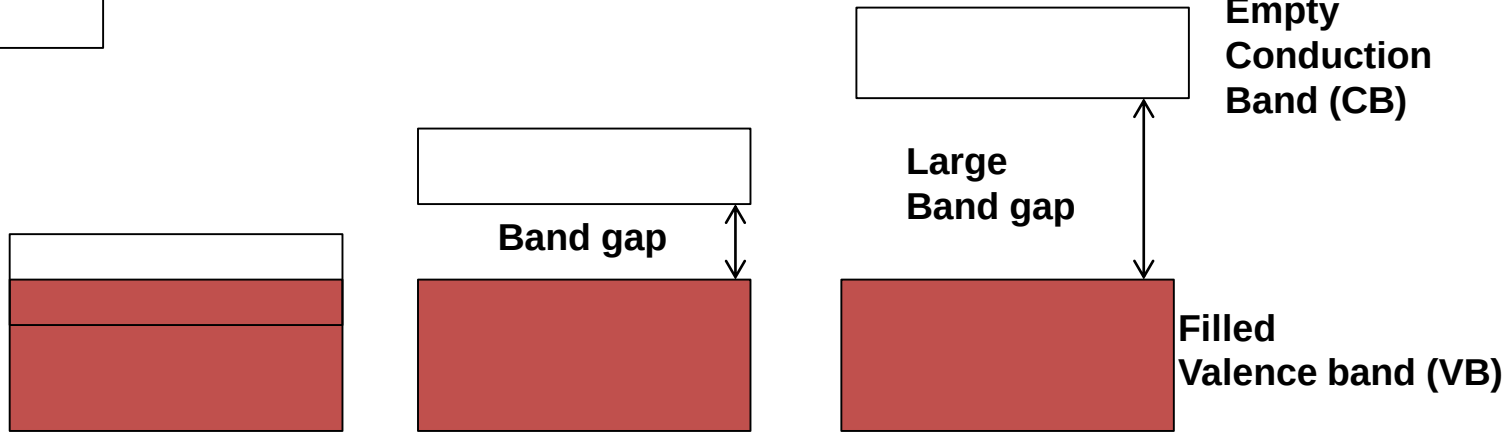
Metal, Semiconductor and Insulator







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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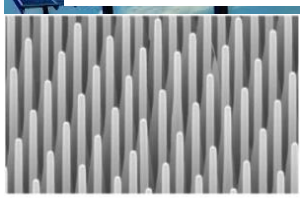
Common Semiconductors




												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										II	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]				

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

*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

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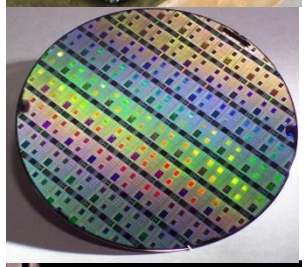
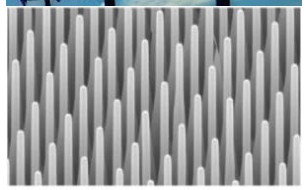
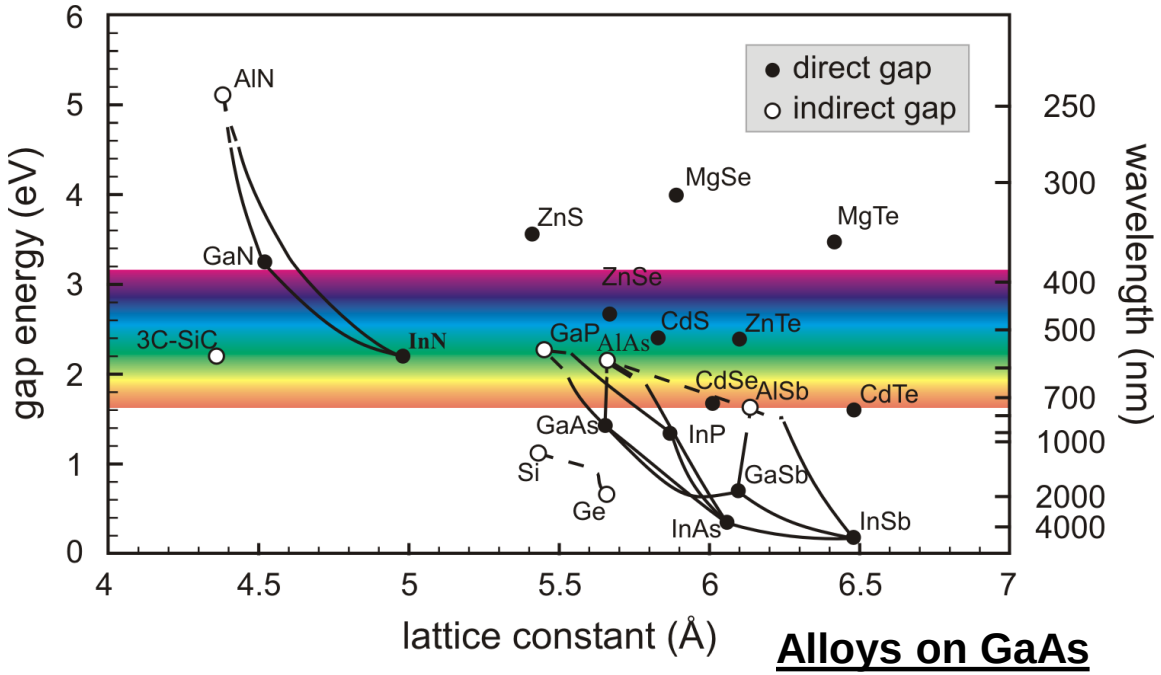
Semiconductor Alloys





