

Modern Particle Physics Detectors I

Theory

Applications

Practice

Lesson 2: Silicon Photo-Detectors (part a)

Theory of p-n Junction (Diode)

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<http://dpnc.unige.ch/PhD>

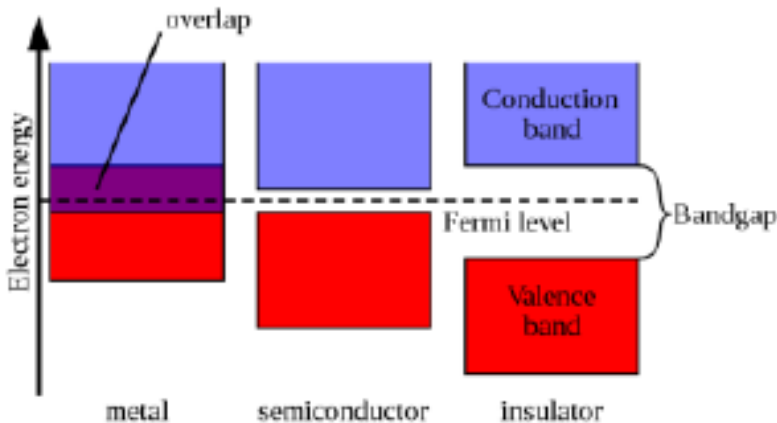
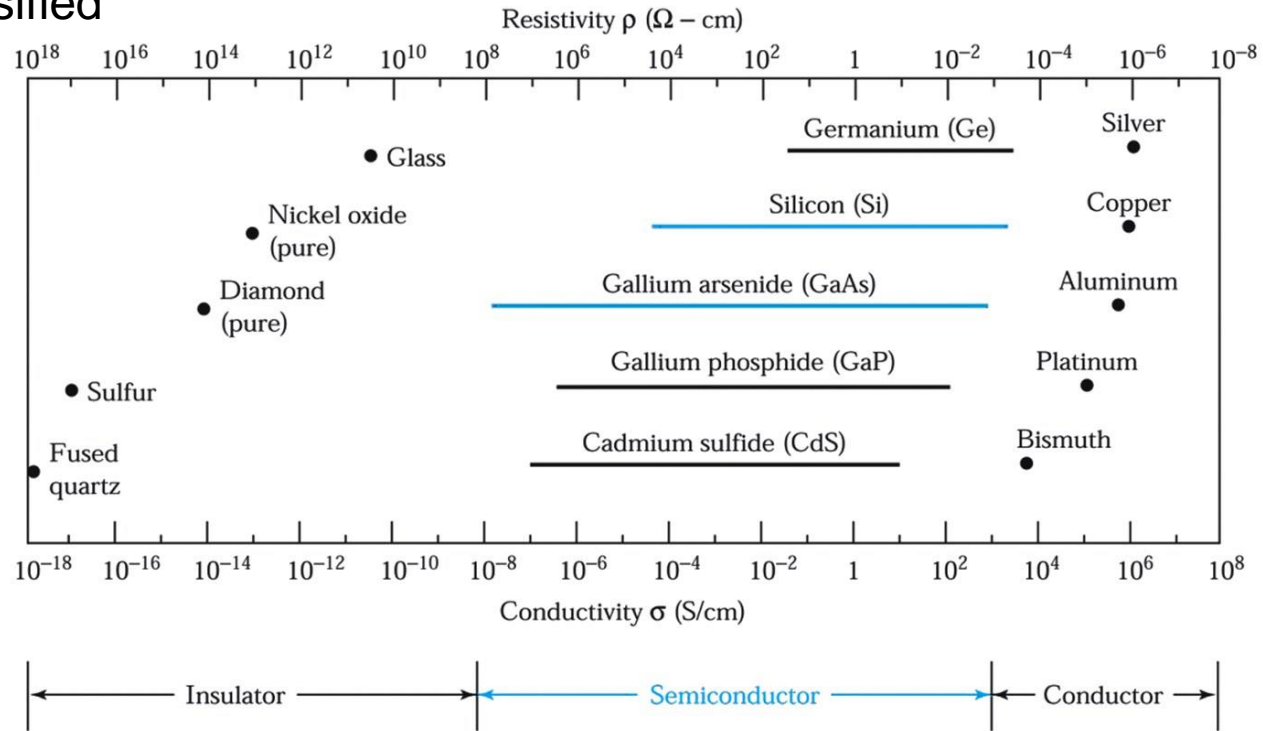


Conductors

Materials are generally classified into

- conductors
- semi-conductors
- insulators

based e.g. on their intrinsic resistivity (not only)



or the energy band structure
i.e. the energy required to move one electron from the valence to the conduction band)

$$E_g \sim O[10 \text{ eV}] \text{ in insulators}$$

$$E_g \sim O[\text{eV}] \text{ in semiconductors}$$

non-existing (overlap) in metals.

Advantage of Semi-Conductor Detectors

very small steady current “*leakage current*”

(this becomes a noise contribution when integrated in the electronics read-out)

very small energy necessary to create an e^-h^+ pair

(in Si 3.6 eV for a charged particle, and 1.2 eV for a photon)

high density (i.e. large energy loss dE/dx)

fast charge collection (i.e. the high speed of the signal)

operation in magnetic field

all together compact, fast and high resolution detectors

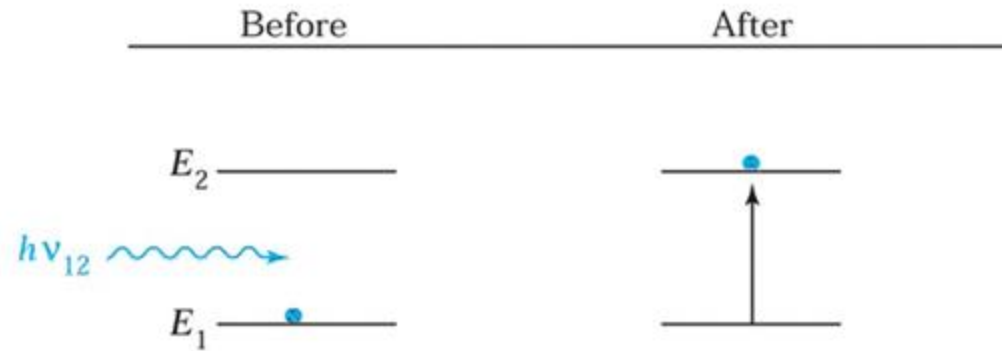
many individual diodes (of any shape) can be implanted on a silicon substrate:

they can act as independent sensing elements provided they are isolated from each other (some physical or electronics x-talk is unavoidable).

