Semiconductor materials and devices

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Material Properties

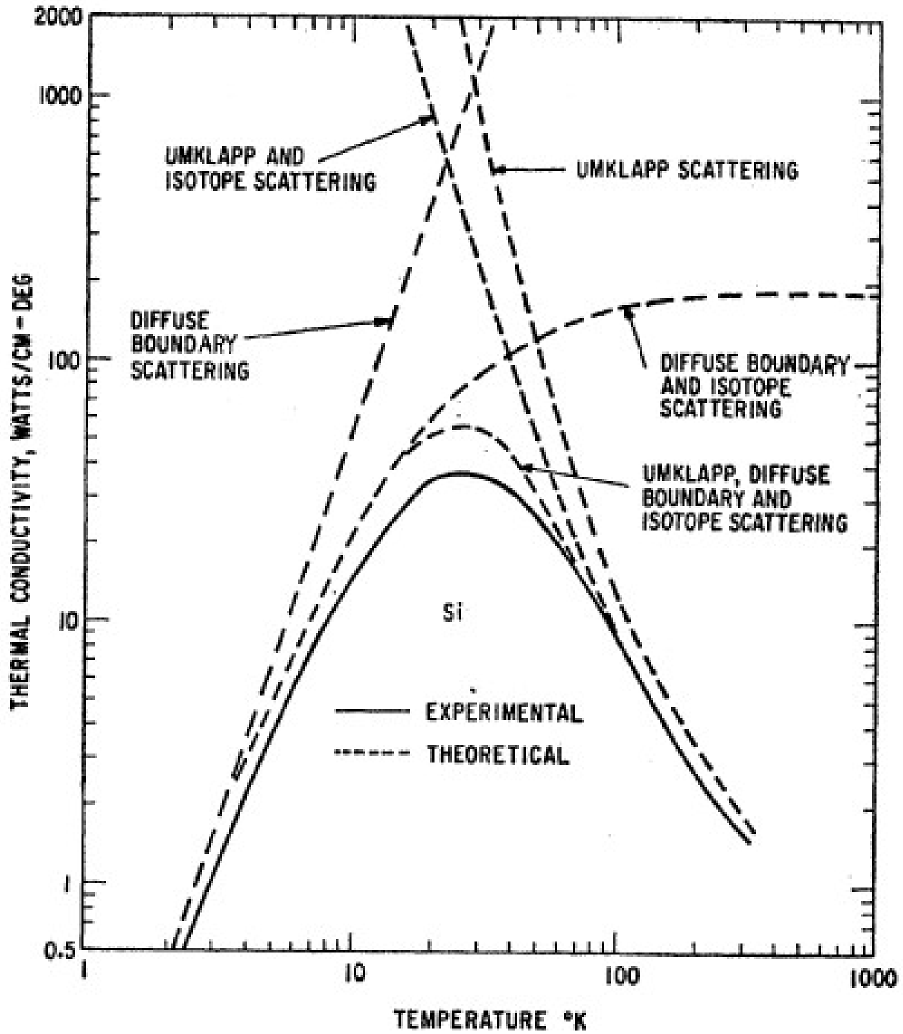
6.777J/2.751J Material Properties Database

Material

Aluminum (incl. alloys w/ Si or Si+Cu)
Aluminum Oxide (CVD)
Chromium (PVD)
Copper (PVD or electroplated)
Gold (PVD or electroplated)
Indium Tin Oxide
Nickel (PVD or electroplated)
Parylene C
PDMS (polydimethylsiloxane)
PMMA
Polyimide (select one particular type)
Pyrex Glass
Amorphous Silicon
Si-Ge alloy
APCVD Silicon Dioxide
LPCVD Silicon Dioxide
PECVD Silicon Dioxide
Thermal Silicon Dioxide
LPCVD Silicon Nitride (silicon-rich)
LPCVD Silicon Nitride (stoichiometric)
PECVD Silicon Nitride
SU-8 Photoresist
Titanium (PVD) [1]
Titanium (PVD) [2]
Tungsten (PVD or CVD)

Property	Value	Reference	Image/URL (optional)
~~Mass density~~	~~3960 kg/m^3~~	Matweb.com	~~http://www.matweb.com/search~~ /SpecificMaterial.asp?bassnum=BA1A
Young's modulus	370 Gpa	Matweb.com	http://www.matweb.com/search /SpecificMaterial.asp?bassnum=BA1A
Poisson ratio	0.2	Matweb.com	http://www.matweb.com/search /SpecificMaterial.asp?bassnum=BA1A
Stiffness Constants	Not found		
Tensile or fracture strength	300 MPa	Matweb.com	http://www.matweb.com/search /SpecificMaterial.asp?bassnum=BA1A
Residual stress on silicon	Not found		
Specific heat	850 J/(kgK)	Matweb.com	http://www.matweb.com/search /SpecificMaterial.asp?bassnum=BA1A
Thermal conductivity	30 W/(mK)	Matweb.com	http://www.matweb.com/search /SpecificMaterial.asp?bassnum=BA1A
Dielectric constant	9.9	Matweb.com	http://www.matweb.com/search /SpecificMaterial.asp?bassnum=BA1A
Index of refraction	1.76	Matweb.com	http://www.matweb.com/search /SpecificMaterial.asp?bassnum=BA1A

Thermal conductivity $\vec{j}_U = -K\nabla T$



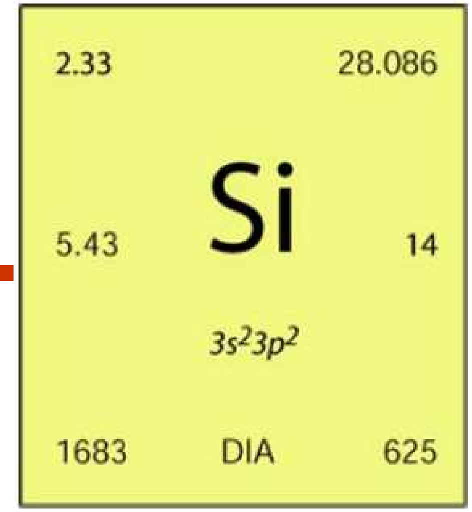
Imperfections in the crystal or grain boundaries decrease the mean free path and the thermal conductivity.

At high temperatures, the mean free path is limited by Umklapp processes. At low temperatures the Umklapp processes freeze out and the mean free path is limited by imperfections.

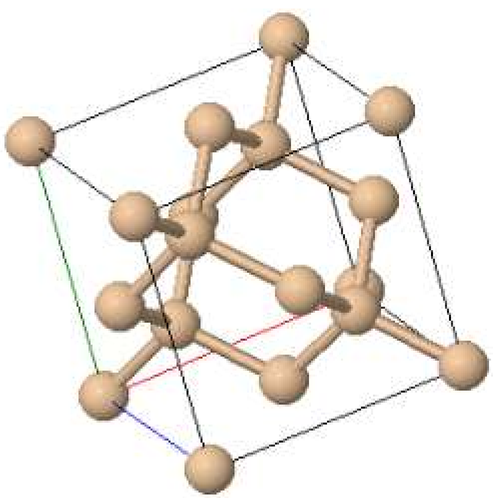
Materials depend on

Temperature
Pressure
Impurities
Microstructure
Electric and Magnetic fields

Silicon



- Important semiconducting material
- 2nd most common element on earths crust (rocks, sand, glass, concrete)
- Often doped with other elements
- Oxide SiO_2 is a good insulator



silicon crystal = diamond crystal structure

Franssila

4

Silicon

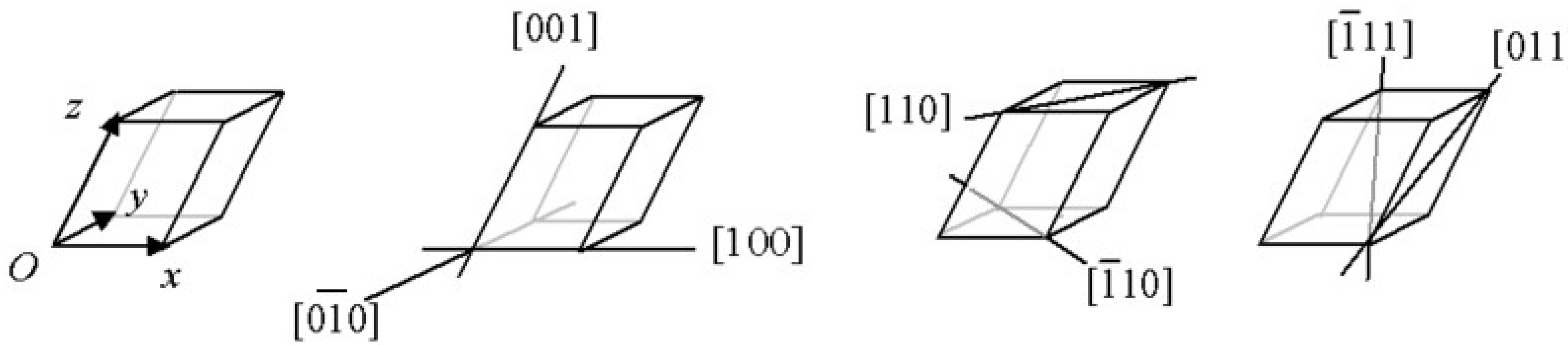
ıe first transistor was made of polycrystalline germa-um in 1947. Electron mobility in germanium is higher an in silicon, and germanium was readily available. owever, silicon, with its larger band gap, was favoured ecause of smaller leakage currents. Initially there was consensus whether single crystalline or polycrystalline aterial was better, but the rapid development of sin-e crystal silicon growth in the 1950's soon dominated e market. The real breakthrough came when the bene-cial role of silicon dioxide was recognized: it provided ıssivation of semiconductor surfaces, and it resulted in ıproved transistor reliability. When it was further no-ced that the SiO_2 layer could act as a diffusion mask ıd as isolation for integrated metallization, the way was ıen for the invention of the integrated circuit.

multicrystalline silicon! As short forms, c-Si is used for crystalline silicon and a-Si for amorphous silicon, while polycrystalline silicon is known simply as poly. In the solar cell industry crystalline silicon is sometimes called X-Si.

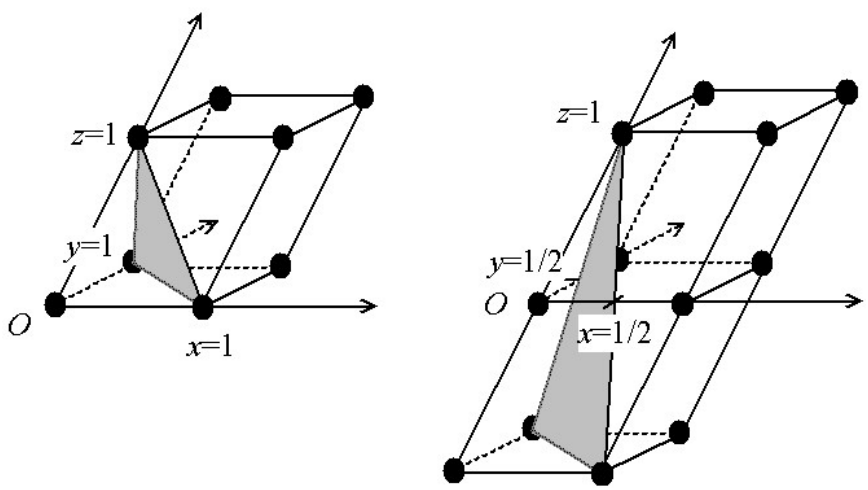
4.1 Silicon Material Properties

Silicon material properties are an excellent compromise between performance and stability. An energy gap of 1.12 eV makes silicon devices less prone to thermal noise than germanium devices with a 0.67 eV gap. Silicon is transparent in the infrared (above 1.1 µm wavelength) which means that it can used as an optical material at 1.55 µm telecom wavelength applications.

Crystal planes and directions: Miller indices



plan (111) plan (221)



A plane with the intercepts $1/h$, $1/k$, $1/l$ is the (h,k,l) plane.

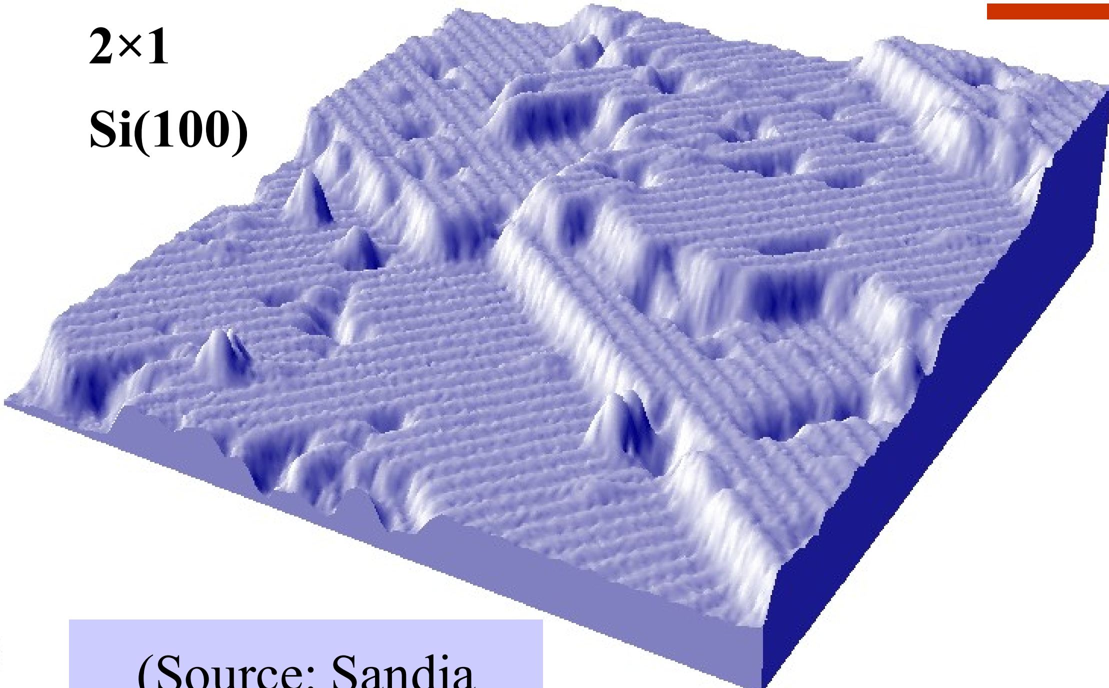
[ ] specific direction
< > family of equivalent directions
( ) specific plane
{ } family of equivalent planes

MOSFETs are made on <100> wafers

Silicon surfaces

2×1

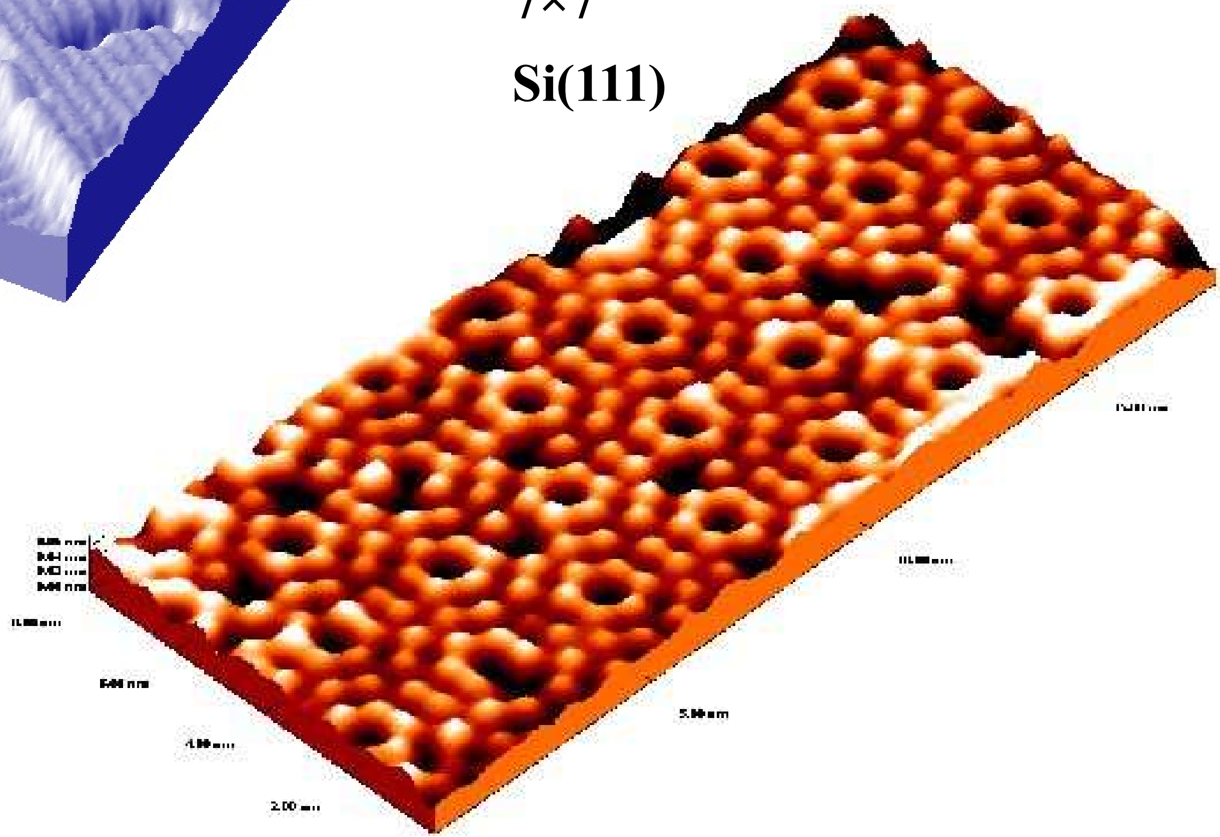
Si(100)



(Source: Sandia Nat.Labs.)