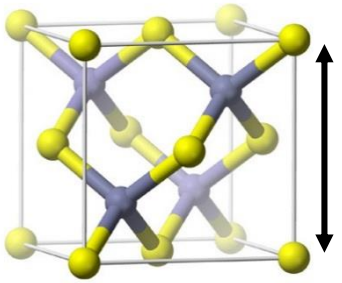


Widely available substrates

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 constant

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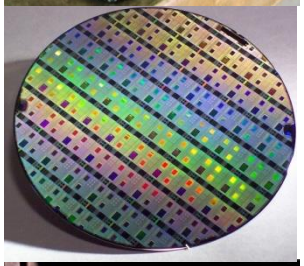
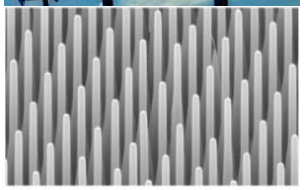
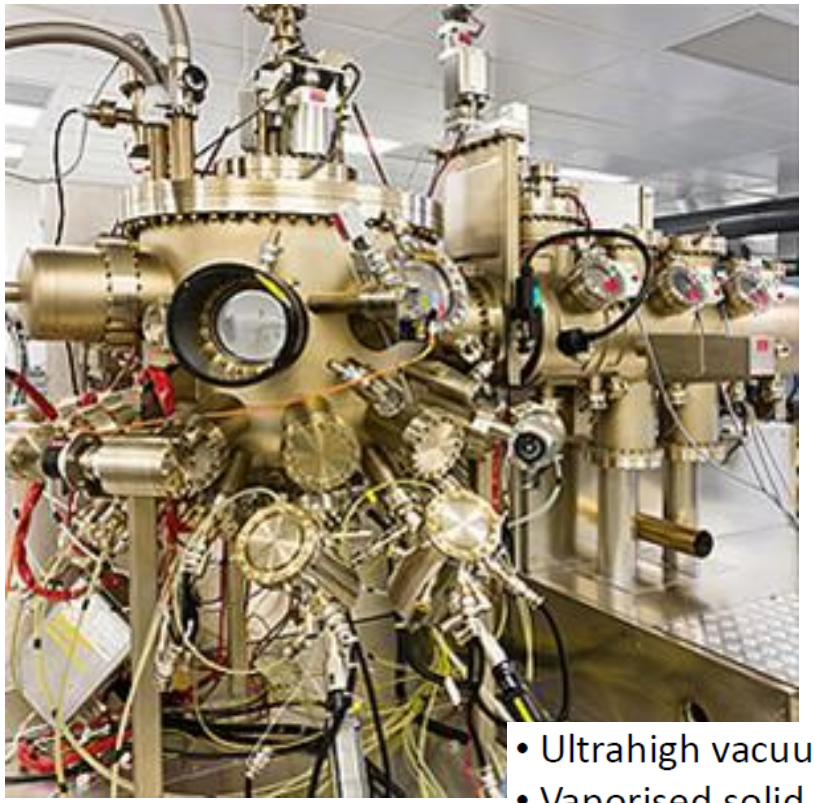
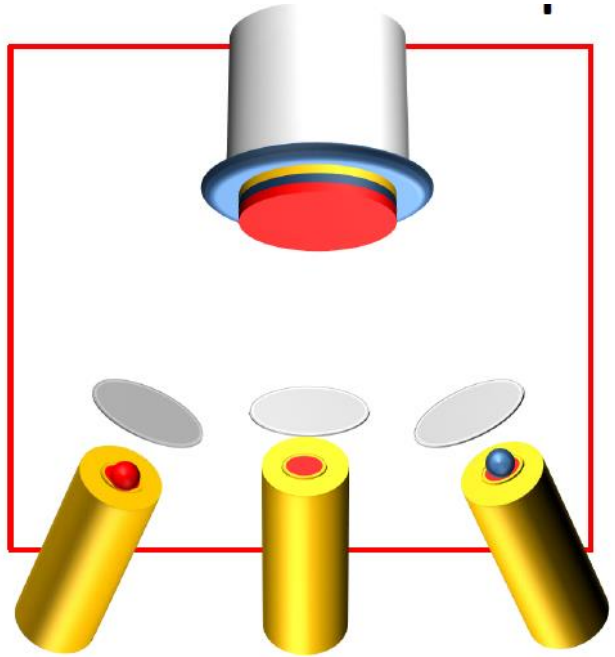
Ultra high vacuum molecular beam epitaxy









- 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

http://www.epsrciii-vcentre.com/working-us/facilities/

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 $\times^{10-4}$
	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	

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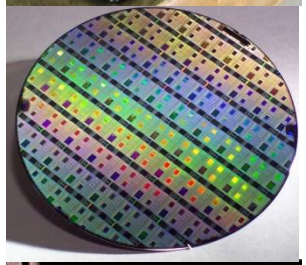
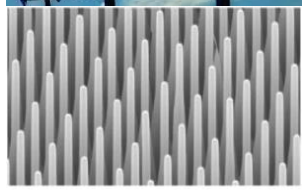
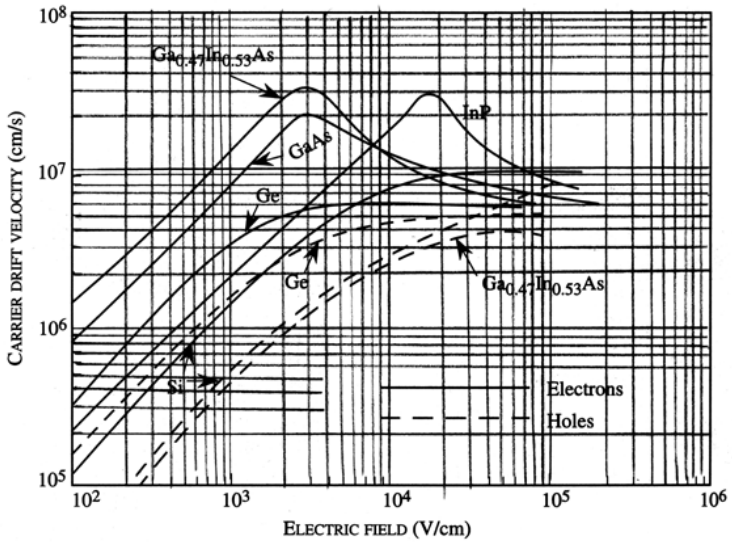
Carrier mobility





- Why is carrier mobility an important parameter?