This gives freedom to the detector designers and add another important advantage to this technique.

Photon Absorption / Emission

absorption



spontaneous emission

τ – characteristic lifetime
of the excited state



stimulated emission

the emitted photon is in
phase with the incident one



Optical Absorption

Basic transitions in a semiconductor

when illuminated, photons are absorbed and create electron – hole pairs:

intrinsic transitions

a) $h\nu = E_g$

an electron – hole pair is created

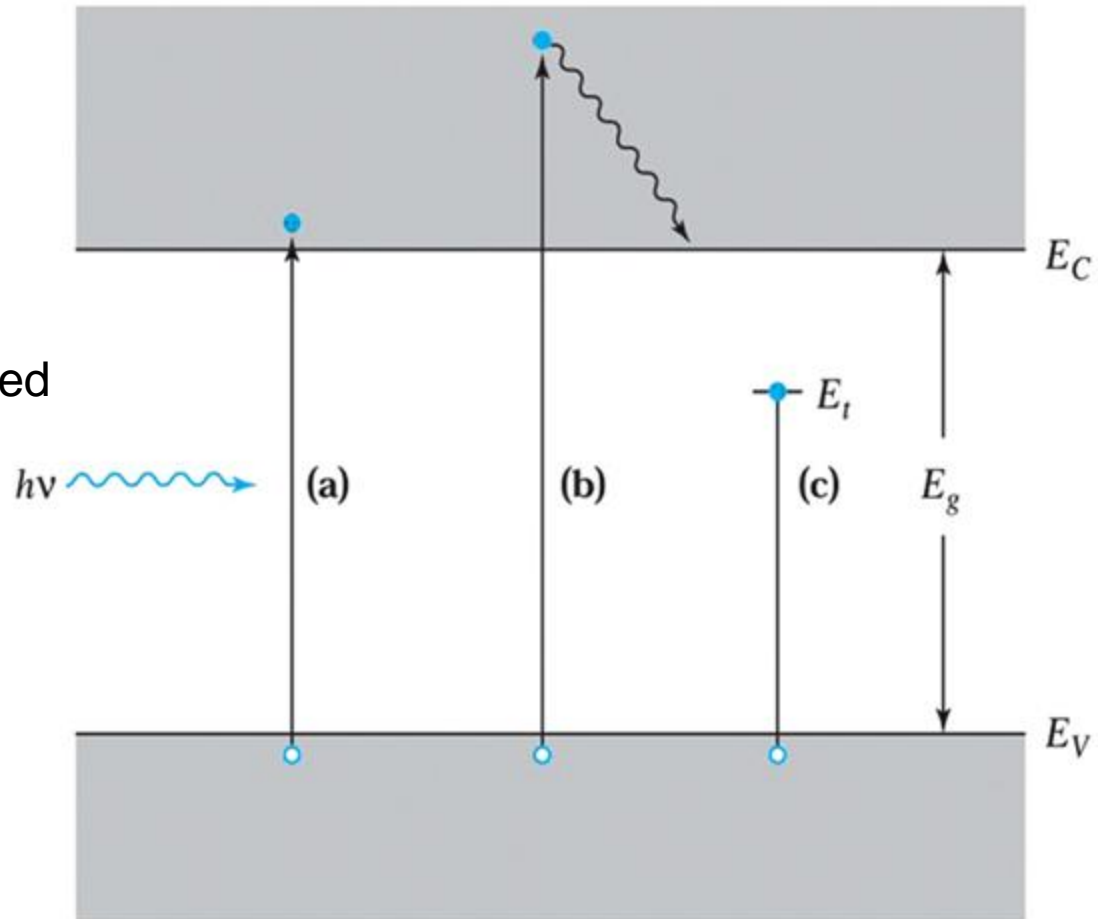
b) $h\nu > E_g$

an electron – hole pair is created and the excess energy is dissipated in form of heat (phonons)