7×7

Si(111)



Density of surface atoms

(100) 6.78×10^{14} 1/cm²

(110) 9.59×10^{14} 1/cm²

(111) 7.83×10^{14} 1/cm²

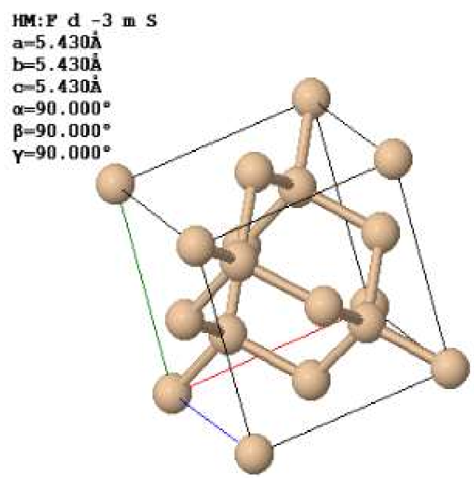
Silicon

Silicon is the second most common element in the earth's crust and an important semiconducting material.

Structural properties

Crystal structure: Diamond
Bravais lattice: face centered cubic
Space group: 227 (F d -3 m), Strukturbericht: A4, Pearson symbol: cF8
Point group: m3m (O_h) six 2-fold rotations, four 3-fold rotations, three 4-fold rotations, nine mirror planes, inversion
Lattice constant: $a = 0.543$ nm
Atomic weight 28.09
Atomic density $n_{atoms} = 4.995 \times 10^{22}$ 1/cm³
Density $\rho = 2.33$ g/cm³
Density of surface atoms

(100) 6.78×10^{14} 1/cm²
(110) 9.59×10^{14} 1/cm²
(111) 7.83×10^{14} 1/cm²



Conventional unit cell | Primitive unit cell
Asymmetric unit | 2 x 2 x 2 | 3 x 3 x 3 | 5 x 5 x 5
Ball and Stick | Spacefill

H: 1 K: 0 L: 0
show HKL plane | hide HKL plane
draw atoms in HKL plane
Thickness of HKL planes:

The conventional unit cell is a cube with sides of 0.543 nm. There are 8 atoms atoms in the conventional unit cell. (The image can be rotated with a mouse.)

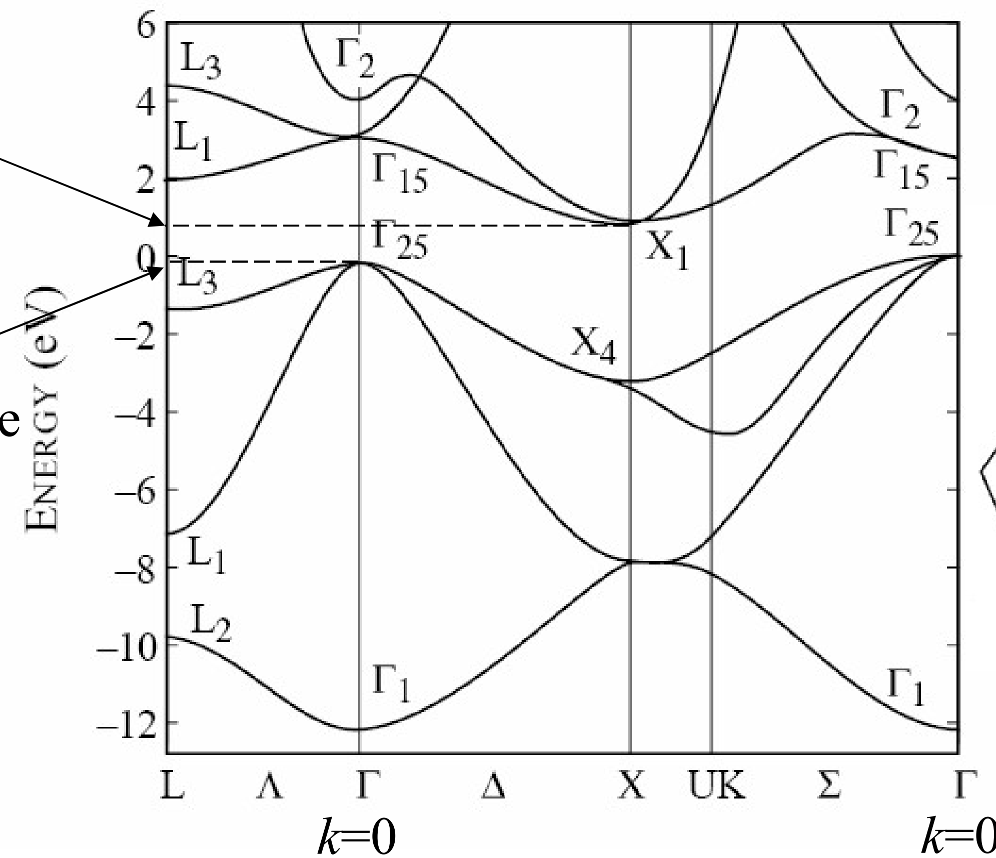
JSmol

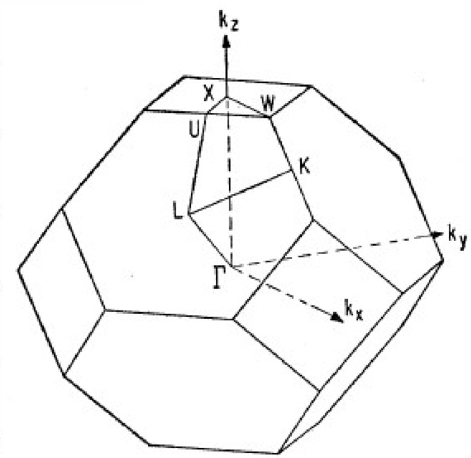
Silicon band structure

E_c = bottom of the conduction band

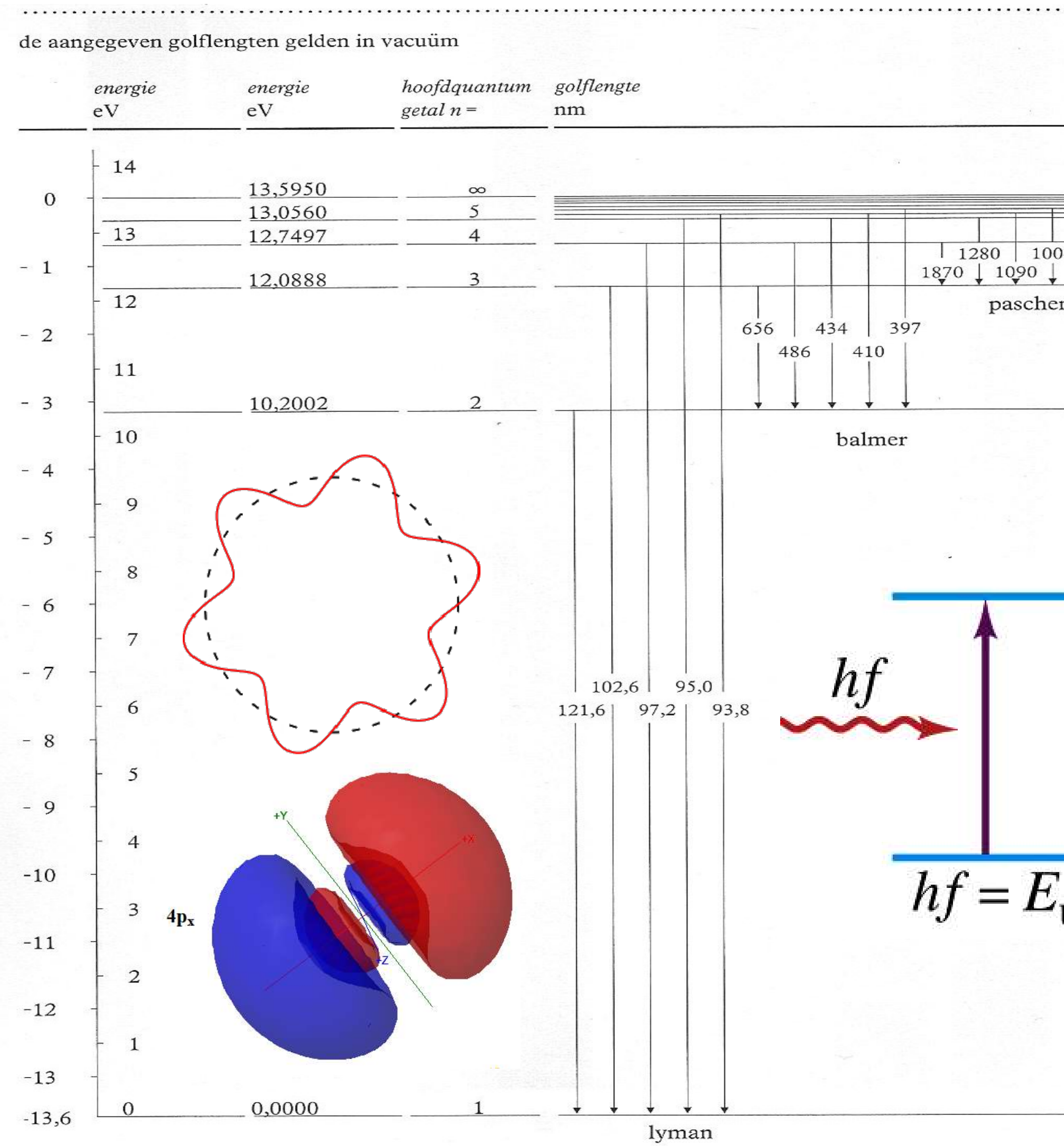
$E_g = E_c - E_v$

E_v = top of the valence band





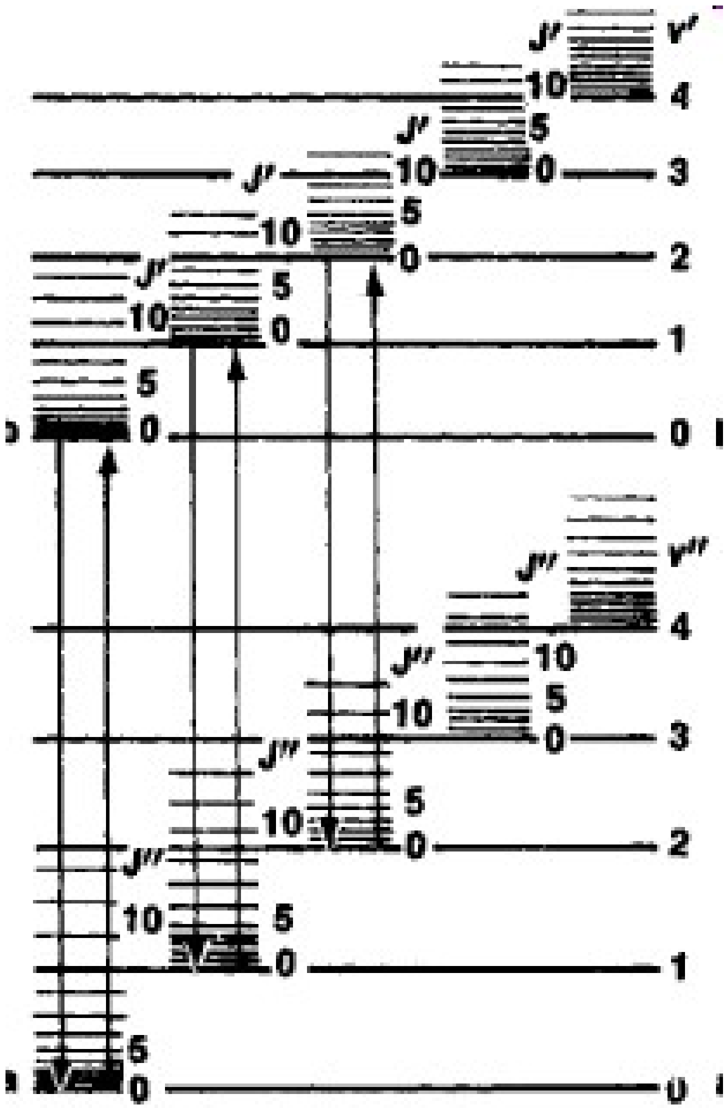
Electrons with energies in the gap are reflected out of the crystal.