High mobility increases carrier drift velocity



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

High mobility increases conductivity (reduces resistivity)

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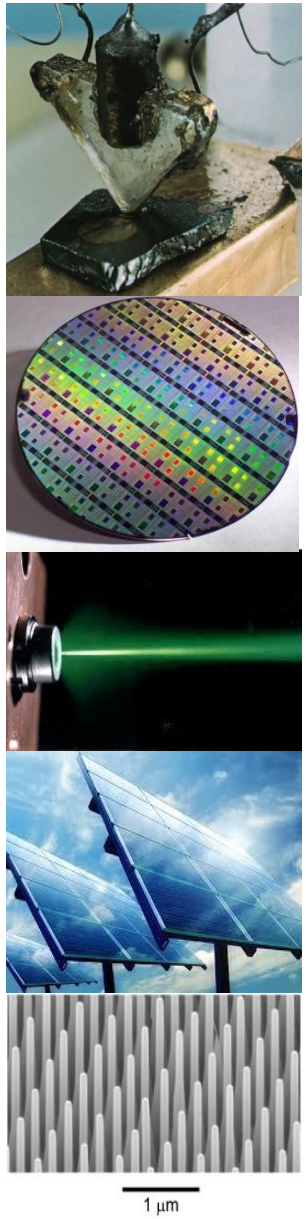
Speed of semiconductor devices

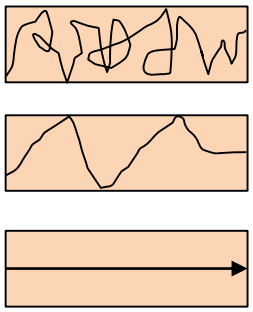


The speed of a semiconductor device fundamentally depends on the carrier transport. Carrier velocity and device size/geometry are the major factors

Carrier velocity $v = \mu E$ *(μ = mobility, E = electric field)*

$$\mu = \frac{e\tau}{m}$$

- 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)*
- *To increase the speed of devices and logic circuits, we need to increase the carrier mobility.*



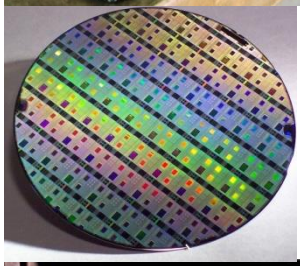
High scattering

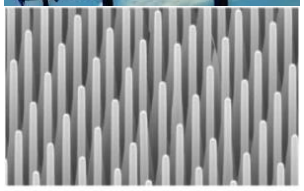
Quasi-ballistic

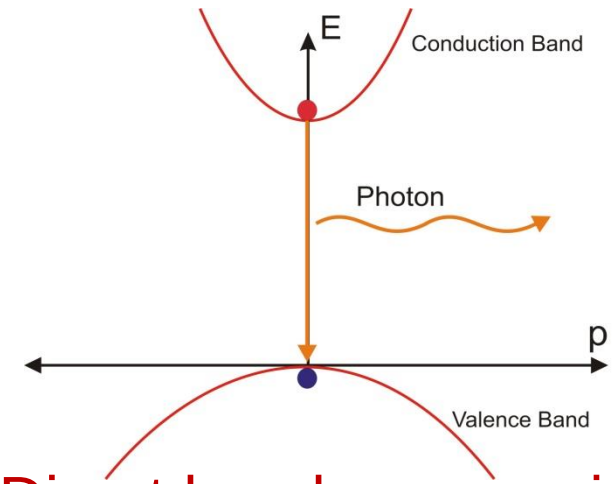
Ballistic

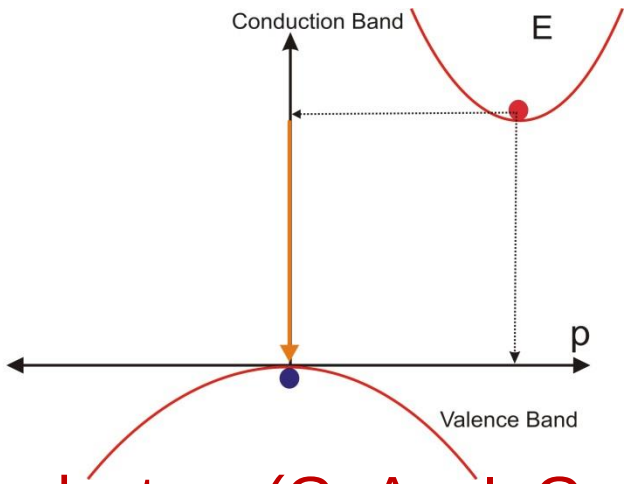
Materials from Si to graphene have been developed into high speed transistors. Mobility of 15,000 $cm^2V^{-1}s^{-1}$ demonstrated in graphene (however the theoretical value is 200,000 $cm^2V^{-1}s^{-1}$)

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. The emission and absorption wavelengths are also determined by the band gap.

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

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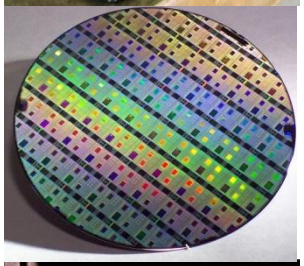
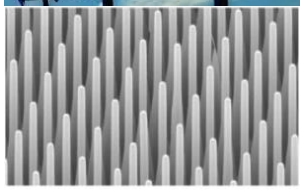
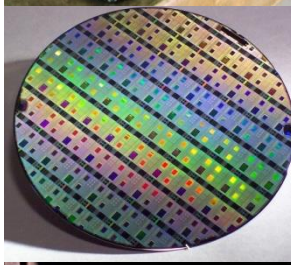


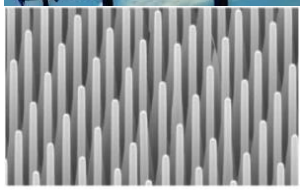


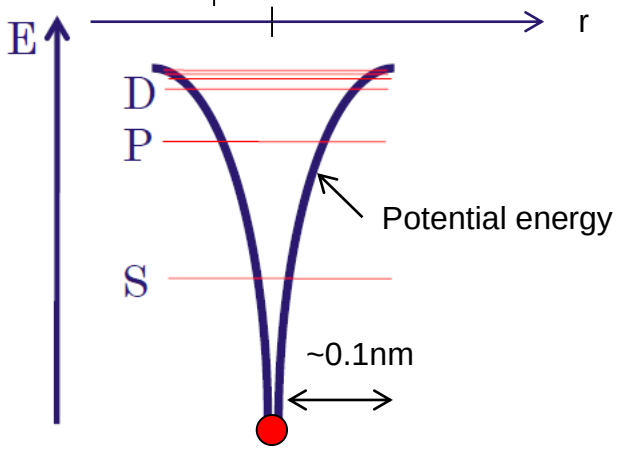
How do we design and optimise electronic and optoelectronic devices?