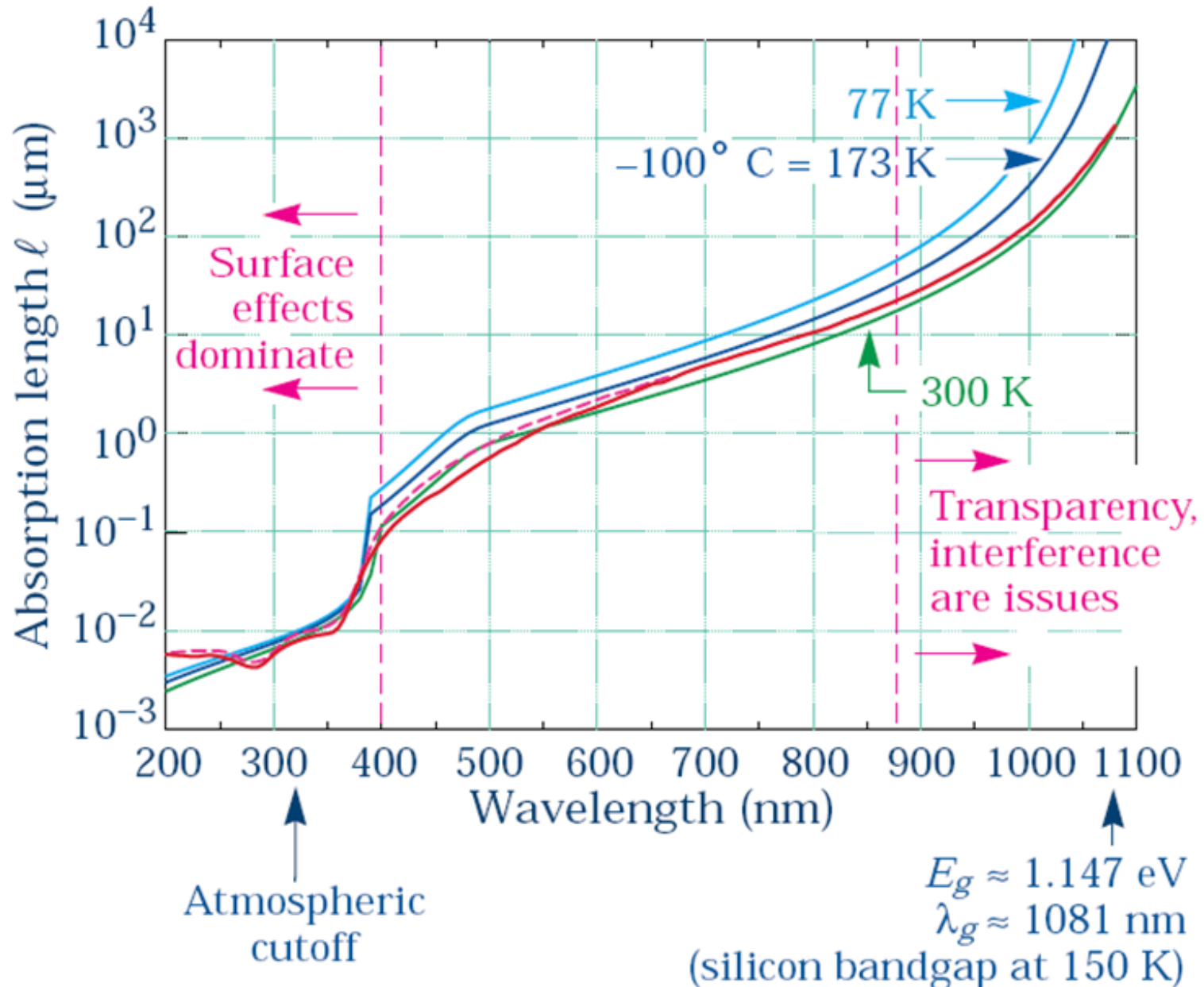
extrinsic transition

c) $h\nu < E_g$

this transition is possible, if there are available energy states in the the forbidden bandgap due to chemical impurities or physical defects



Light Absorption in Silicon



Optical Absorption Coefficient

photon flux attenuation

$$\Phi(x) = \Phi_0 e^{-\mu(\lambda)x}$$

μ – absorption coefficient which depends on λ

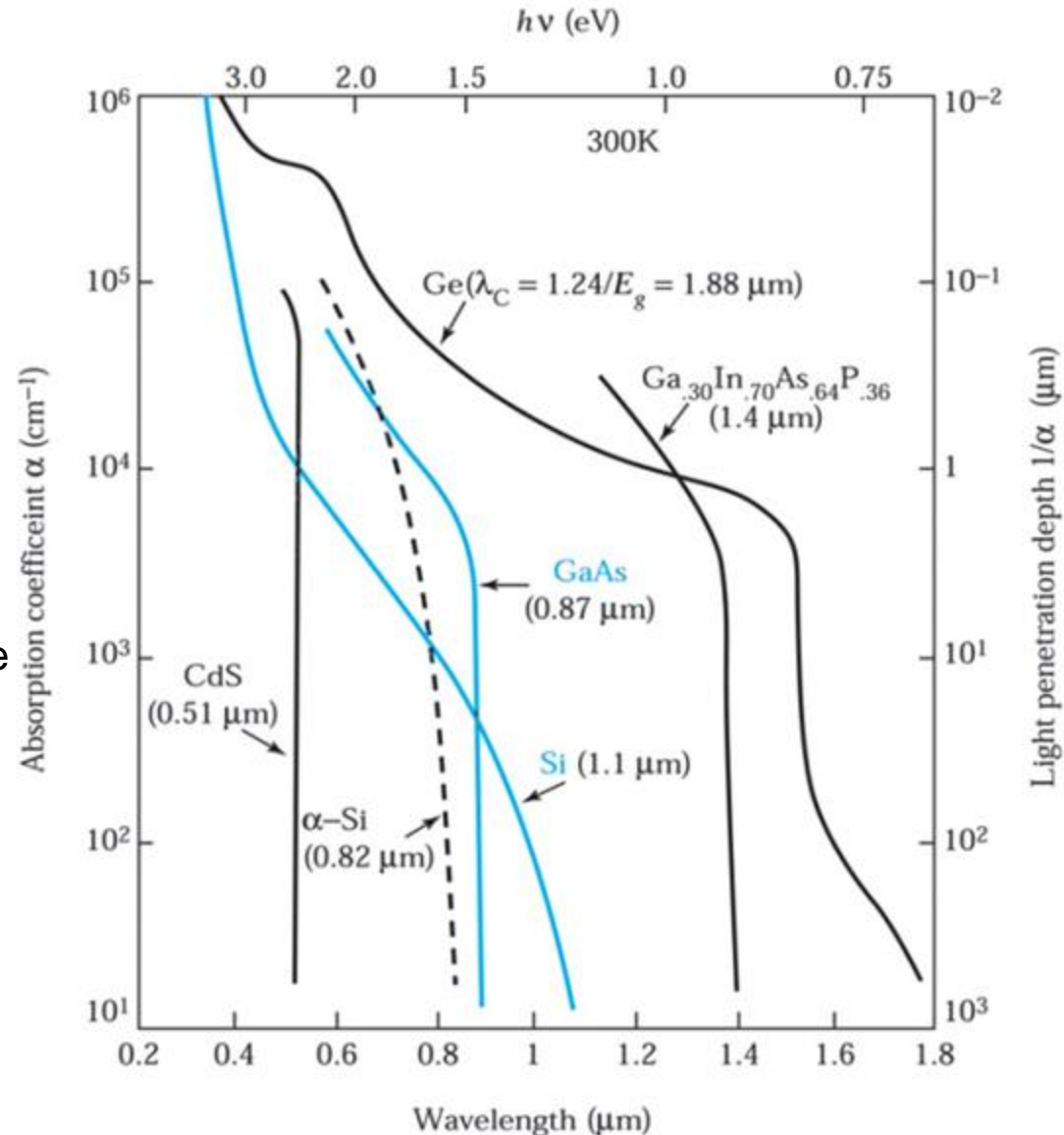
that has implications in the design of a silicon photodetector :