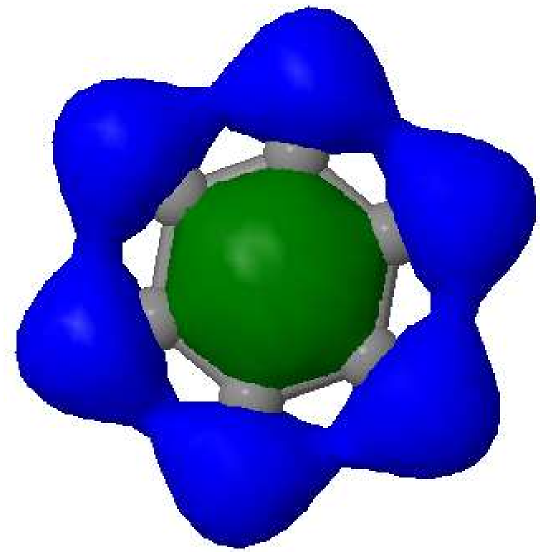


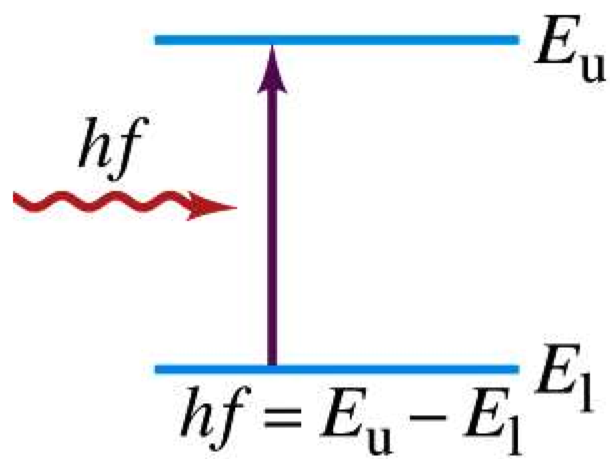
Fluorescent lamp

$$hf = E_u - E_l$$

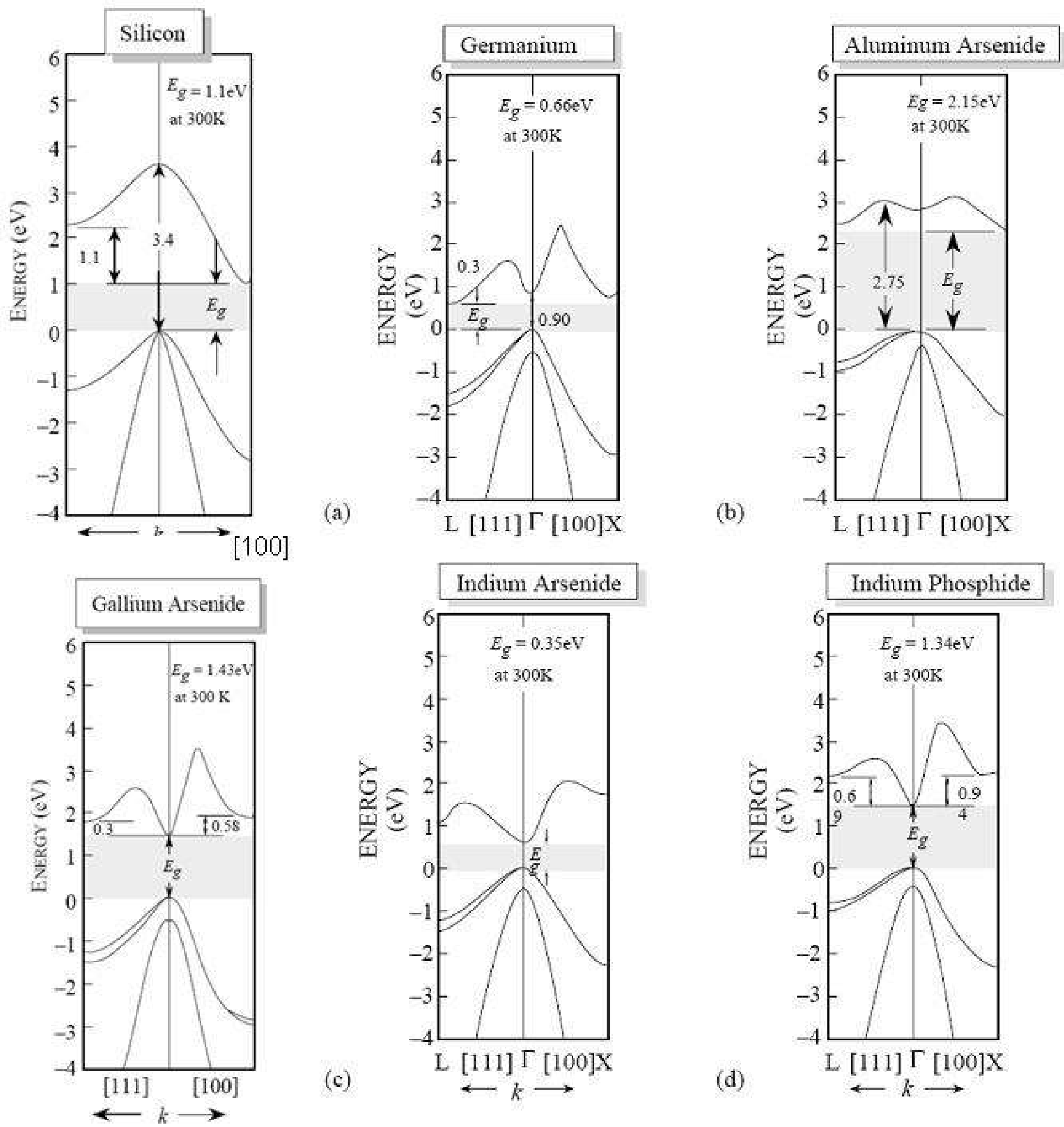
Molecular energy levels



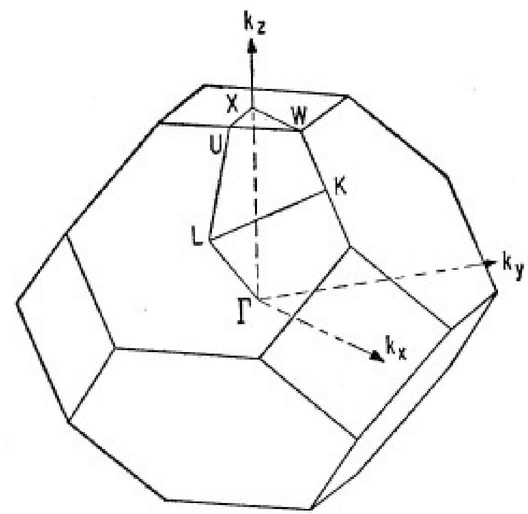




Semiconductors



valence band
conduction band
band gap



molecular orbitals
are plane waves

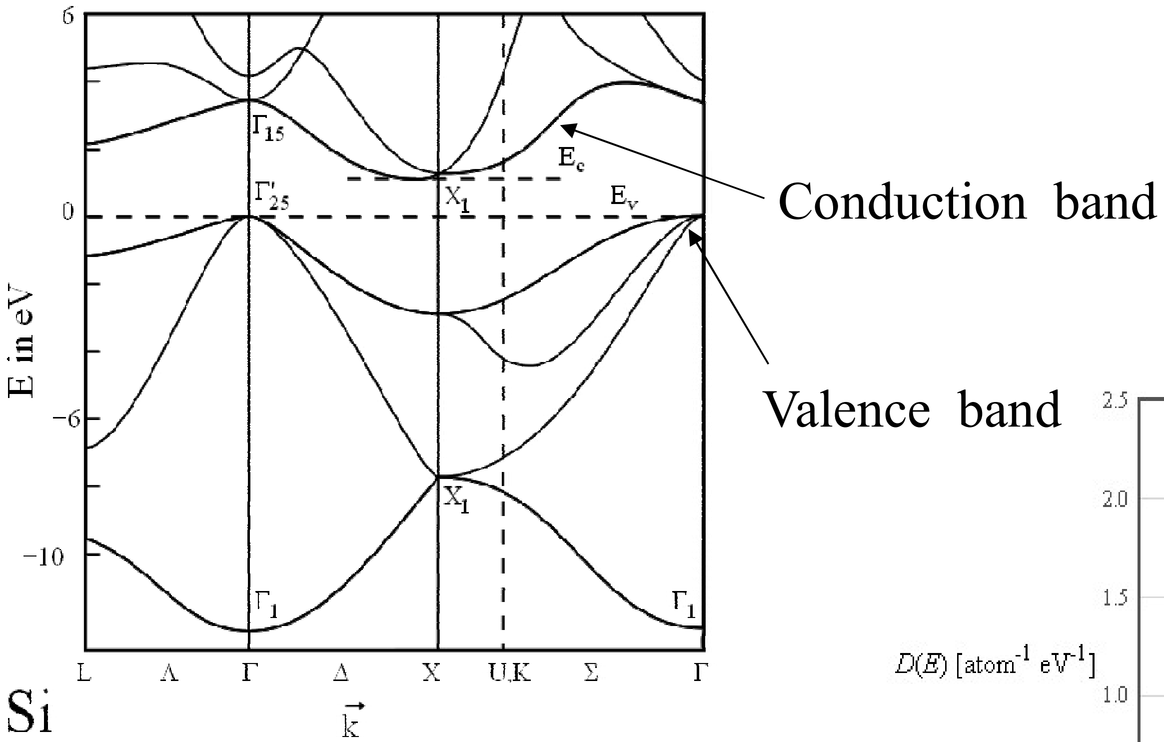
wave vector k

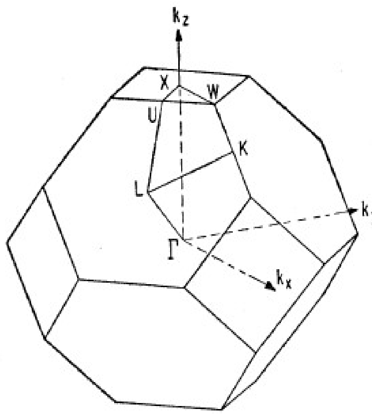
A *k*-vector points in the direction a wave is propagating.

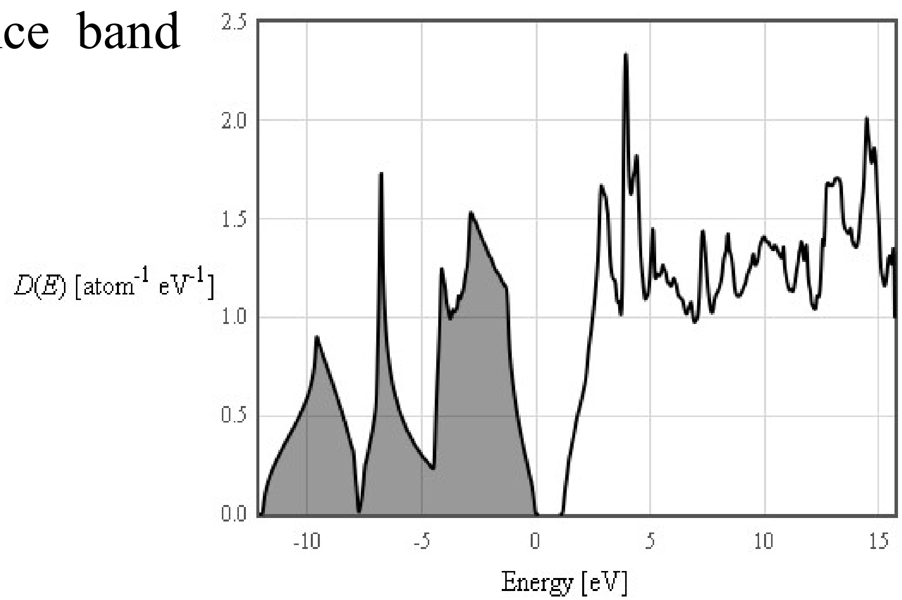
wavelength: $$\lambda = \frac{2\pi}{\left|\vec{k}\right|}$$

momentum: $$\vec{p} = \hbar\vec{k}$$

Silicon electronic structure



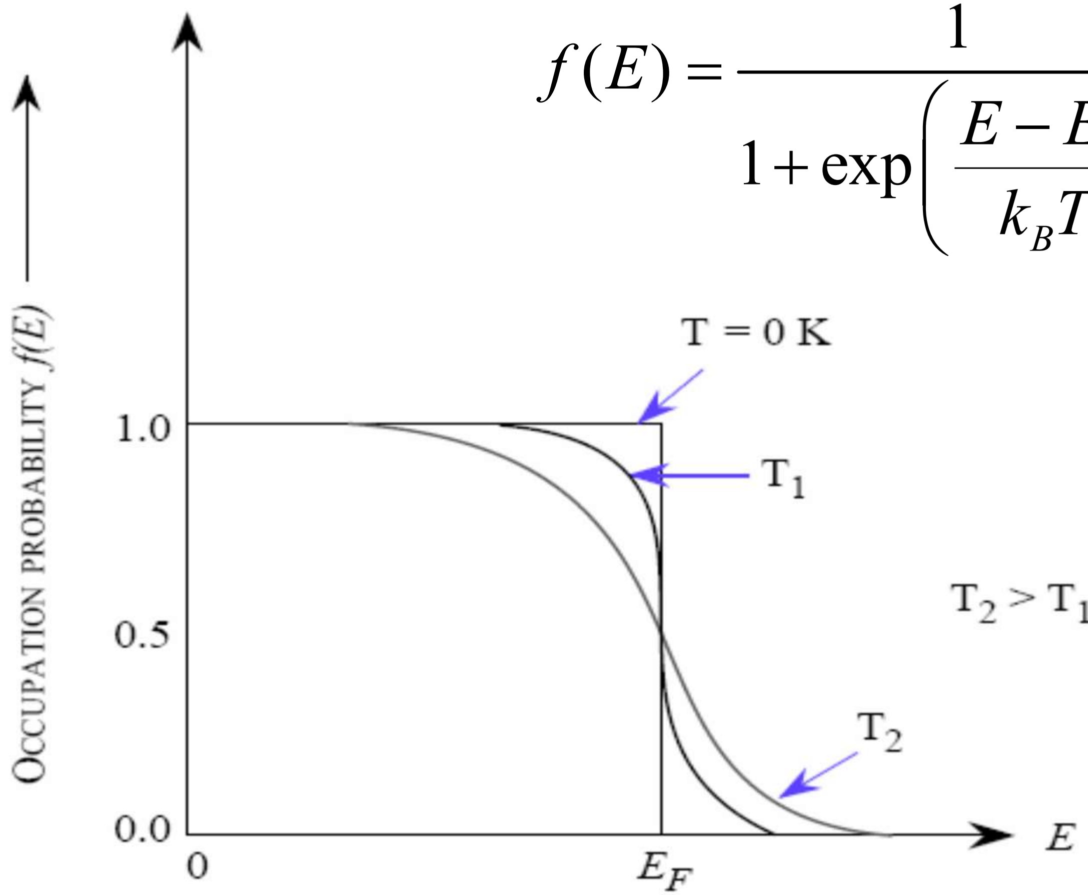




Fermi function

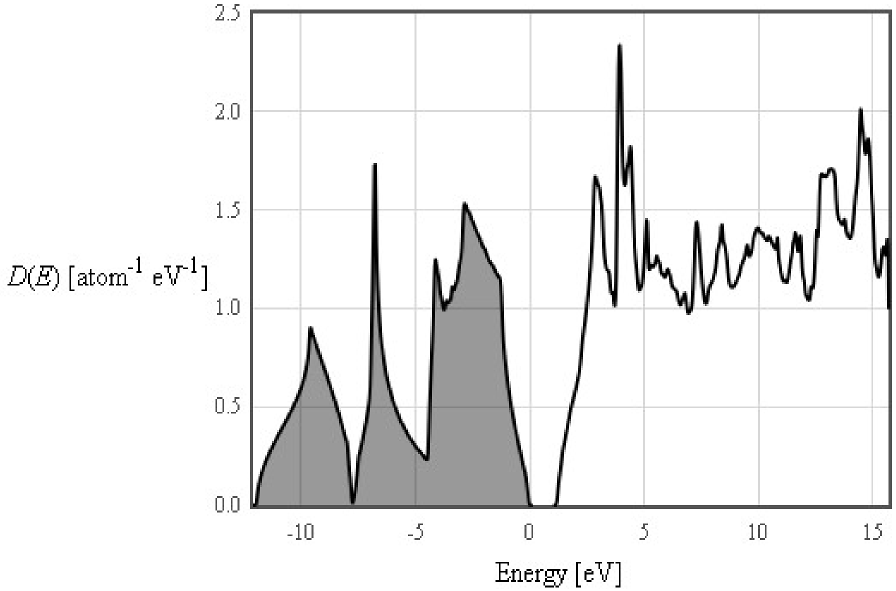
$f(E)$ is the probability that a state at energy E is occupied.