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

Quantised energy level

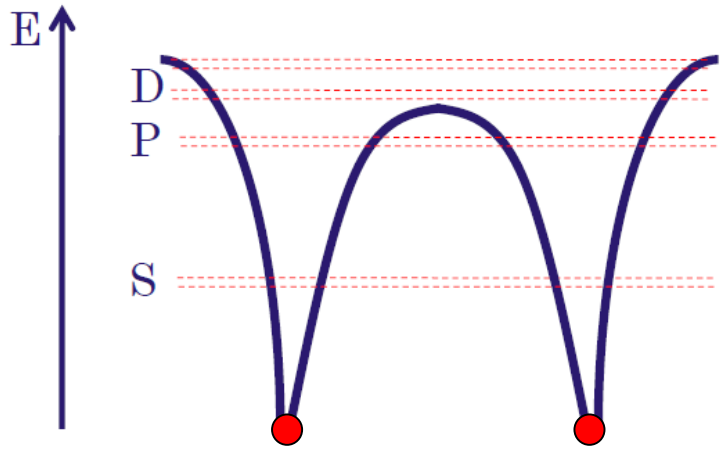






In an isolated hydrogen atom $E_H = -13.6/n^2$ eV

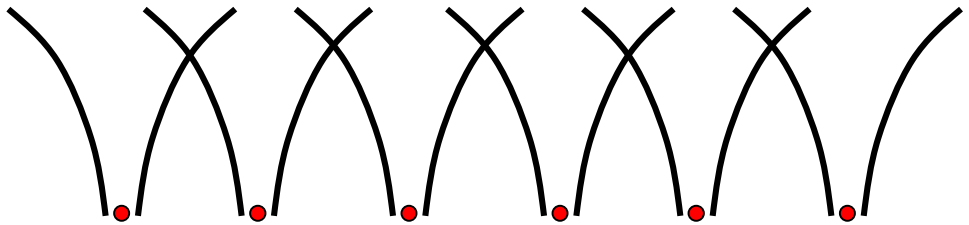
Fixed energy levels (quantum mechanics).
Potential energy barrier bind electrons to the nucleus.
Electrons in upper states are more weakly bounded to the nucleus.



Quantum mechanics (Pauli exclusion principle) does not allow identical states

→the two states split

How about in a crystal?



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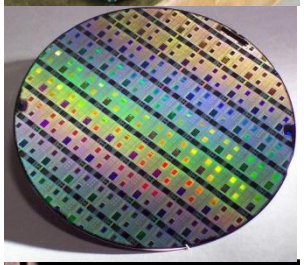
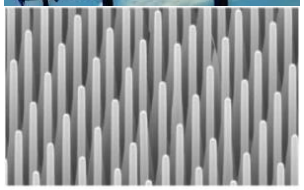
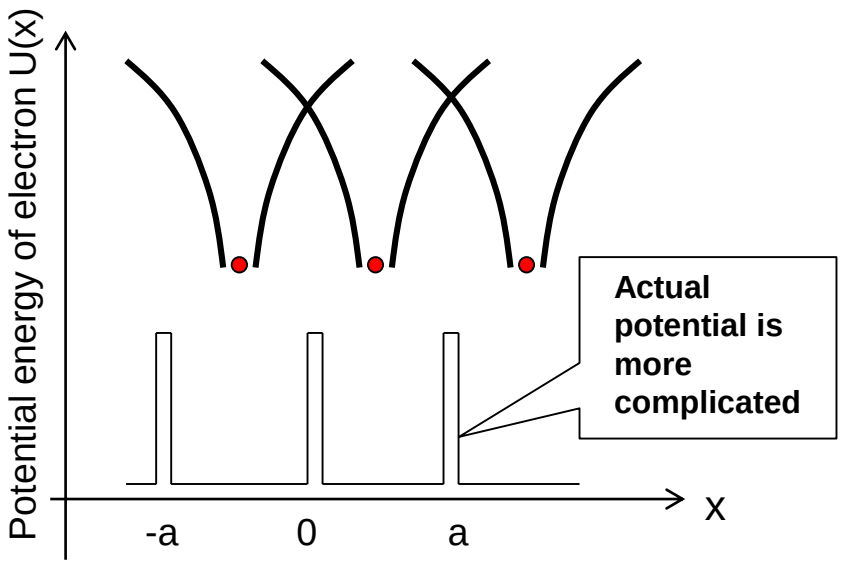
Band structure







Presence of other electrons, different atoms, and different spacing in different directions will influence the potential energy. However the important fact is the periodicity of the potential energy.