1. the entrance window must be as thin as possible
2. to detect most photons the sensitive volume must be sufficiently thick

cutoff wavelength λ_c

$$\lambda_c = \frac{1.239}{E_g [\text{eV}]} \mu\text{m}$$

at longer wavelengths, the device becomes transparent



Si Photo-Detector (Example)

Imagine a photon hitting a small Si cube (0.1 mm × 0.1 mm × 0.1 mm) and freeing an electron to the conduction band via the photo-electric effect.

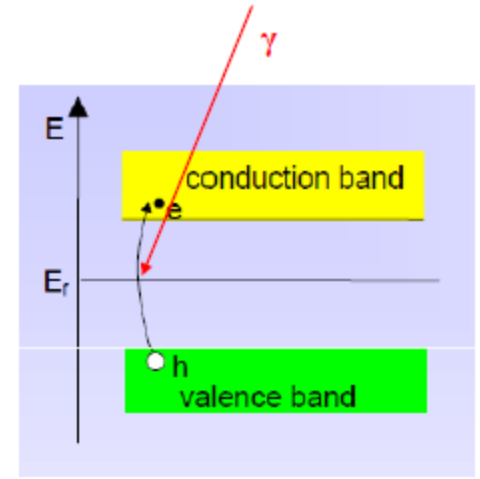
In a pure semiconductor (undoped) semiconductor the number of free electrons in the conduction band is

$$n_i = 9.65 \times 10^9 \text{ cm}^{-3} \times (0.1 \text{ mm})^3 \sim 10000$$

much larger compared to the single freed electron.

The signal is overwhelmed by the noise

- cannot do much about the signal (ionization detector)
- must reduce the noise



With a lot of light (i.e. a large number of photons > 1000) the signal becomes detectable, e. g. as a change in the resistance of the Si cube.

This is the principle of operation of the **photo-resistor**.

What can we do to improve the situation ?

1. empty (deplete) the Si cube of free charges → **pin photo-diode**
still not enough to detect single photons (too small charge)
it works with ~100 photons
2. add internal amplification → **avalanche photo-diode**

The Silicon Photo Resistor

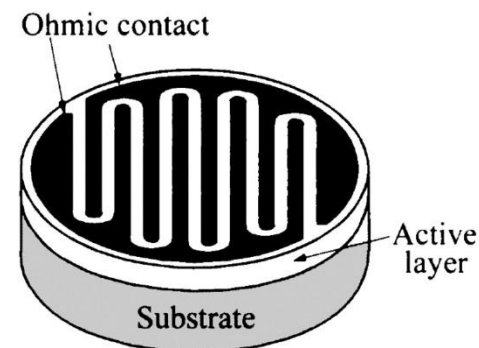
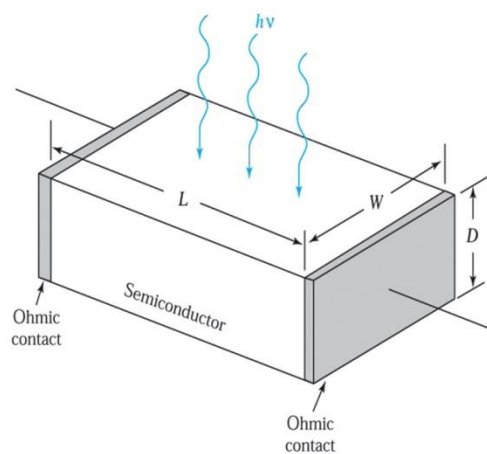
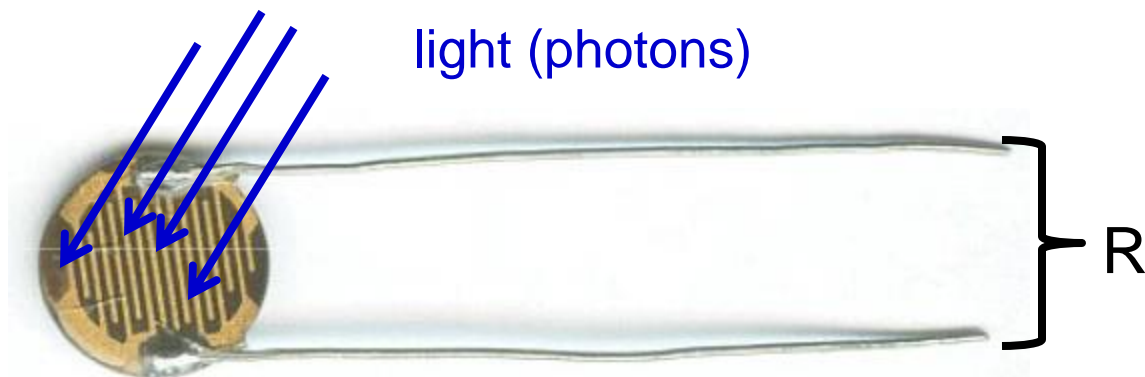
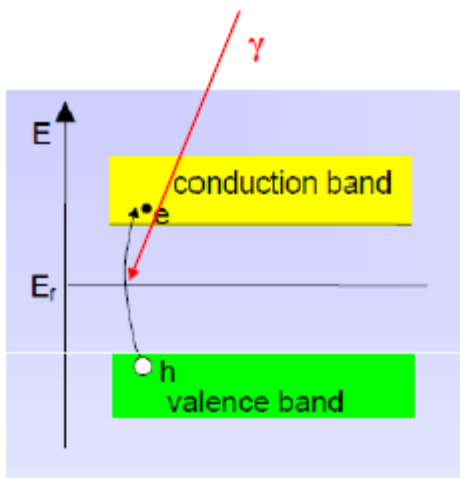