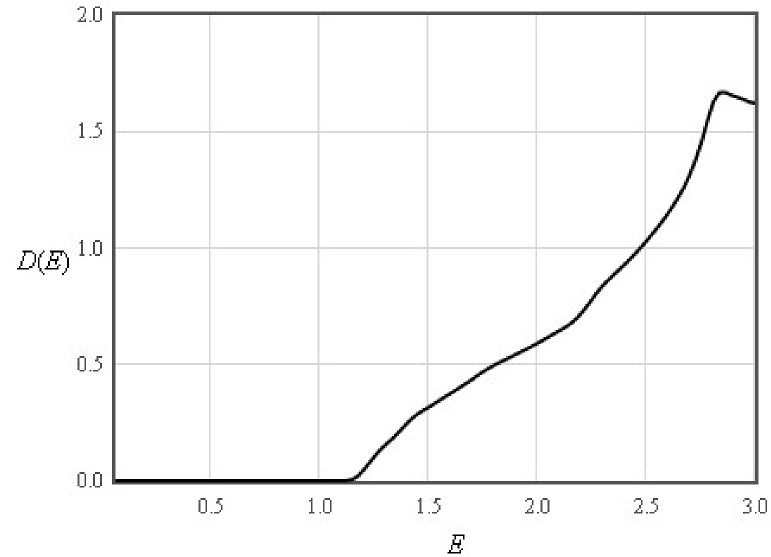
$$f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)}$$

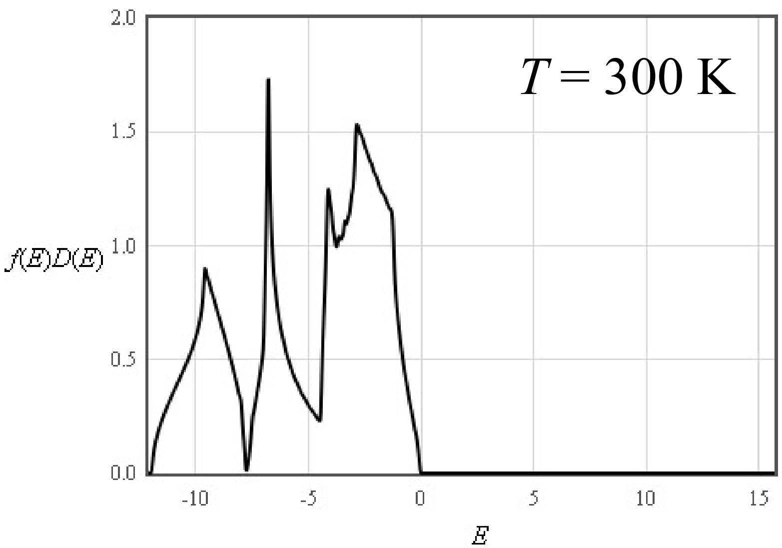


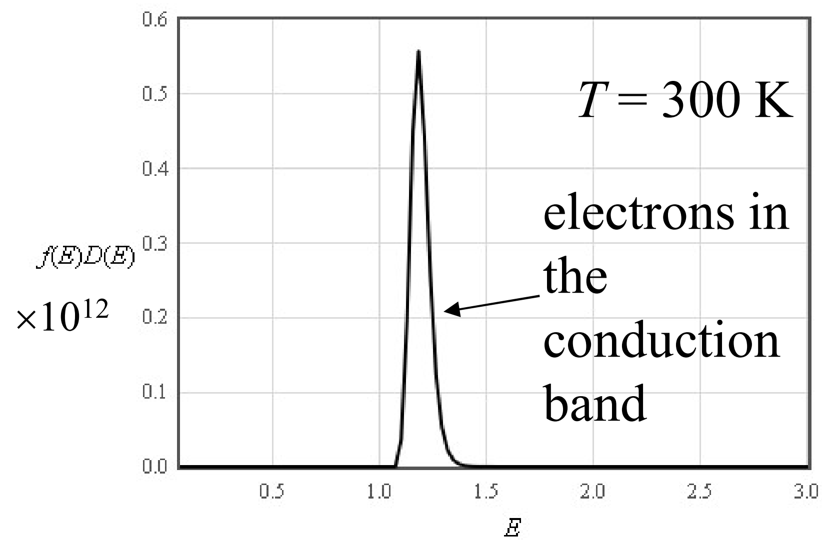
Electrons in the conduction band

$$n = N_c \left(\frac{T}{300}\right)^3 \exp\left(\frac{E_F - E_c}{k_B T}\right)$$

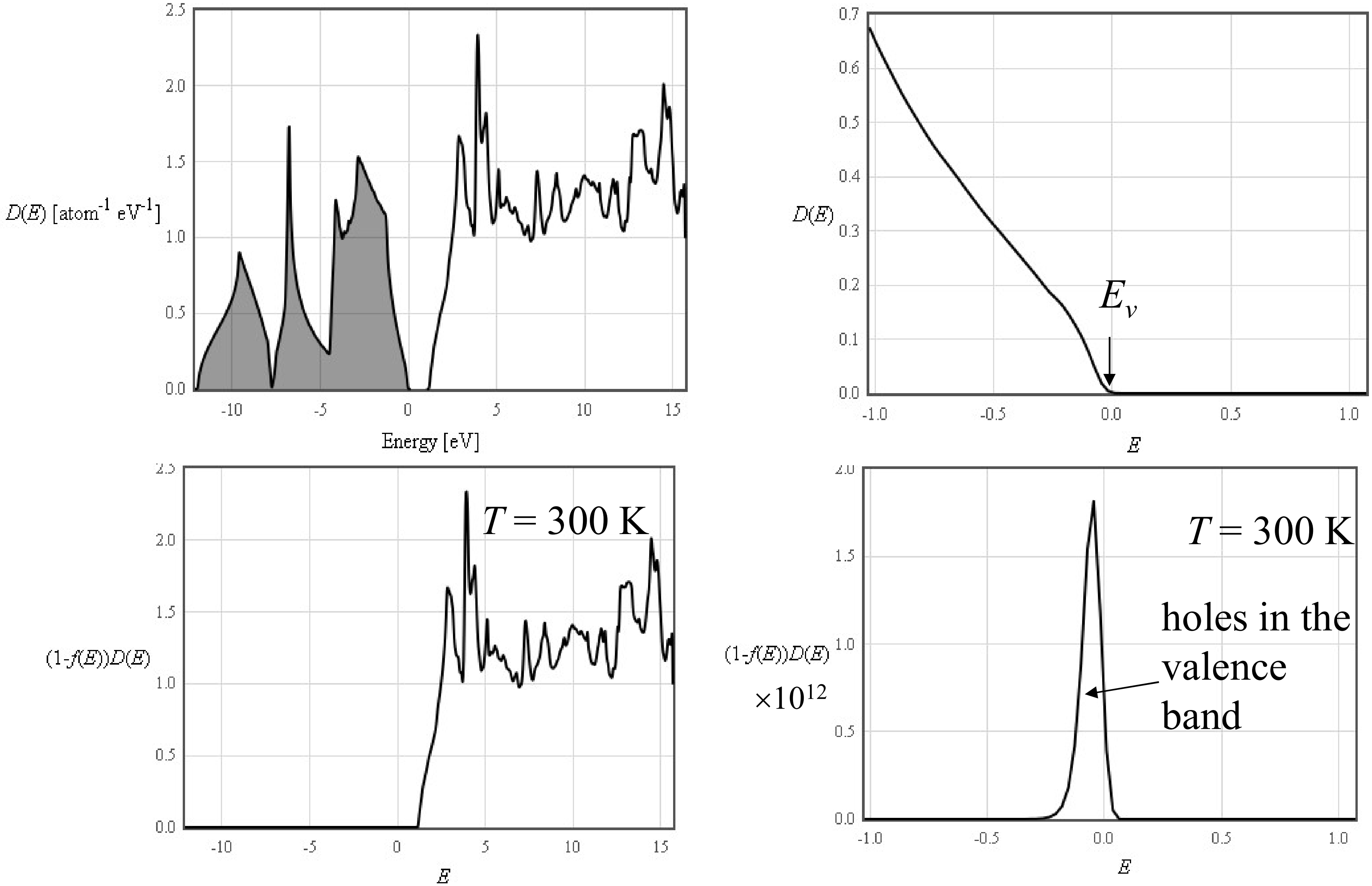




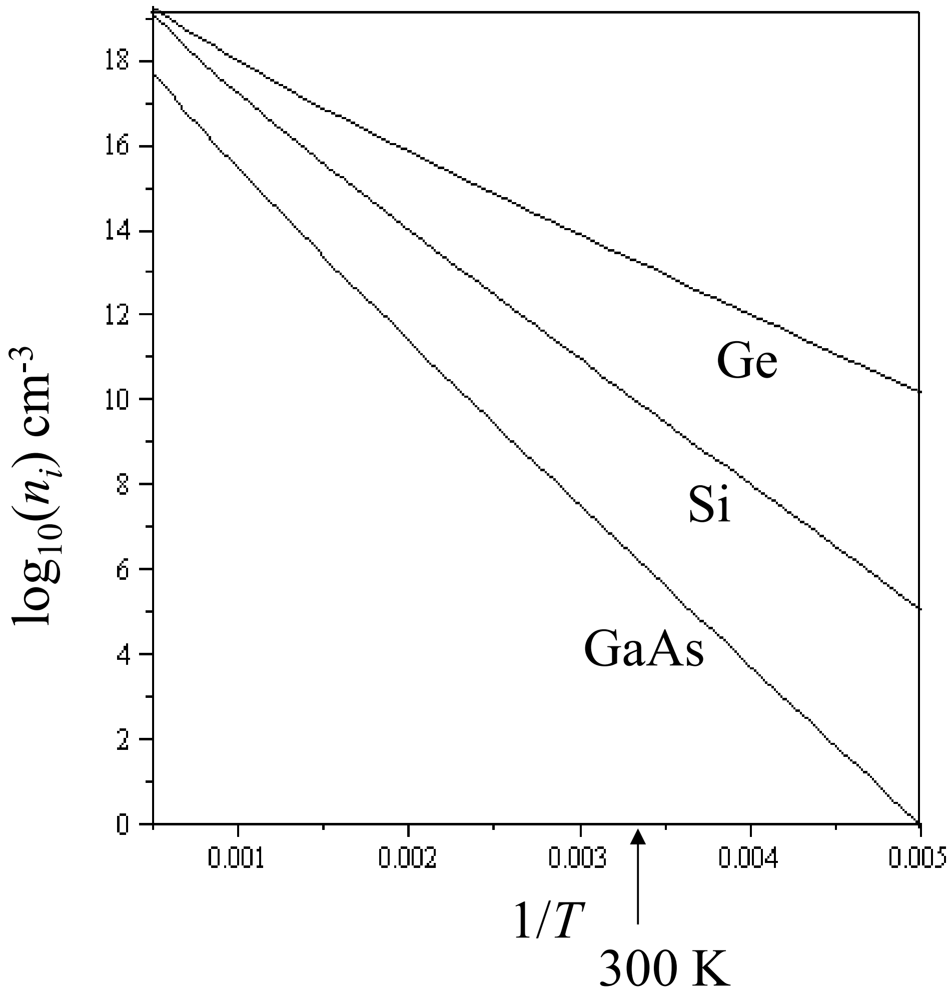




Silicon density of states



Intrinsic carrier concentration

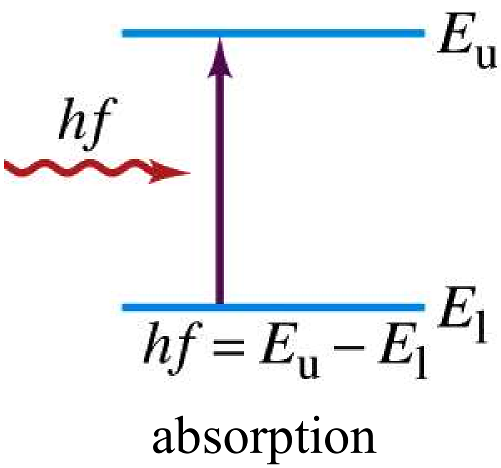


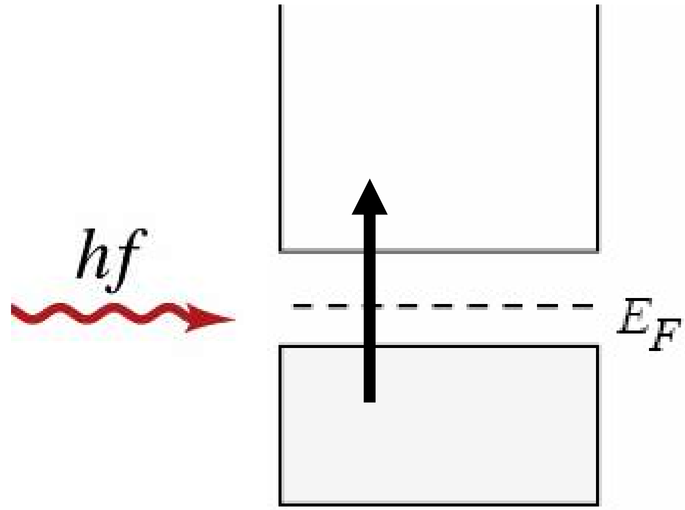
$$n = p = n_i$$

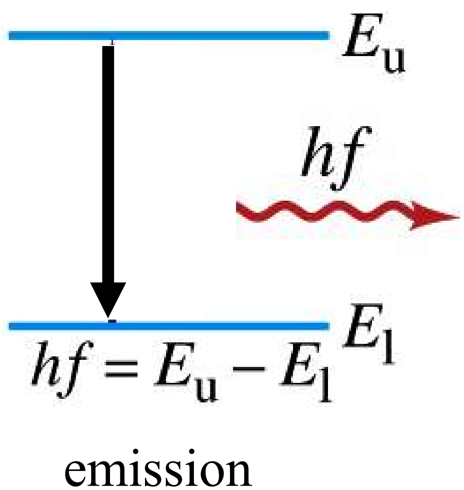
$$n_i = \sqrt{N_v N_c \left(\frac{T}{300}\right)^3} \exp\left(-\frac{E_g}{2k_B T}\right)$$

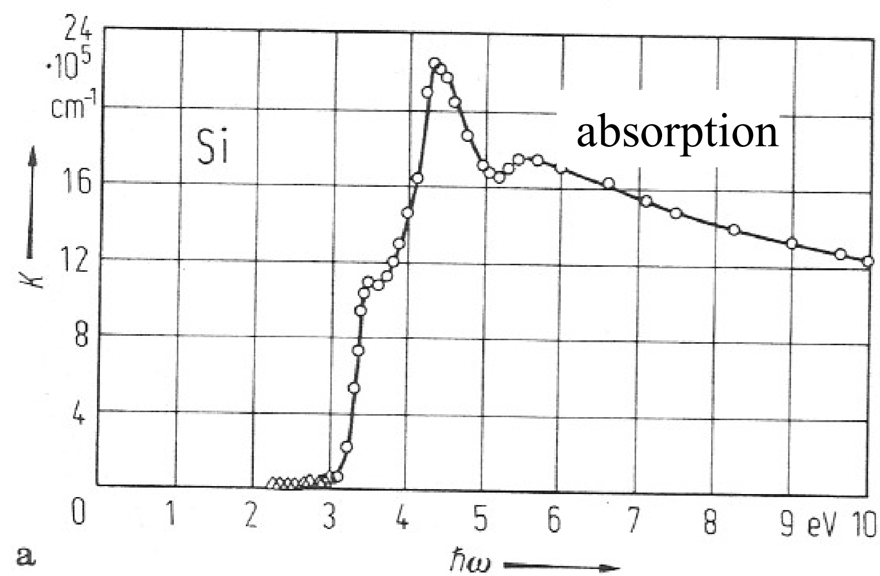
$\sim 5 \times 10^{22}$ atoms/cm^3

Absorption and emission of photons





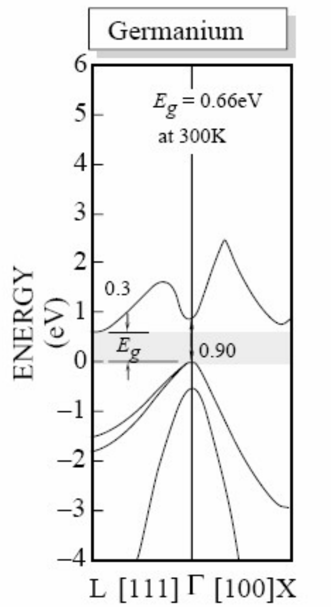




Direct and indirect band gaps

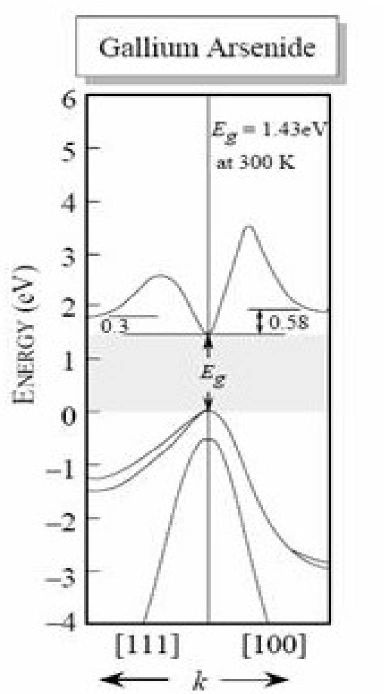
indirect bandgap
$\Delta k \neq 0$

phonons are emitted



direct bandgap:
$\Delta k = 0$

photons can be emitted



Momentum must be conserved when photons are absorbed or emitted.