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

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

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

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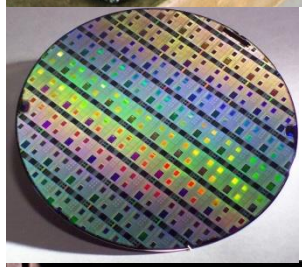
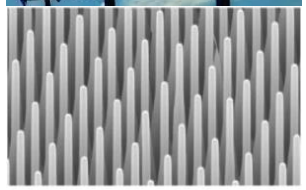
Band structure

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 (see p.7-9, Pulfrey) produces

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

f(E)

f(E)

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

1

cos(ka)= 1

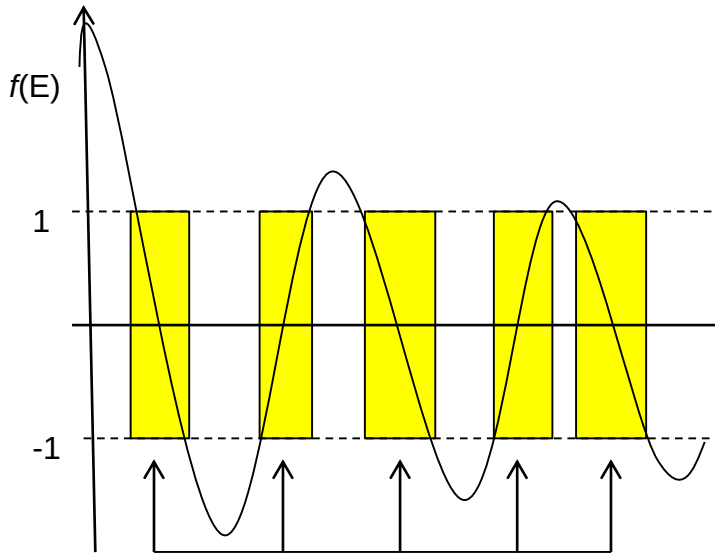
Electron energy

-1

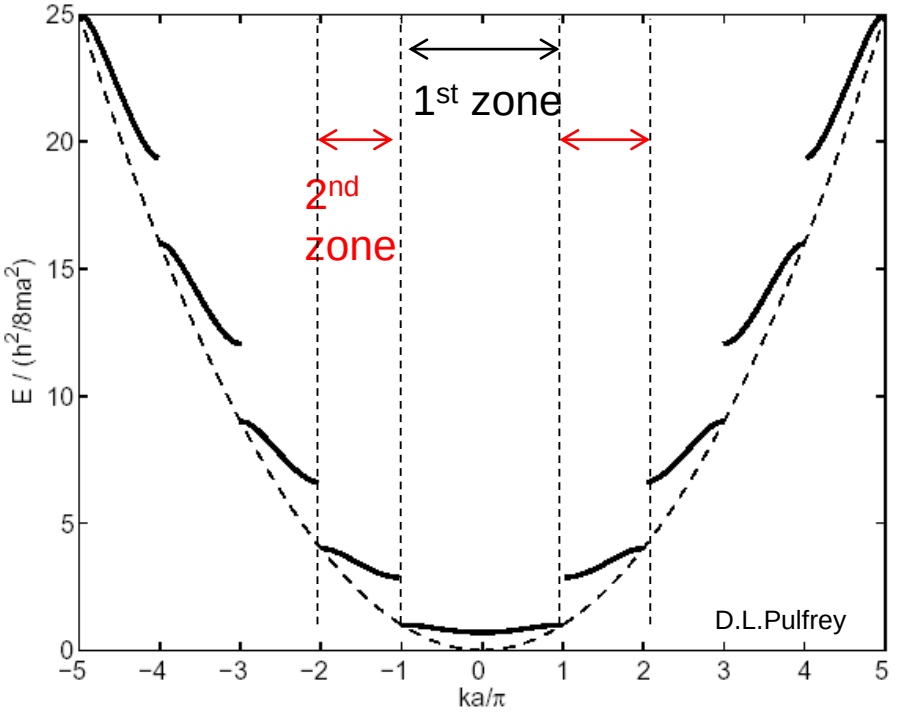
cos(ka)= -1

Allowed energy bands

Band structure

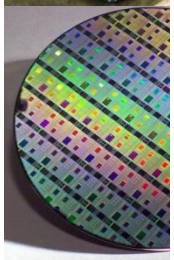


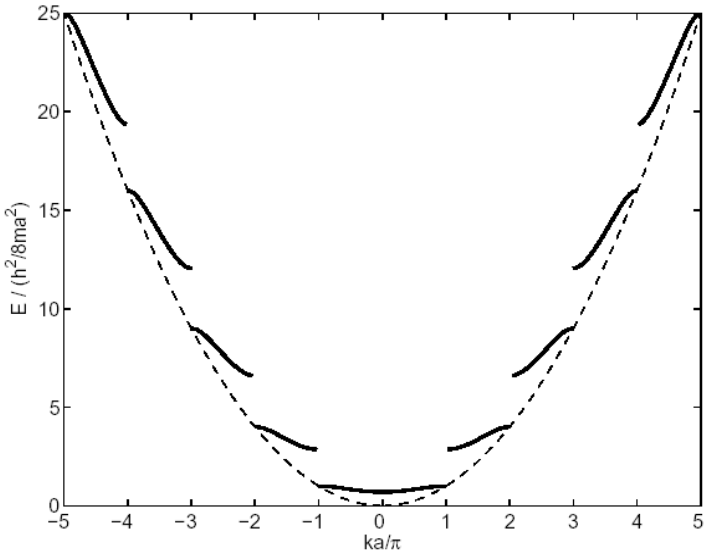
Allowed energy bands



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

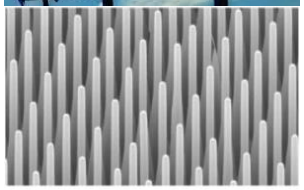


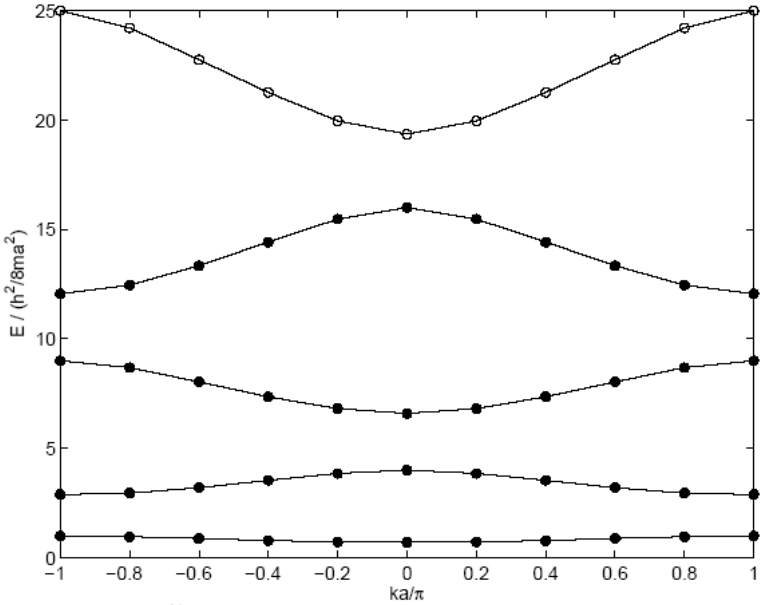


The extended zone is transformed to a reduced-zone called the Brilloun zone. Depending on the number of valence electrons present, the lower bands will be filled with electrons. In the case of Si the first 4 bands are filled with electrons. Hence the bandgap is the energy separation between the 4th and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