Figure 10.1b
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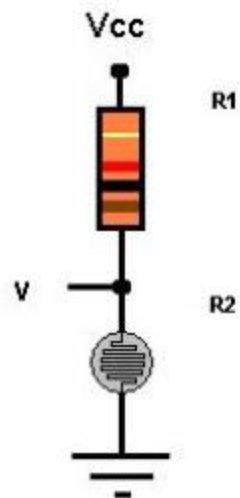
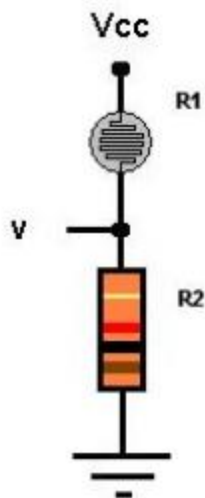


Figure 10.1a
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low sensitivity

low speed $\sim O(1 \text{ ms})$

used for exponents, photo-relays, etc.

Semiconductor Photonic Devices

Photonic devices are devices in which the basic particle of light – the photon – plays a major role. The dominant photo-absorption process is the **photoelectric effect**.

Photonic devices went through a tremendous development over the last 50 years thanks to the broad spectrum of applications. Today they represent an important fraction of industrial electronics development.

They are almost everywhere. Just to give some common examples : DVD players, optical fiber communication, solar panels, computer screens, LED TVs, infra-red light detectors, barcode readers, range meters, lab instruments, ...

Usually **photonic devices** are divided into four major groups

- light-emitting diodes (LED)**

 - convert electrical energy into optical energy

- lasers**

 - light amplification by stimulated emission, which converts electrical energy into optical energy

- photo-detectors**

 - electrically detect optical signals

- solar cells**

 - convert optical energy into electrical energy

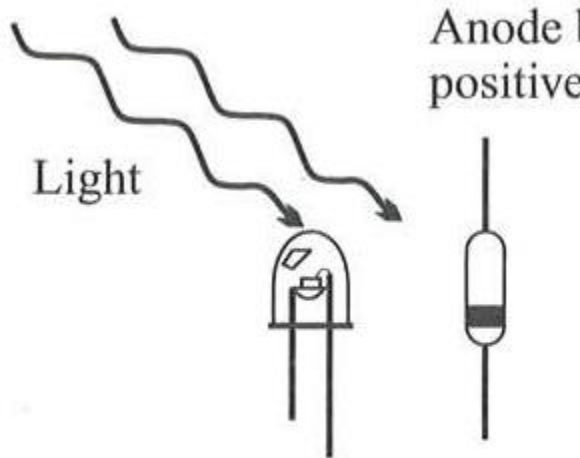
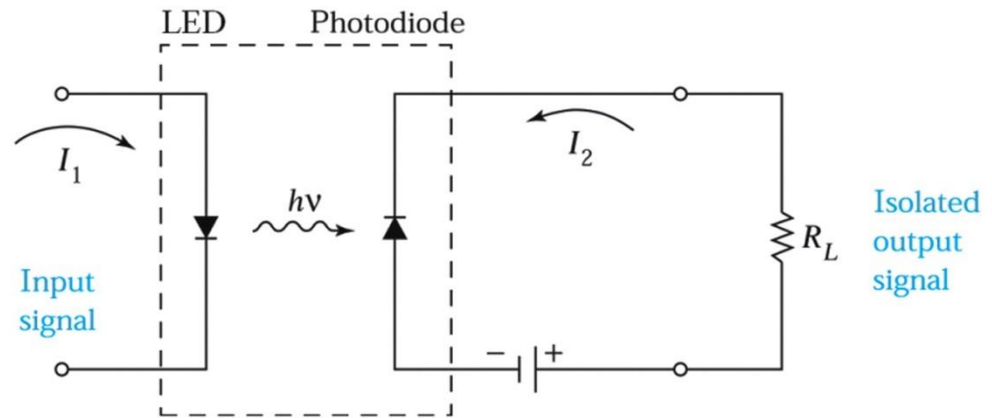
However, as they are, **they are not suited for single photon detection**.

A Small Experiment

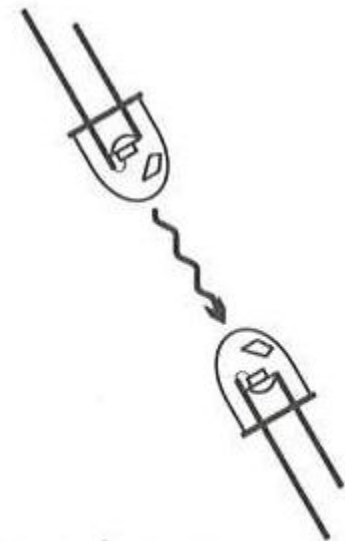
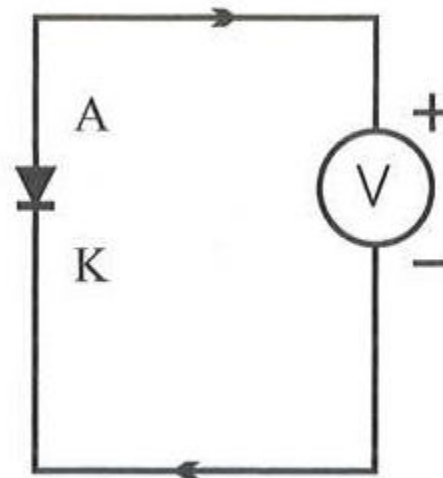
Light emitting diodes (LEDs) are also excellent photo-detectors.

Try to illuminate a “red” diode with a “blue” diode and measure the voltage across the “red” diode terminals.

Then repeat the experiment with a “blue” diode illuminating a “red” one. What is the voltage on the “blue” diode terminals ?