What color light does GaAs emit?

$$E = 1.6022 \times 10^{-19} \times 1.43 \text{ J} = hf = \frac{hc}{\lambda}$$

$$\lambda = 867 \text{ nm} \quad \text{infrared}$$

Extrinsic semiconductors

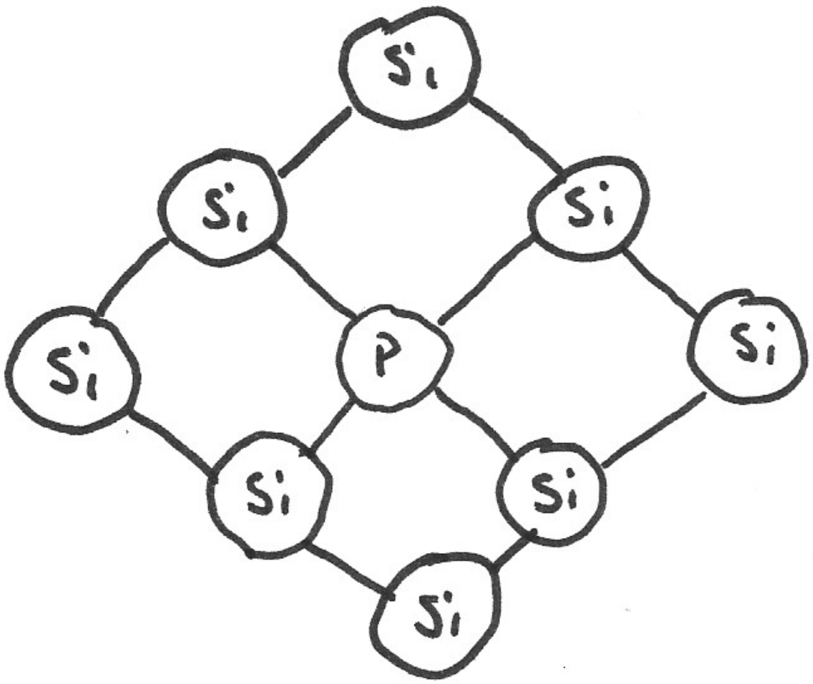
The introduction of impurity atoms that can and electrons or holes is called doping.

n-type : donor atoms contribute electrons to the conduction band. Examples: P, As in Si.

p-type : acceptor atoms contribute holes to the valence band. Examples: B, Ga, Al in Si.

IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te

Ionization of dopants



Easier to ionize a P atom in Si than a free P atom

$$E_n = -\frac{me^4}{8\varepsilon_0^2 h^2 n^2}$$

Ionization energy is smaller by a factor: $\frac{m^*}{m}\left(\frac{\varepsilon_0}{\varepsilon_r \varepsilon_0}\right)^2$

Ionization energy ~ 25 meV

Direct Observation of Friedel Oscillations around Incorporated Si_{Ga} Dopants in GaAs by Low-Temperature Scanning Tunneling Microscopy

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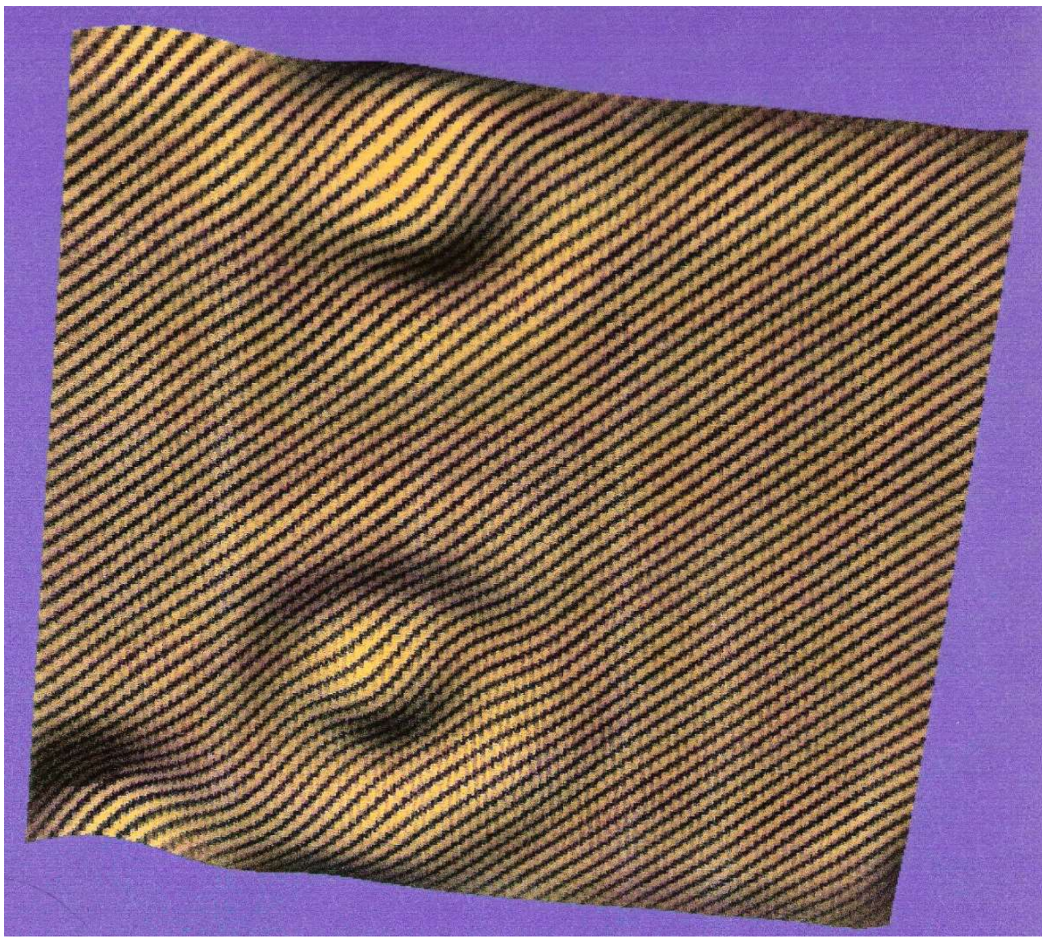
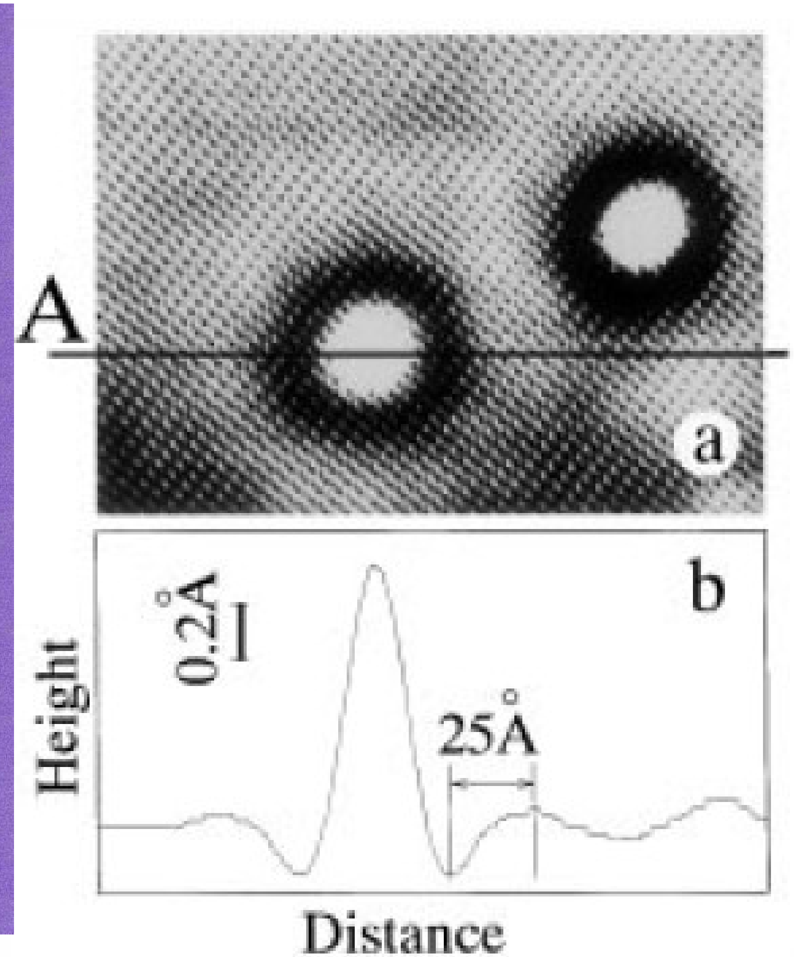
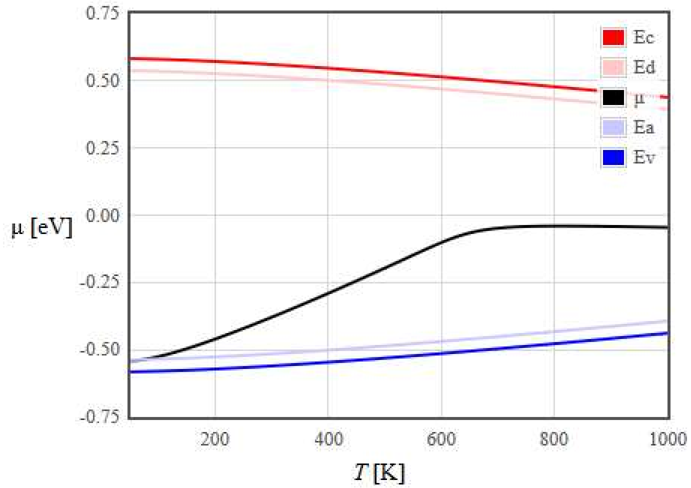
Research Institute for Materials, University of Nijmegen, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands
(Received 25 July 1995)





Extrinsic semiconductors (Boltzmann approximation)

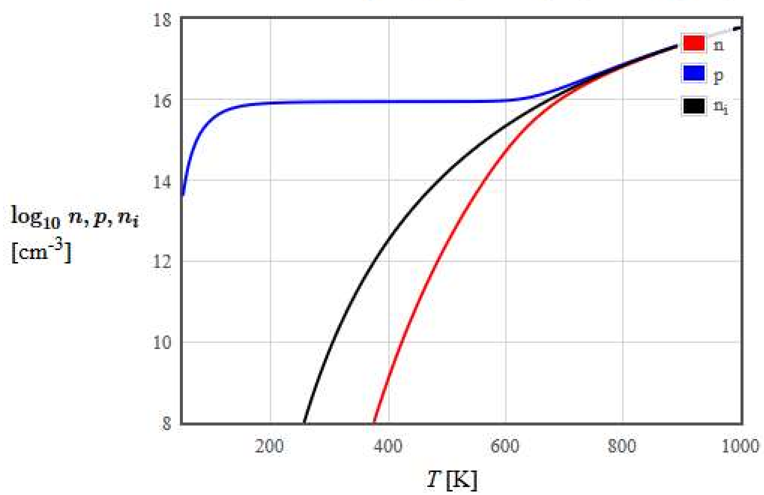
The chemical potential μ of an extrinsic semiconductor is plotted as a function of temperature. At each temperature the chemical potential was calculated by requiring that charge neutrality be satisfied.

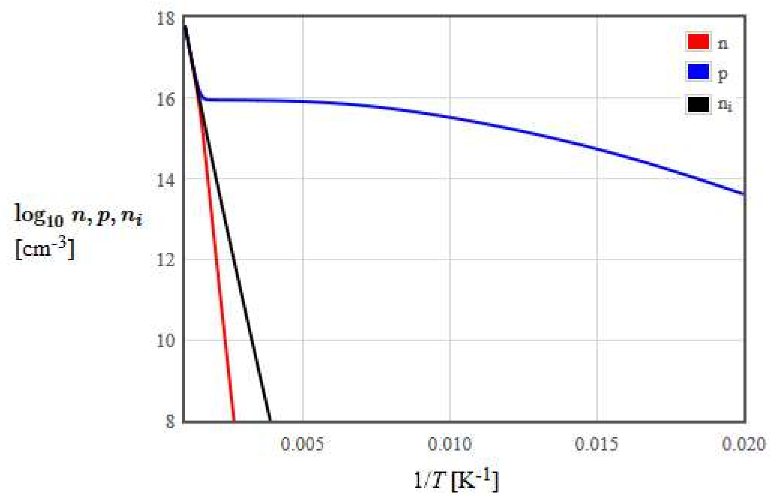


N_c(300 K) =	2.78E19	1/cm³	Semiconductor: Si, Ge, GaAs
N_v(300 K) =	9.84E18	1/cm³	
E_g =	1.166-4.73E-4*T*T/(T+636)	eV	
N_d =	1E15	1/cm³	Donor: P in Si, P in Ge, Si in GaAs
E_c - E_d =	0.045	eV	
N_a =	1E16	1/cm³	Acceptor: B in Si, B in Ge, Si in GaAs
E_a - E_v =	0.045	eV	
T_1 =	50	K	
T_2 =	1000	K	
	Replot		

Once the Fermi energy is known, the carrier densities n and p can be calculated from the formulas, $n = N_c\left(\frac{T}{300}\right)^{3/2}\exp\left(\frac{\mu - E_c}{k_BT}\right)$ and $p = N_v\left(\frac{T}{300}\right)^{3/2}\exp\left(\frac{E_v - \mu}{k_BT}\right)$.

The intrinsic carrier density is $n_i = \sqrt{N_c\left(\frac{T}{300}\right)^{3/2} N_v\left(\frac{T}{300}\right)^{3/2}}\exp\left(\frac{-E_g}{2k_BT}\right)$.