Empty states

Filled with electrons





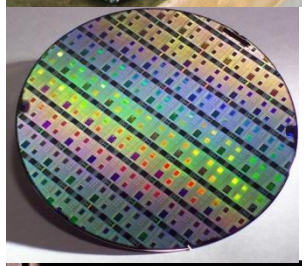
Conduction band

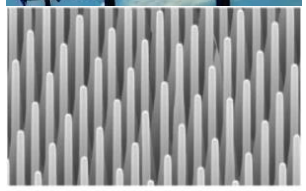
Valence band

D.L.Pulfrey

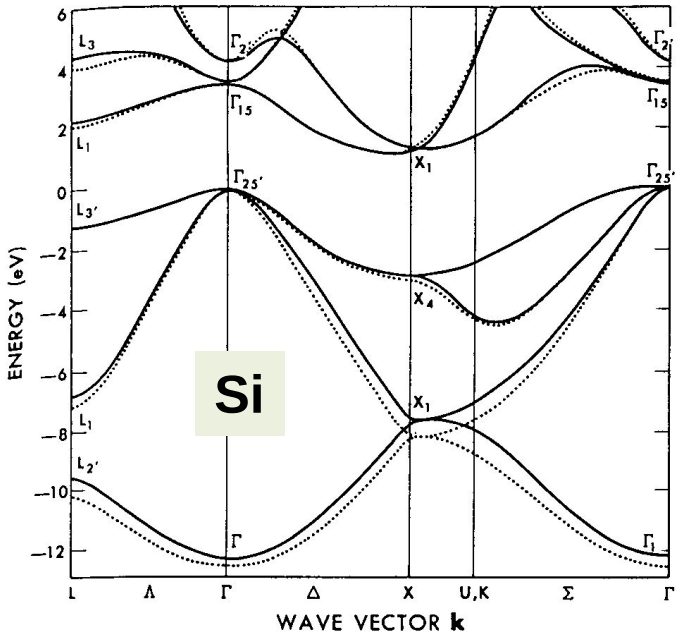
C H Tan

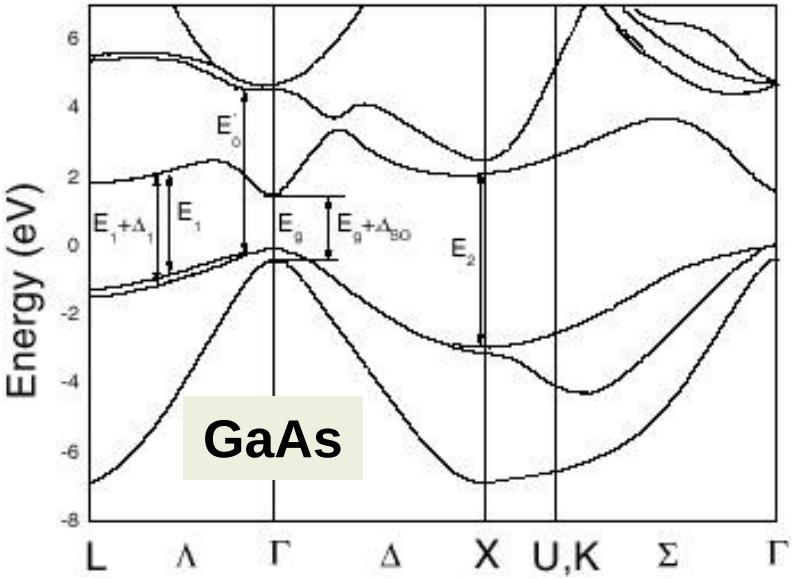
Band structure

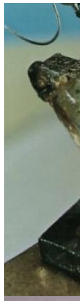
The simple 1-D example provides a conceptual illustration of how band structure is computed. In a 3-D case the potential energy is much more complicated and usually a numerical calculation is required to compute the energy versus momentum (E vs. k) band diagram.

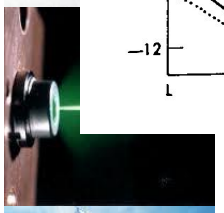


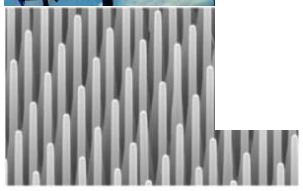


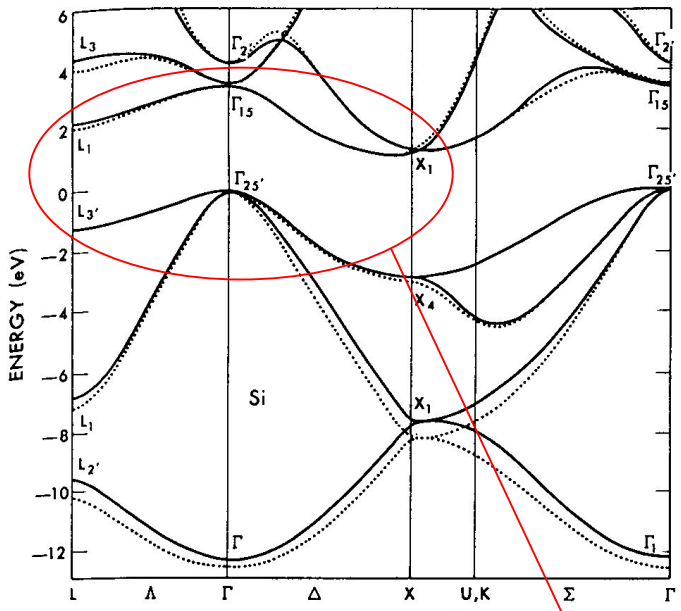
The valence bands are relatively similar they are related to the similar bonding coordination of diamond and zinc blende. The conduction bands are more different as the electrons are “freer” than the valence electrons.