Any glass-encapsulated silicon diode (e.g., 1N4148) or LED



Similar LEDs detect their own light

Various Solid State Photo-Detectors

Photo-Resistor

Semiconductor photo-diode (PN diode)

PIN diode

Avalanche PD (APD)

Visual light photon counters (VLPC)

Avalanche photo-diode operated in Geiger mode (G-APD) / Si-PM

Charged Coupled Devices (CCD)

CMOS Image Sensors (digital cameras)

.....

HybridPD, HybridAPD

semiconductors, pn junction diodes

This part based on

W. Shockley

Electrons and Holes in Semiconductors (1966)

S. M. Sze and M.-K. Lee

Semiconductor Devices – Physics and Technology (2012)

Semiconductors

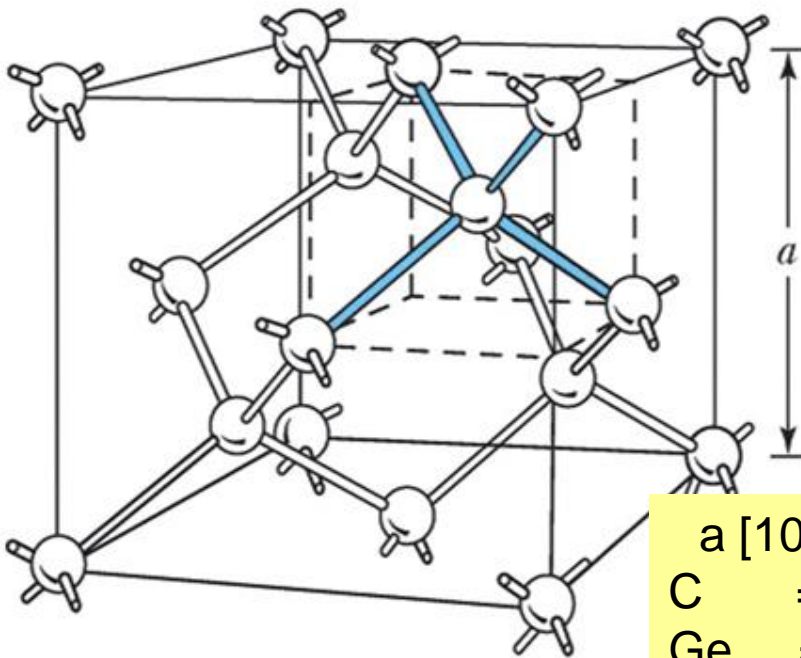
In semiconductor crystals the atoms are arranged in a lattice structure with typical inter-atomic spacing of few 10^{-10} m

intrinsic semiconductors

formed by elements in Group IV (C, Si, Ge)

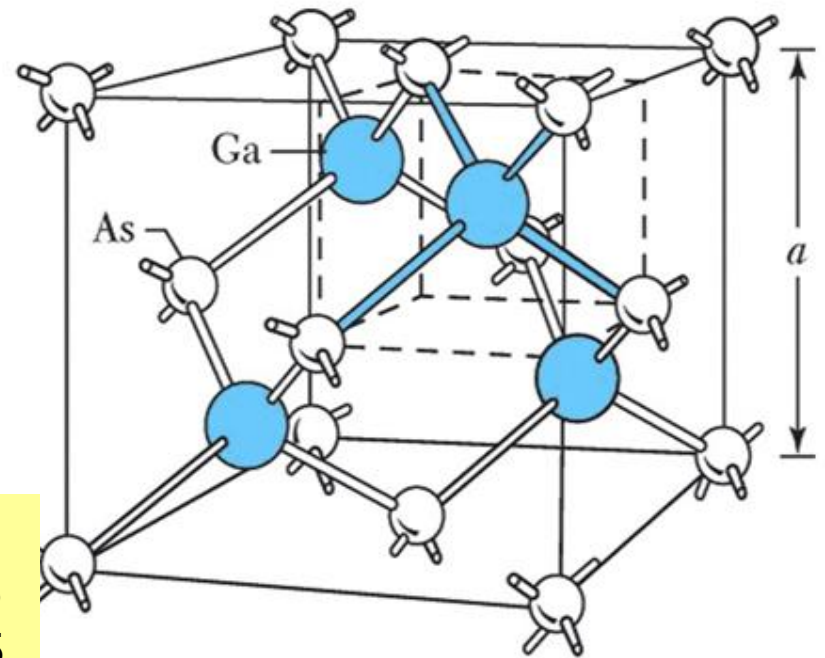
compound semiconductors

formed by binary combinations of elements in Group III and V (GaAs, GaP, InAs, ...) or Group II and VI (ZnO, CdTe, ...)