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Dopant concentration, N_D
10^{15}
cm^{-3}
Resistivity, ρ
4.58
Ω·cm
MATERIAL INPUTS
Semiconductor
c-Silicon
Dopant species
Phosphorus
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Semiconductors on NSM

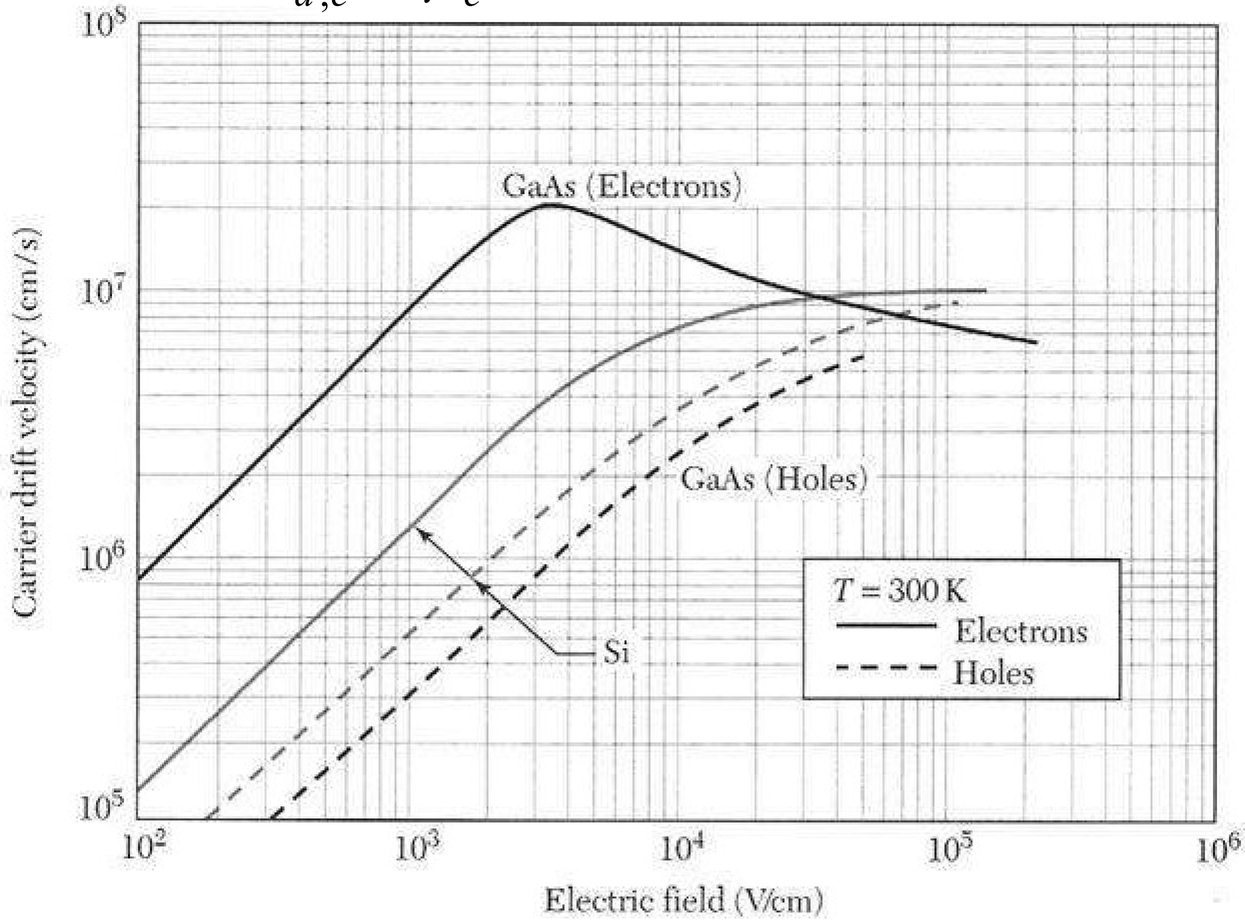
Si	- Silicon	Ge	- Germanium
GaP	- Gallium Phosphide	GaAs	- Gallium Arsenide
InAs	- Indium Arsenide	C	- Diamond
GaSb	- Gallium Antimonide	InSb	- Indium Antimonide
InP	- Indium Phosphide	$GaAs_{1-x}Sb_x$	- Gallium Arsenide Antimonide
$Al_xGa_{1-x}As$	- Aluminium Gallium Arsenide		
AlN	- Aluminium Nitride	InN	- Indium Nitride
BN	- Boron Nitride	GaN	- Gallium Nitride

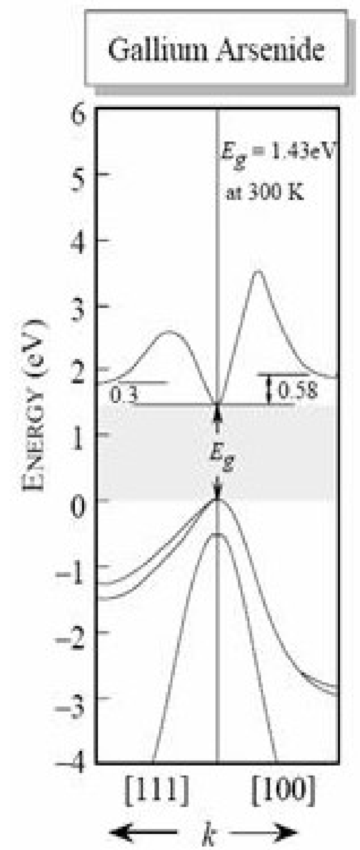
We are going to add new data for:

$Ga_xIn_{1-x}As_ySb_{1-y}$	- Gallium Indium Arsenide Antimonide	$Ga_xIn_{1-x}P$	- Gallium Indium Phosphide
$Ga_xIn_{1-x}As$	- Gallium Indium Arsenide	$Ga_xIn_{1-x}Sb$	- Gallium Indium Antimonide
$InAs_{1-x}Sb_x$	- Indium Arsenide Antimonide	$Ga_xIn_{1-x}As_yP_{1-y}$	- Gallium Indium Arsenide Phosphide
$Si_{1-x}Ge_x$	- Silicon Germanium	SiC	- Silicon Carbide

High fields

$$\vec{v}_{d,e} = \mu_e \vec{E} \qquad \vec{v}_{d,h} = \mu_h \vec{E}$$

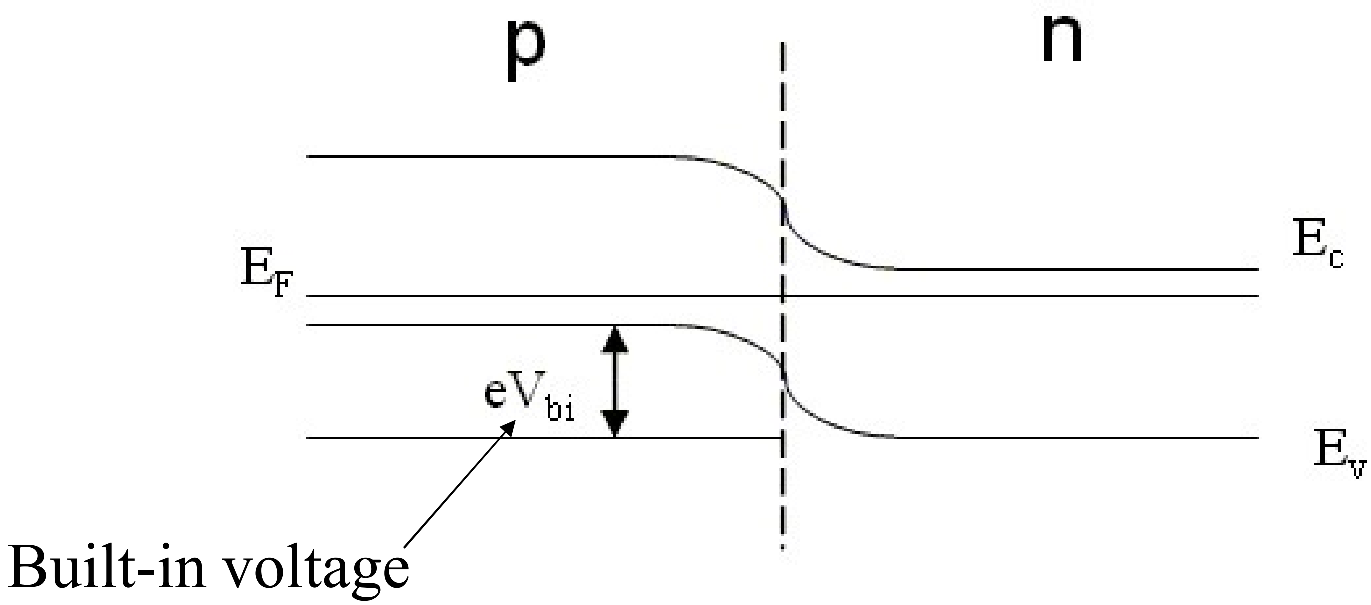




Emission of optical phonons causes the saturation of electron velocity.
There are no semiconductors without optical phonons.

pn junction

semiconductors in contact



Abrupt junction: the doping changes abruptly from p to n

$$eV_{bi} = k_B T \ln\left(\frac{N_D N_A}{n_i^2}\right)$$

Abrupt pn junctions in the depletion approximation

In an abrupt pn junction, the doping changes abruptly from p to n. It is common to solve for the band bending, the local electric field, the carrier concentration profiles, and the conductivity in the depletion approximation. In this approximation it is assumed that there is a depletion width W around the transition from p to n where the charge carrier dens are negligible. Outside the depletion width the charge carrier densities are equal to the doping densities so that the semiconductor is electrically neutral outside the depletion wi Using this approximation it is possible to calculate the important properties of the pn junction.

$N_A =$ 1E15 1/cm³ $N_D =$ 1E15 1/cm³ $E_g =$ 1.166-4.73E-4*T*T/(T+636) eV

$N_v(300) =$ 9.84E18 1/cm³ $N_c(300) =$ 2.78E19 1/cm³ $\epsilon_r =$ 12 $T =$ 300 K

$\mu_p =$ 480 cm²/V s $\mu_n =$ 1350 cm²/V s $\tau_p =$ 1E-10 s $\tau_n =$ 1E-10 s

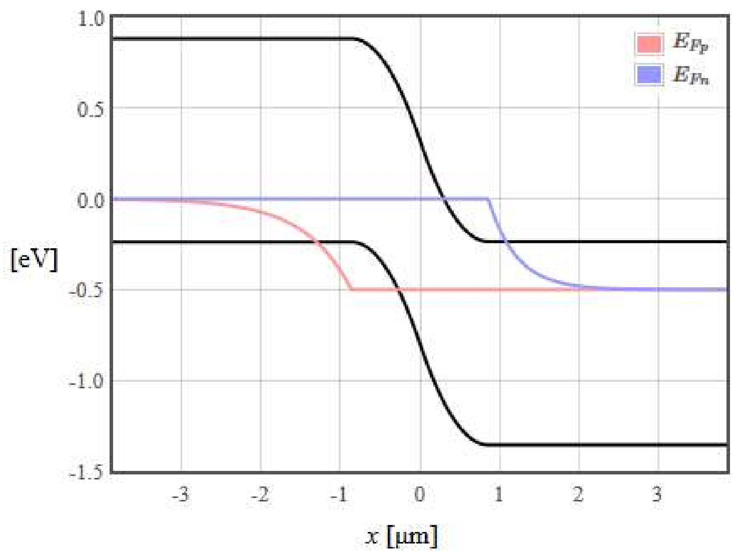
$V =$ -0.5 V

V Submit

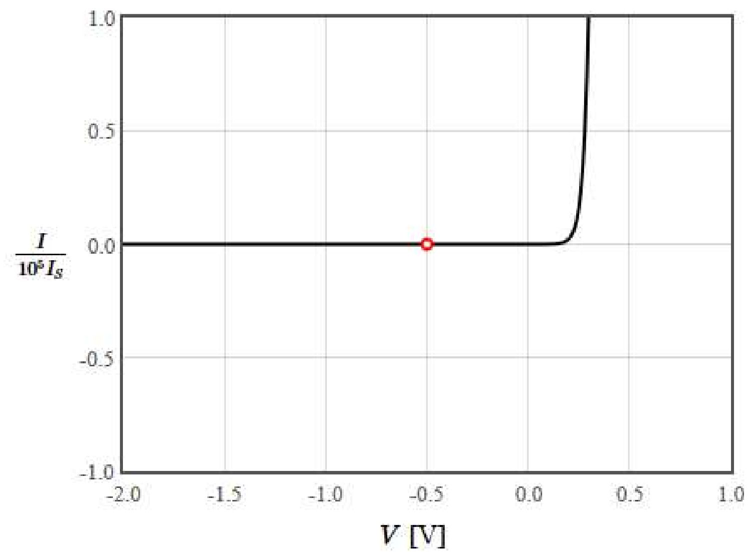
$E_g = 1.12$ eV $W = 1.72$ μm $x_p =$ -0.861 μm $x_n = 0.861$ μm $V_{bi} = 0.618$ V $C_j = 6.17$ nF/cm²

$D_p = 12.4$ cm²/s $D_n = 34.9$ cm²/s $L_p = 0.352$ μm $L_n = 0.591$ μm

Band diagram

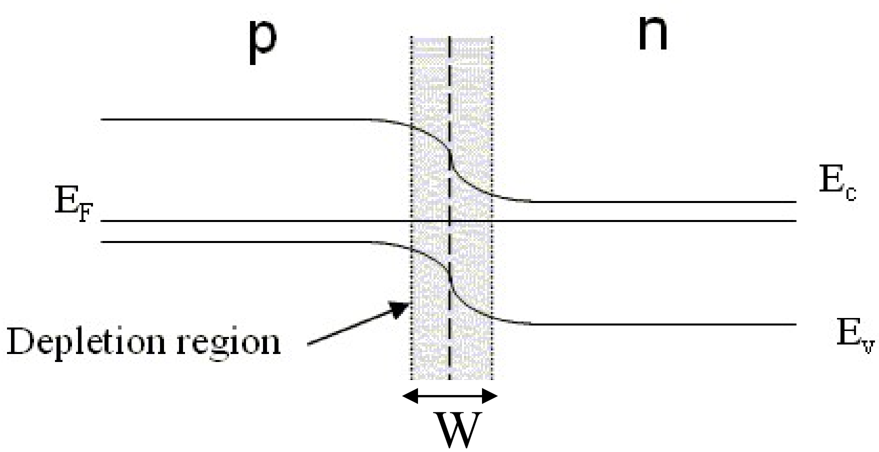


Current-Voltage Characteristics



http://lampx.tugraz.at/~hadley/psd/L6/abrupt.html

Depletion width



$V_{bi} \sim 1\text{V}$

$W \sim 1\mu\text{m}$

$E_{max} \sim 10^4$ V/cm

$v_{sat} \sim 10^7$ cm/sec

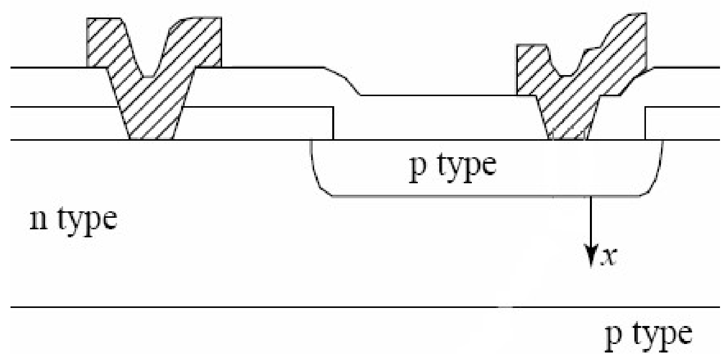
The electric field pushes the electrons towards the n-region and the holes towards the p-region.