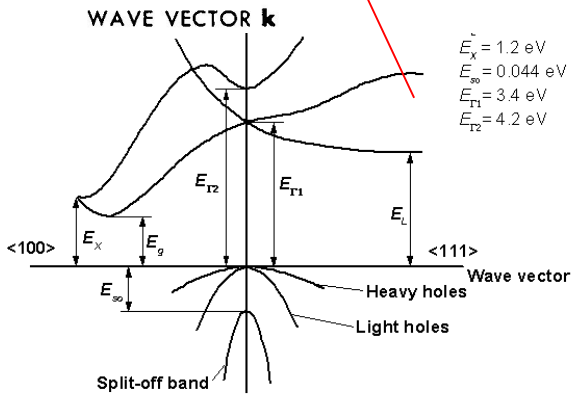
Band structure

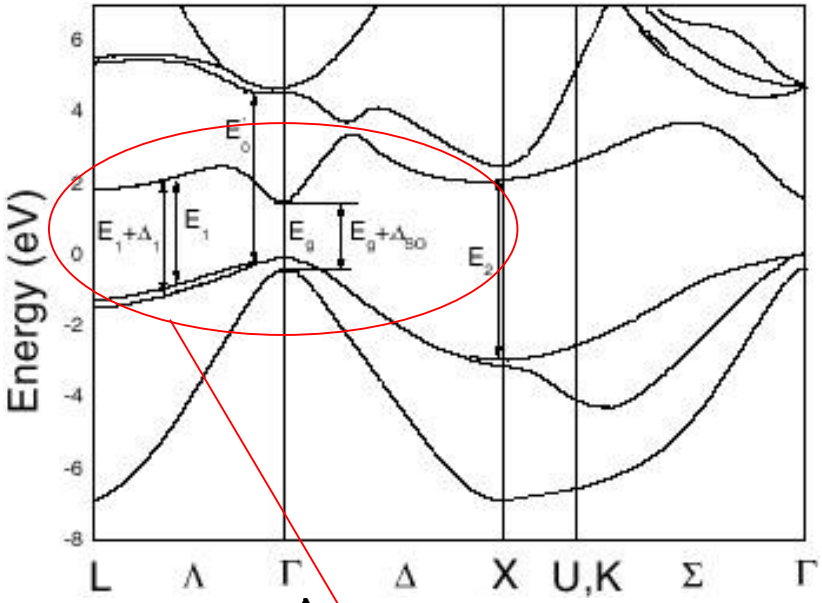




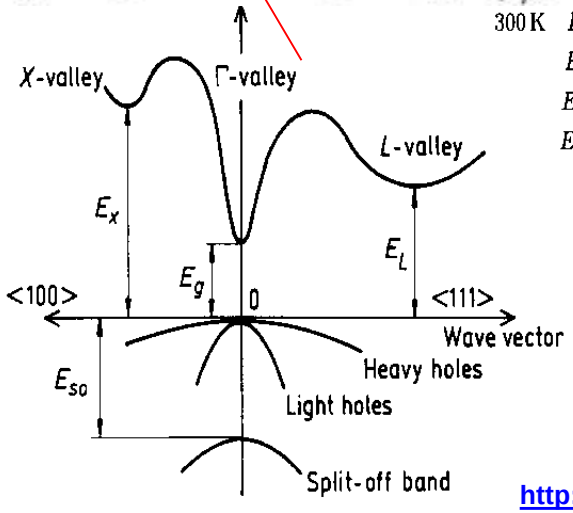








300 K $E_g = 1.42$ eV
$E_L = 1.71$ eV
$E_X = 1.90$ eV
$E_{so} = 0.34$ eV



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

These look very different to the two band schematic earlier

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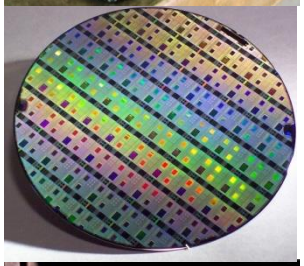
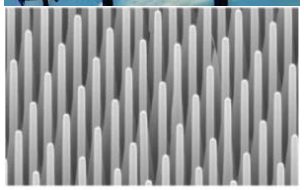
Band structure

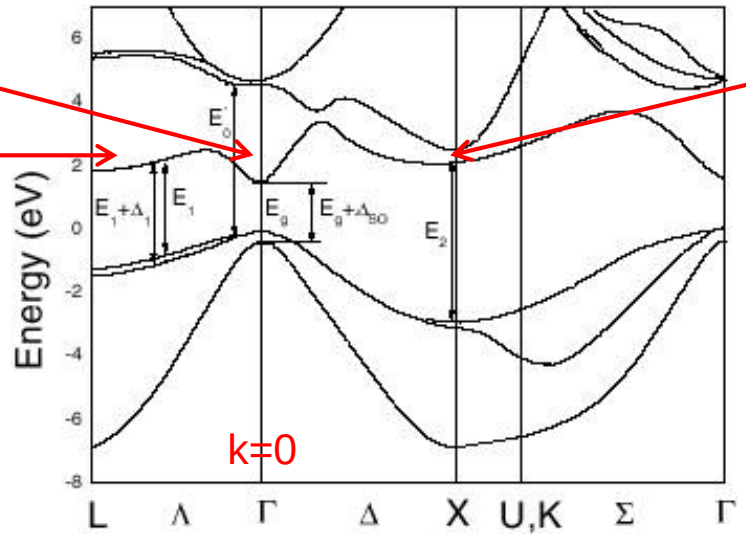



$m_\Gamma^* = 0.067 m_o$

$m_L^* = 0.25 m_o$

$m_X^* = 0.6 m_o$



$$\mu = \frac{e\tau}{m}$$

At k = 0 (Γ valley), the band structure can be described by

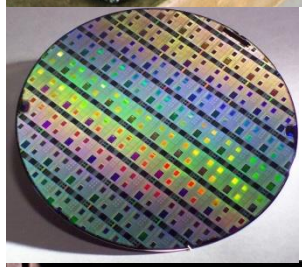
$$E(k) = E_C + \frac{\hbar^2 k^2}{2m^*} \quad \text{or} \quad E(k) = \frac{\hbar^2 k^2}{2m^*} \quad \text{relative to } E_C$$