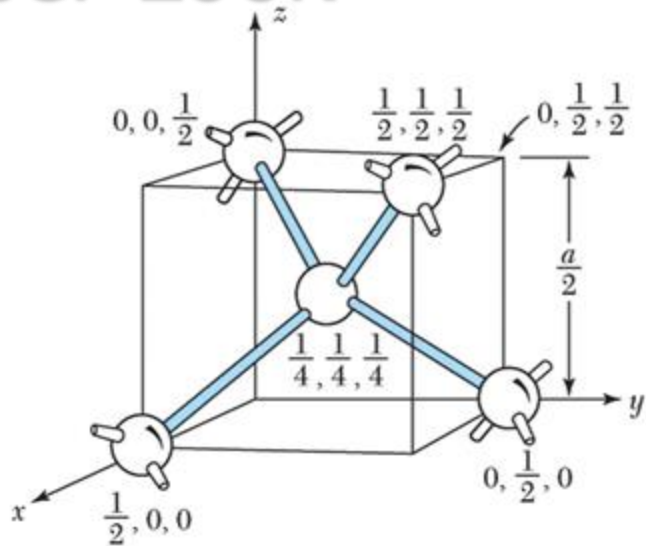
diamond lattice – fcc

a [10^{-10} m]	
C	= 3.56
Ge	= 5.65
Si	= 5.43
GaAs	= 5.65
InSb	= 6.47

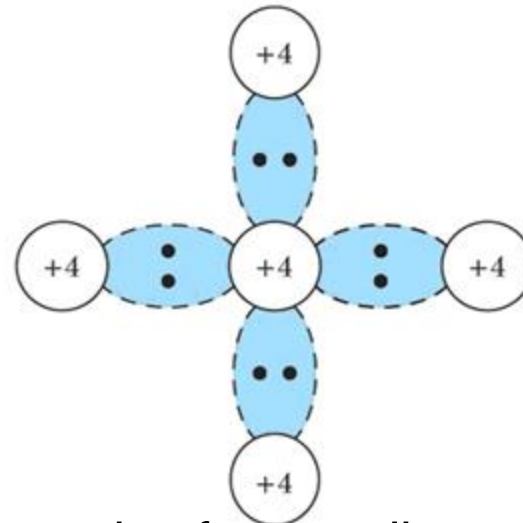


zincblende lattice – fcc

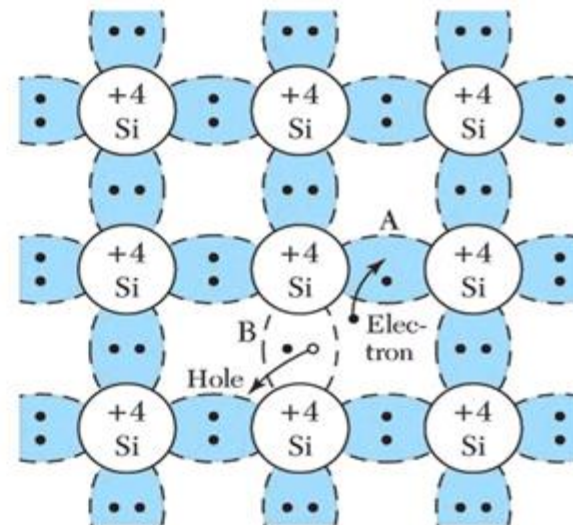
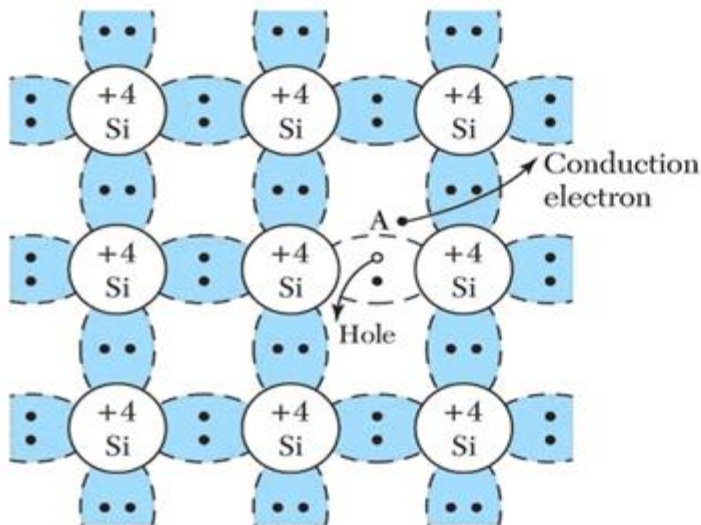
A Closer Look



tetrahedron bond



schematic of a two-dimensional tetrahedron bond



broken bond resulting in a conduction electron and a *hole*

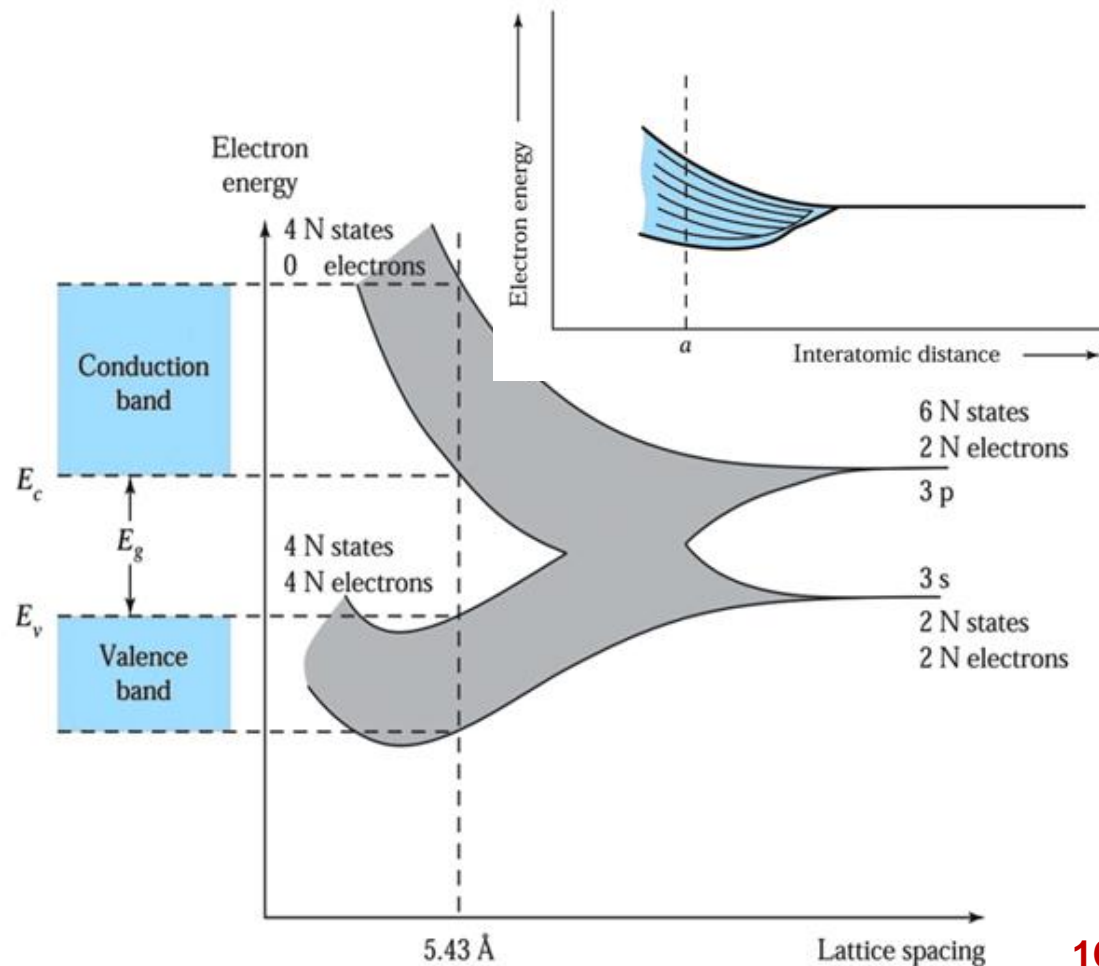
Energy Band Structure

When two atoms approach, the orbitals (wavefunctions) of the constituent atoms overlap.