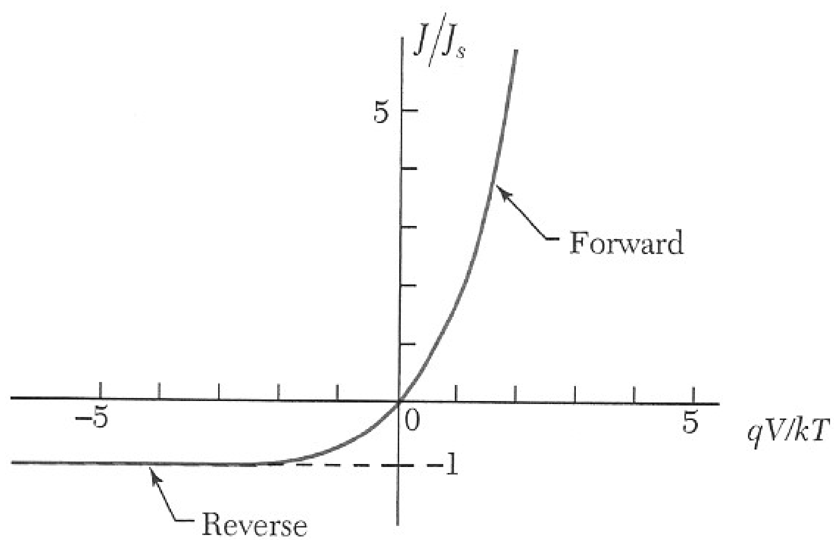
Diffusion sends electrons towards the p-region and holes towards the n-region.

Diodes

isolation
solar cells
Photodectectors
LEDs
laser diodes (CD, AFM, bar code)
signal diodes
surge protection
Zener diodes
thermometers
variable capacitors

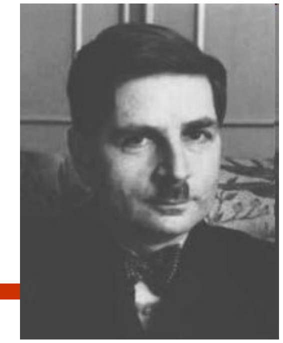
$$I = I_s\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

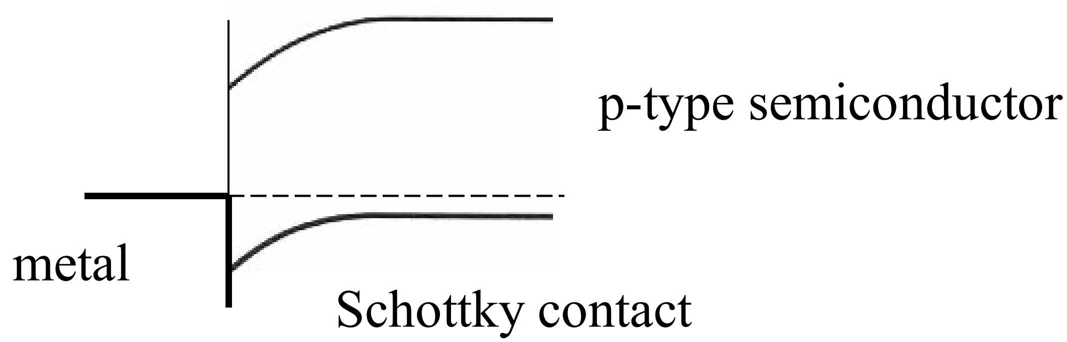


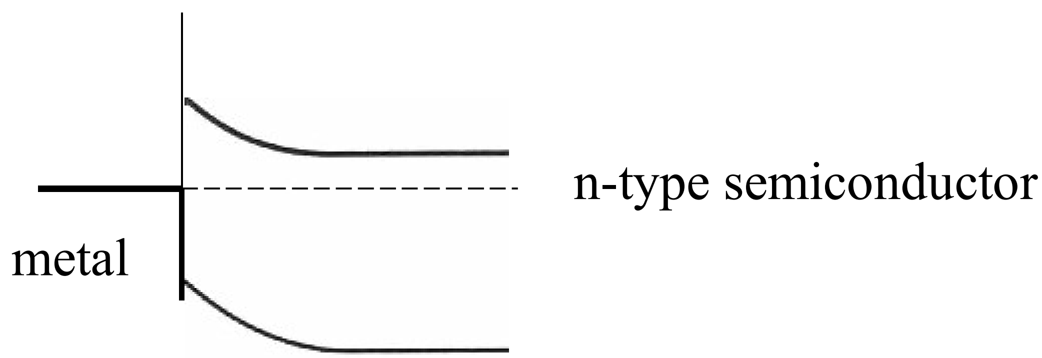


Schottky contact

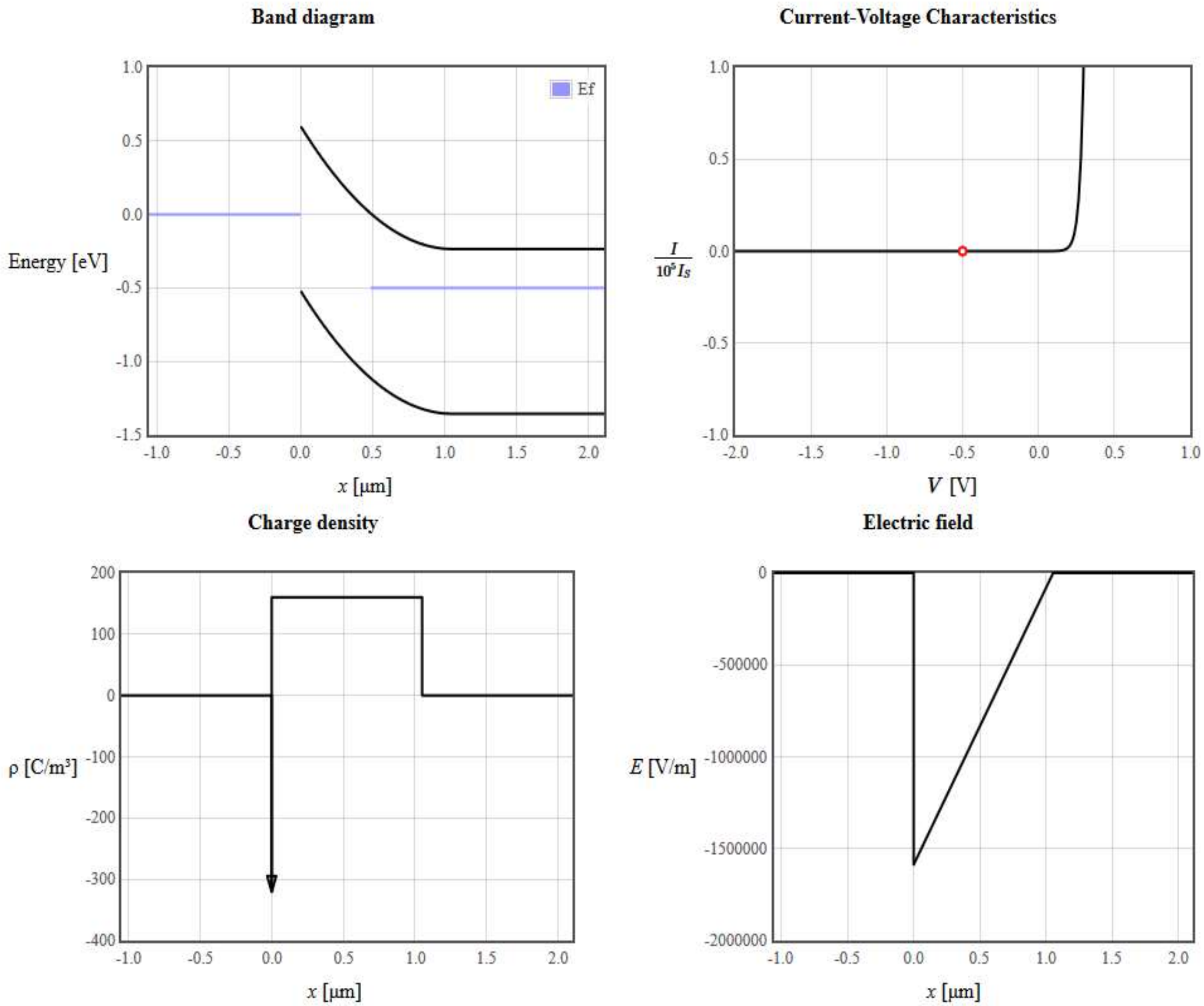
Walter Schottky







Schottky barrier



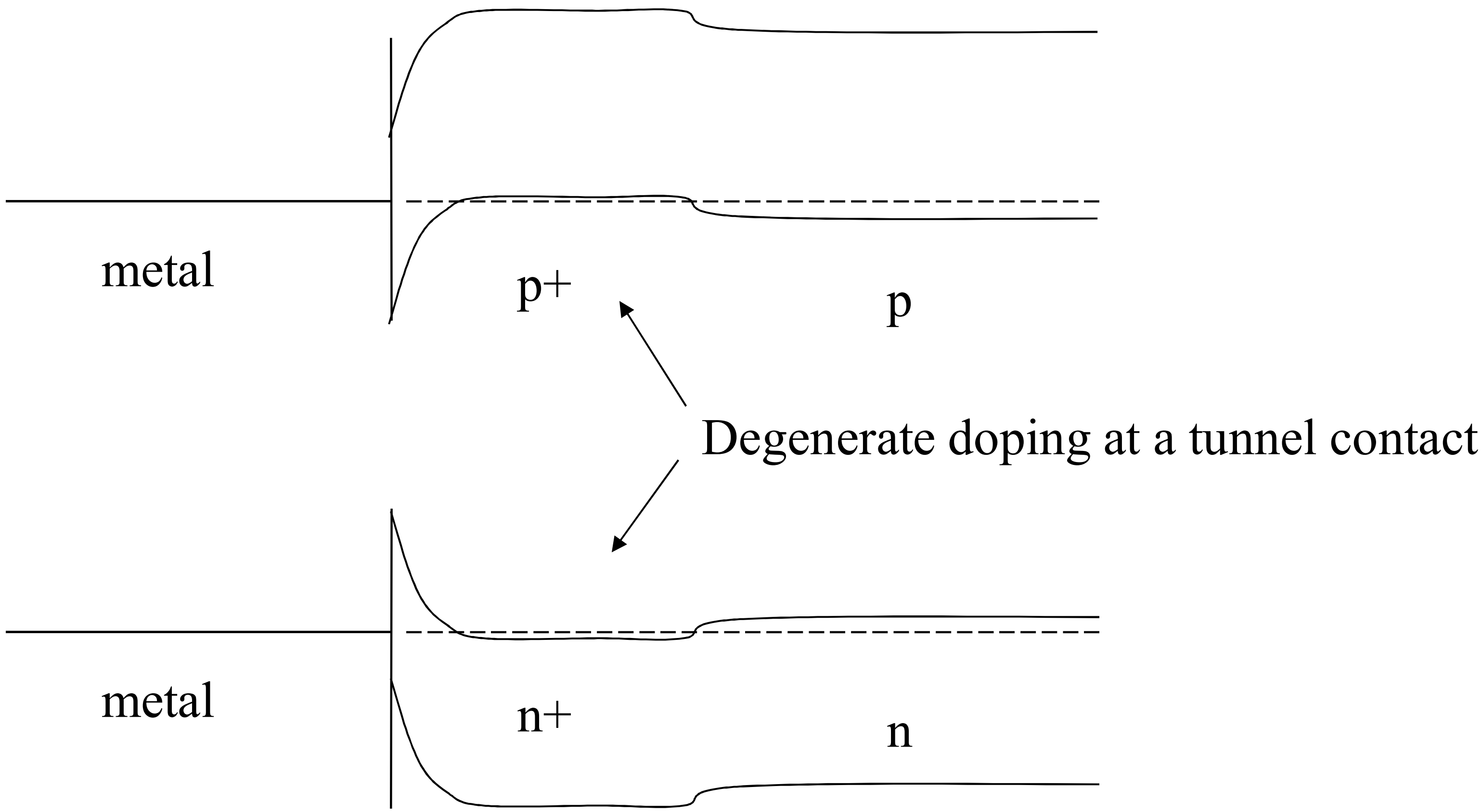
$$eV_{bi} = \phi_b - k_B T \ln\left(\frac{N_c(T)}{N_D}\right)$$

$$E = \frac{eN_D}{\varepsilon_r \varepsilon_0}\left(x - x_n\right) \qquad W \approx x_n = \sqrt{\frac{2\varepsilon\left(V_{bi} - V\right)}{eN_D}} \qquad V = \frac{-eN_D}{\varepsilon}\left(\frac{x^2}{2} - x x_n\right) \qquad 0 > x > x_n$$

Like a one sided junction, the metal side is heavily doped.

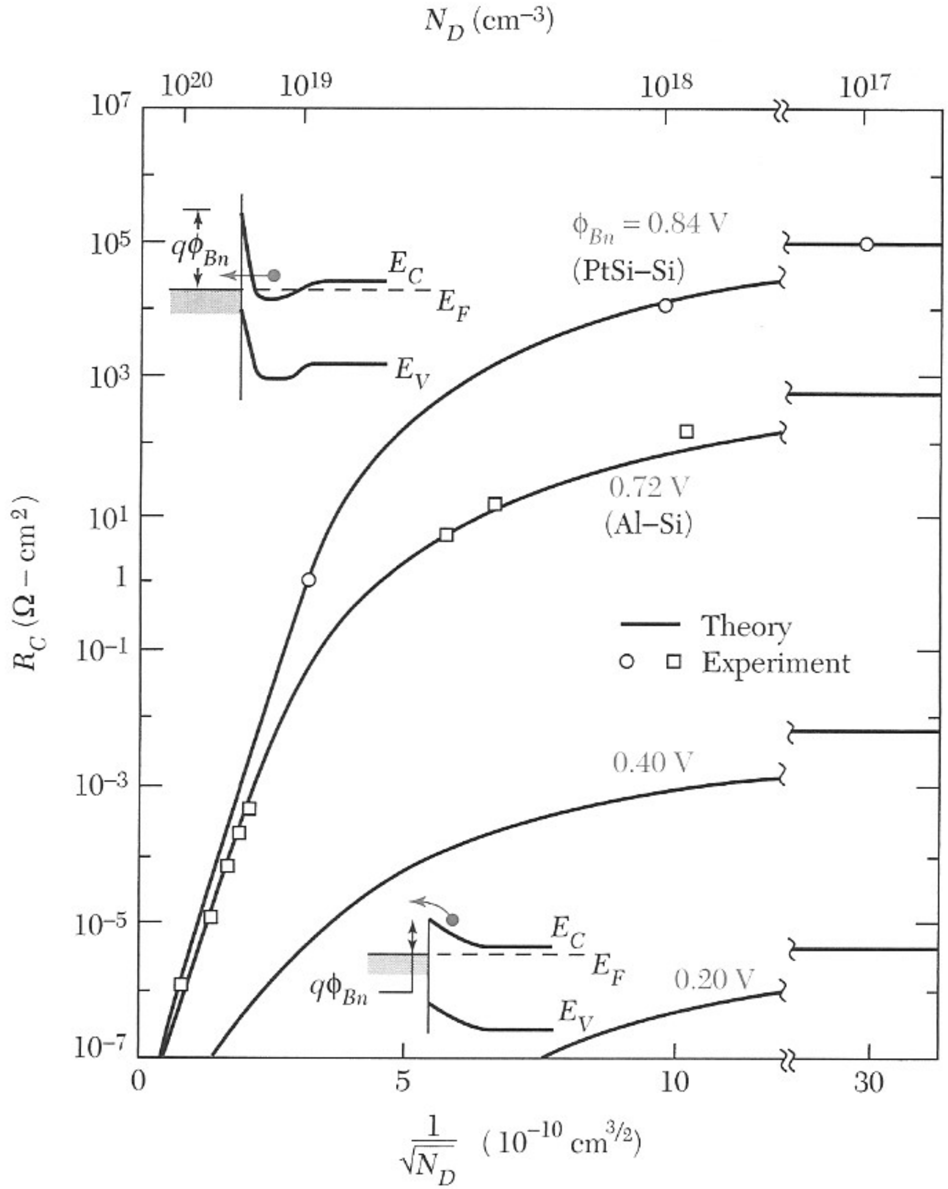
Tunnel contacts

For high doping, the Schottky barrier is so thin that electrons can tunnel through it.