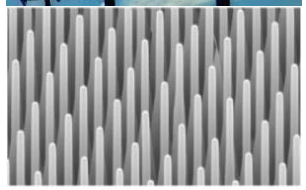
Note that the effective mass m^* replaces the free electron mass m_o. For GaAs $m^* = 0.067\ m_o$. A more accurate relationship is given by

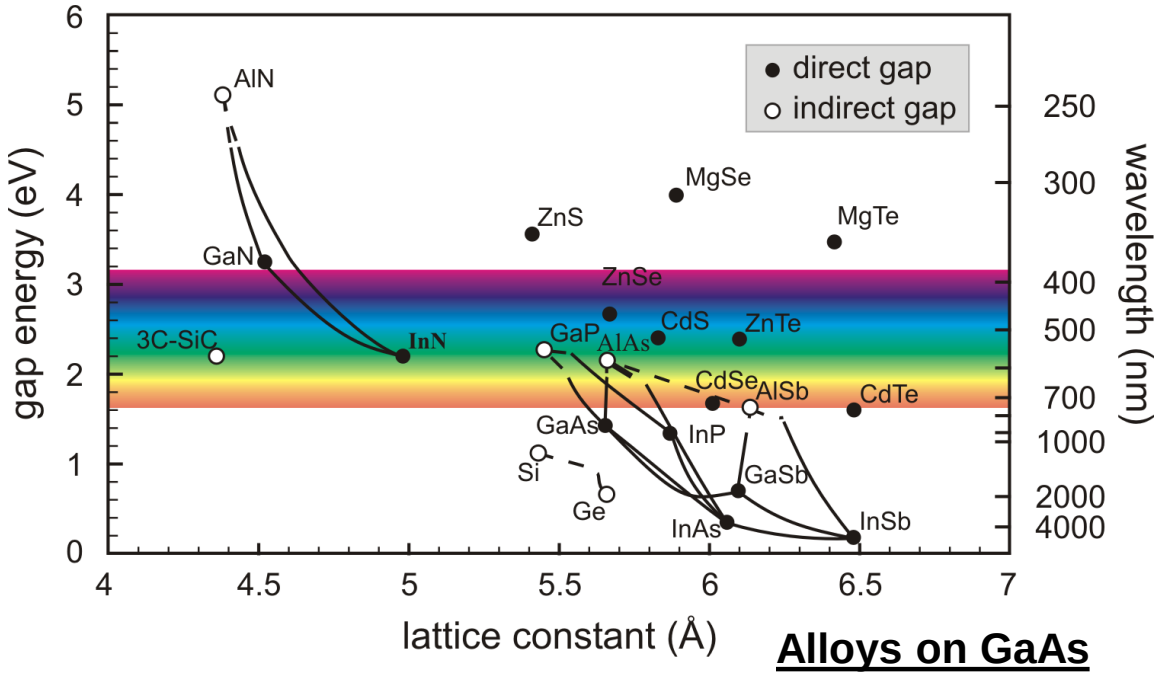
$$E(k)[1+\alpha_p E(k)] = \frac{\hbar^2 k^2}{2m^*}$$

where α_p describes the non-parabolicity of the band structure. For GaAs it has a value of 0.67 eV^{-1}.

Semiconductor Alloys







Widely available substrates

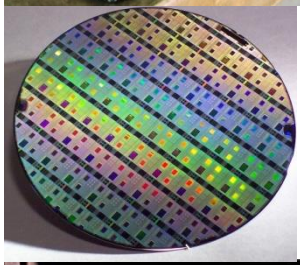
IV	III-V	II-VI
Si	GaAs	CdTe
Ge	InP	CdSe
SiC	InSb	ZnSe
	GaSb	ZnTe
	InAs	

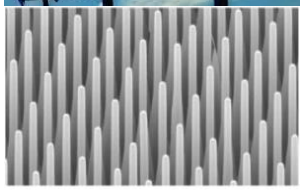
Alloys on GaAs
AlGaAs
InGaP
AlInP

Alloys on InP
InGaAs
InAlAs
GaAsSb
AlAsSb
InGaAsP
InAlGaAs

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

Semiconductor alloys





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

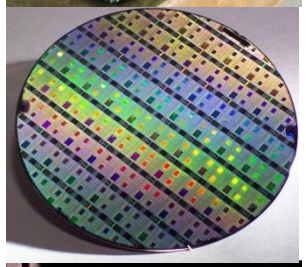
There is a wide range of semiconductor materials that can be used in designing electronic and optoelectronic devices. Band gap, mobility, resistivity, breakdown voltage, emission (and detection) wavelength, mechanical hardness and thermal conductivity are some of the properties that can be optimised by carefully selecting the semiconductor used.

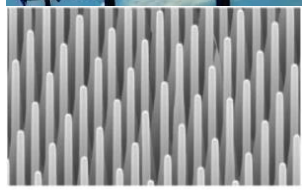
Bandgap

$Al_xGa_{1-x}As$ (1.424+1.247x)

$In_{1-x}Ga_xAs$ ($0.36+0.63x+0.43x^2$)

Semiconductor properties





In addition to this **BULK** semiconductors, many properties can be modified using heterostructures and nanotechnology (quantum well, quantum dot, nanowire) as well as external force such as pressure, temperature, electric and magnetic fields.

Some of the most important heterostructures are Si/SiGe, AlGaAs/GaAs and InP/InGaAs. These are used to form the heterojunction in transistors (HBTs), lasers, photodetectors and optical modulators. They are also used to form quantum well devices.