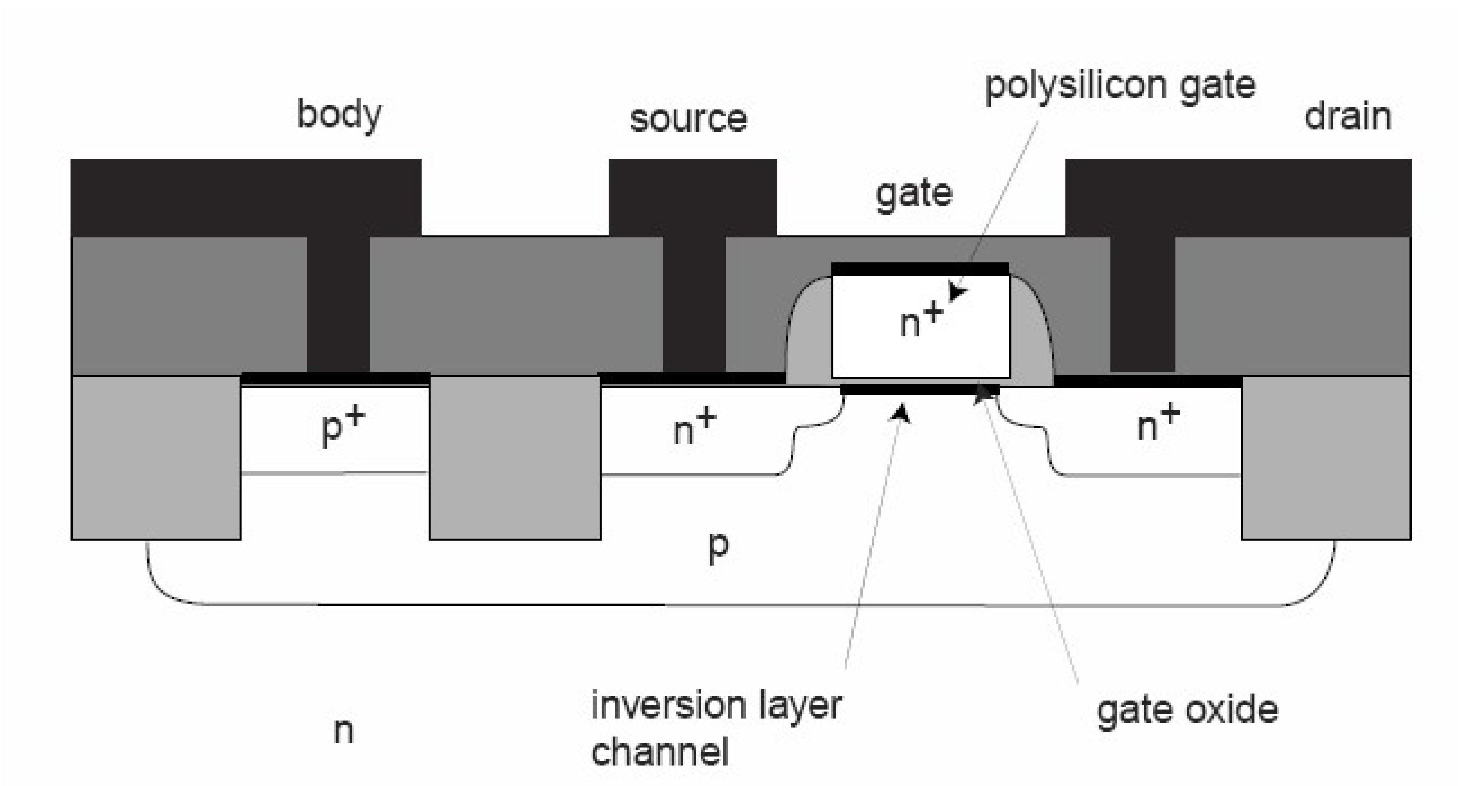
Tunnel contacts have a linear resistance.

Contacts



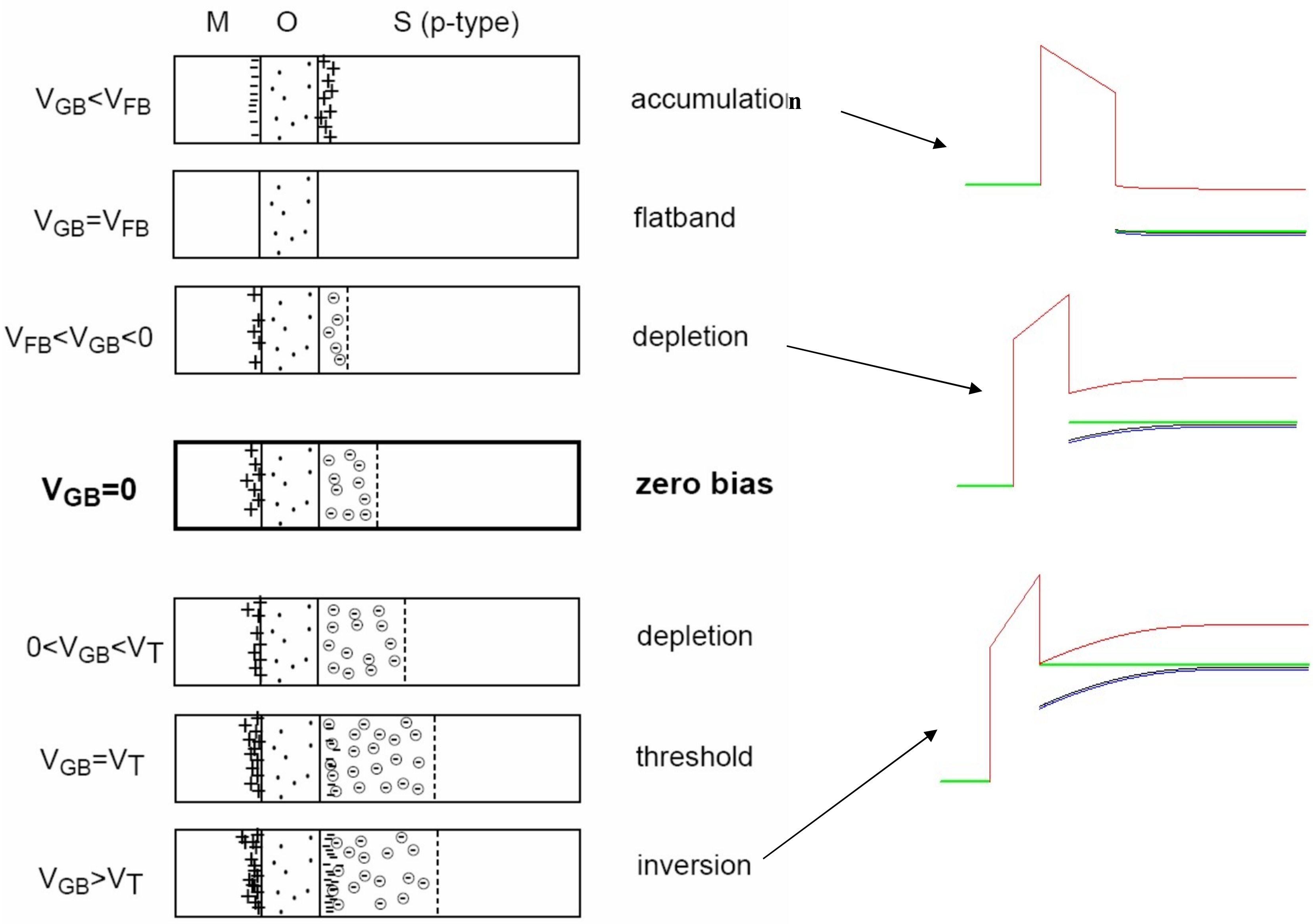
N_D (cm^{-3})
10^{20}
10^{19}
10^{18}
10^{17}
10^7
10^5
10^3
10^1
1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
R_C (Ω − cm^2)
$q\phi_{Bn}$
E_C
E_F
E_V
ϕ_{Bn} = 0.84 V
(PtSi–Si)
0.72 V
(Al–Si)
Theory
Experiment
0.40 V
0.20 V
0
5
10
30
$\frac{1}{\sqrt{N_D}}$ (10^{-10} cm$^{3/2}$)

MOSFET

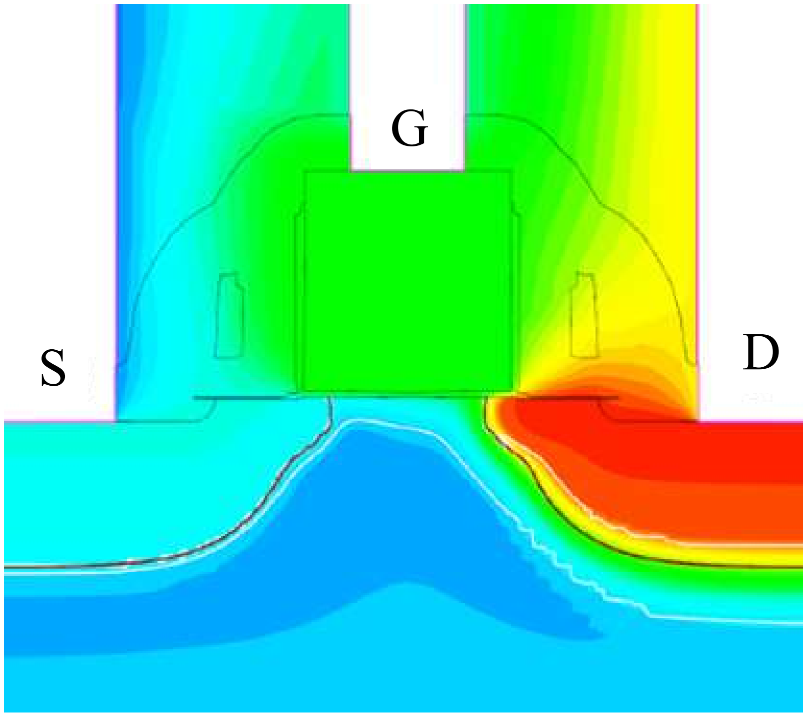


polysilicon gate
body
source
drain
gate
n+
p+
n+
n+
p
n
inversion layer
channel
gate oxide

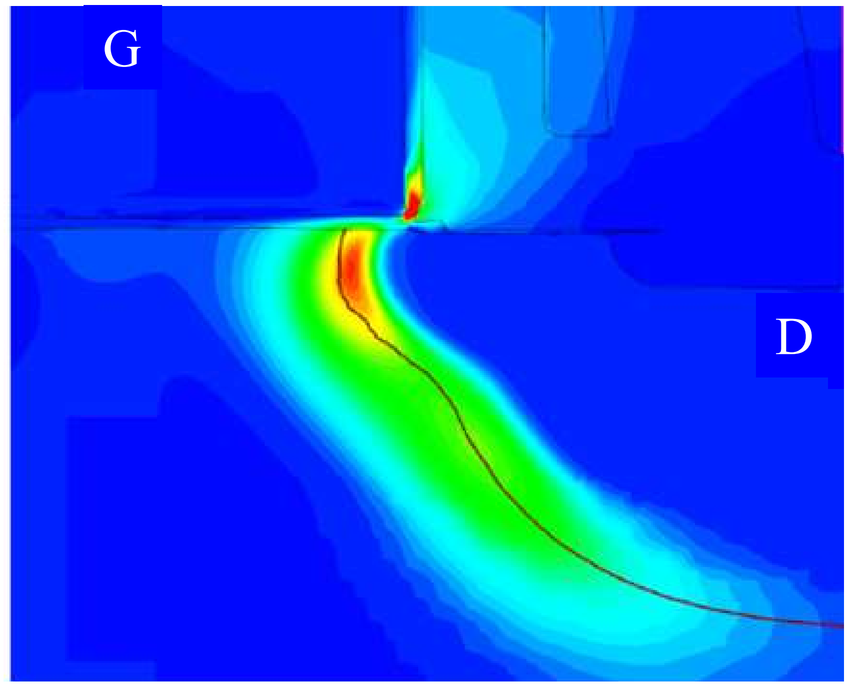
Accumulation/Depletion/Inversion



Saturation



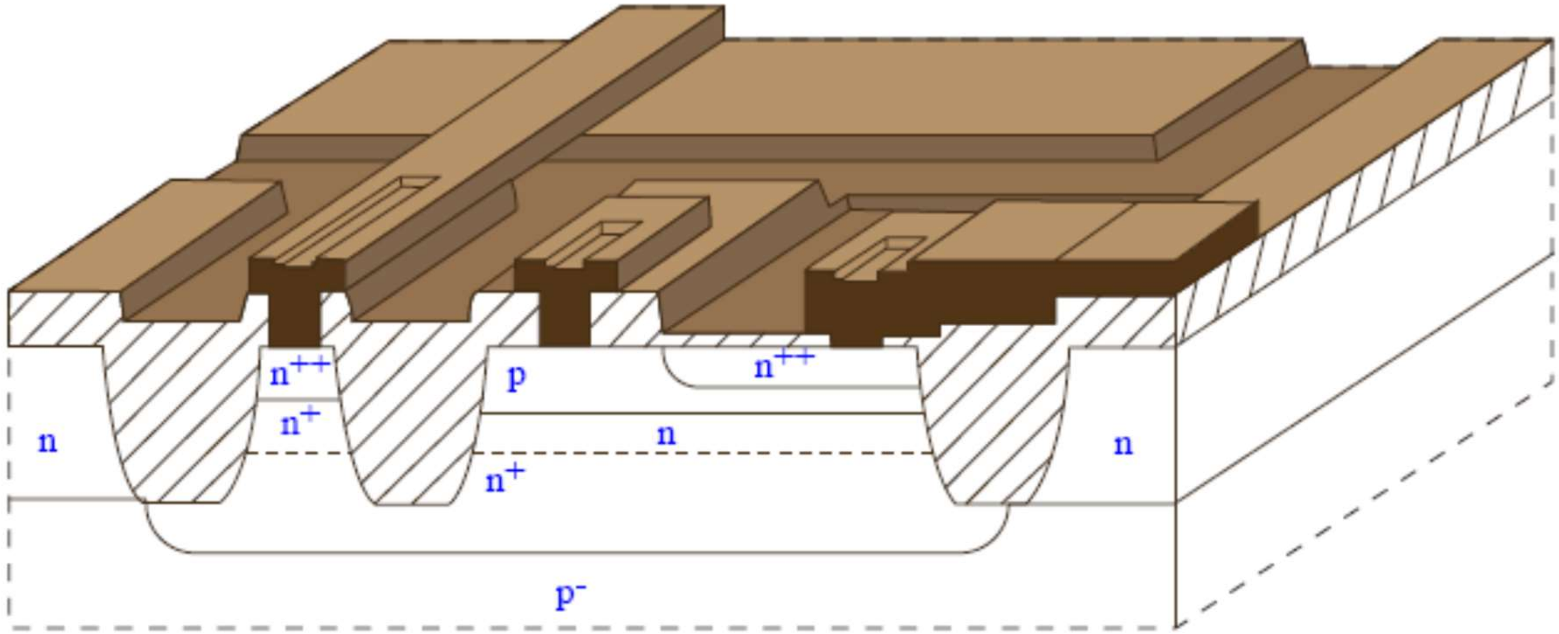
Potential



Electric field strength

Alexander Schiffmann, Master Thesis (2016)

Bipolar Junction Transistor



Oxide isolated integrated BJT - a modern process