In a crystal the orbitals overlap with neighboring atoms in the lattice the discrete atomic states transform into energy bands and each atom contributes its quantum states to each band

The bands are extended states, i.e. the state contributed by an individual atom extends to the whole crystal.

The number of quantum states in the band is equal to the number of states from which the band was formed.



Energy – Momentum Diagram

The energy of a free electron (mass m_0) is given by

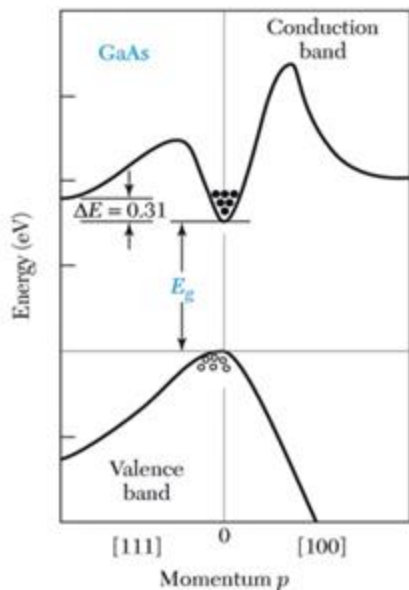
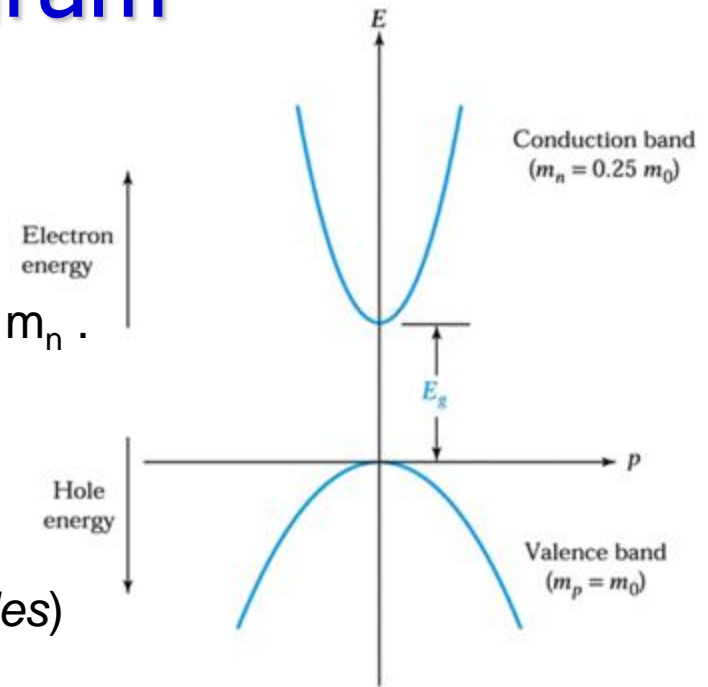
$$E = \frac{p^2}{2m_0} \rightarrow E = \frac{p^2}{2m_n}$$

In a lattice replace m_0 with an effective electron mass m_n .

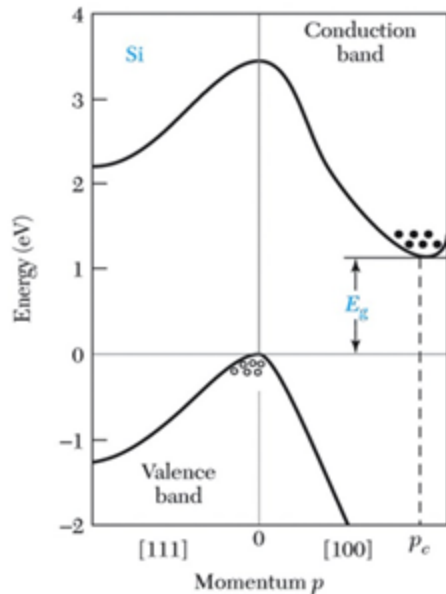
The effective mass m_n can be obtained from

$$m_n = 1 / \left(\frac{d^2 E}{dp^2} \right)$$

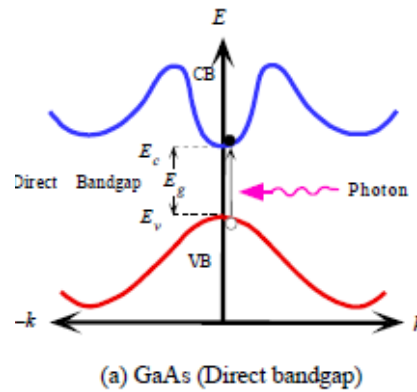
For Si $m_n = 0.19 m_0$ and $m_p = 3 \times m_n \sim 0.6 m_0$ (for holes)



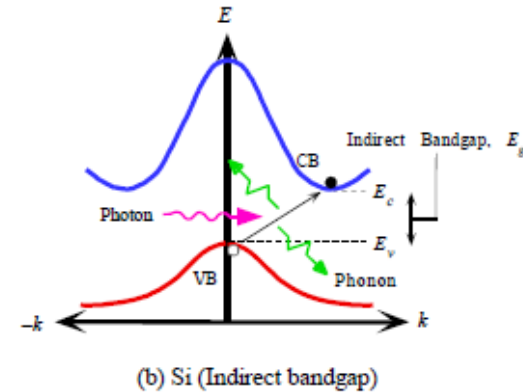
direct



indirect



(a) GaAs (Direct bandgap)



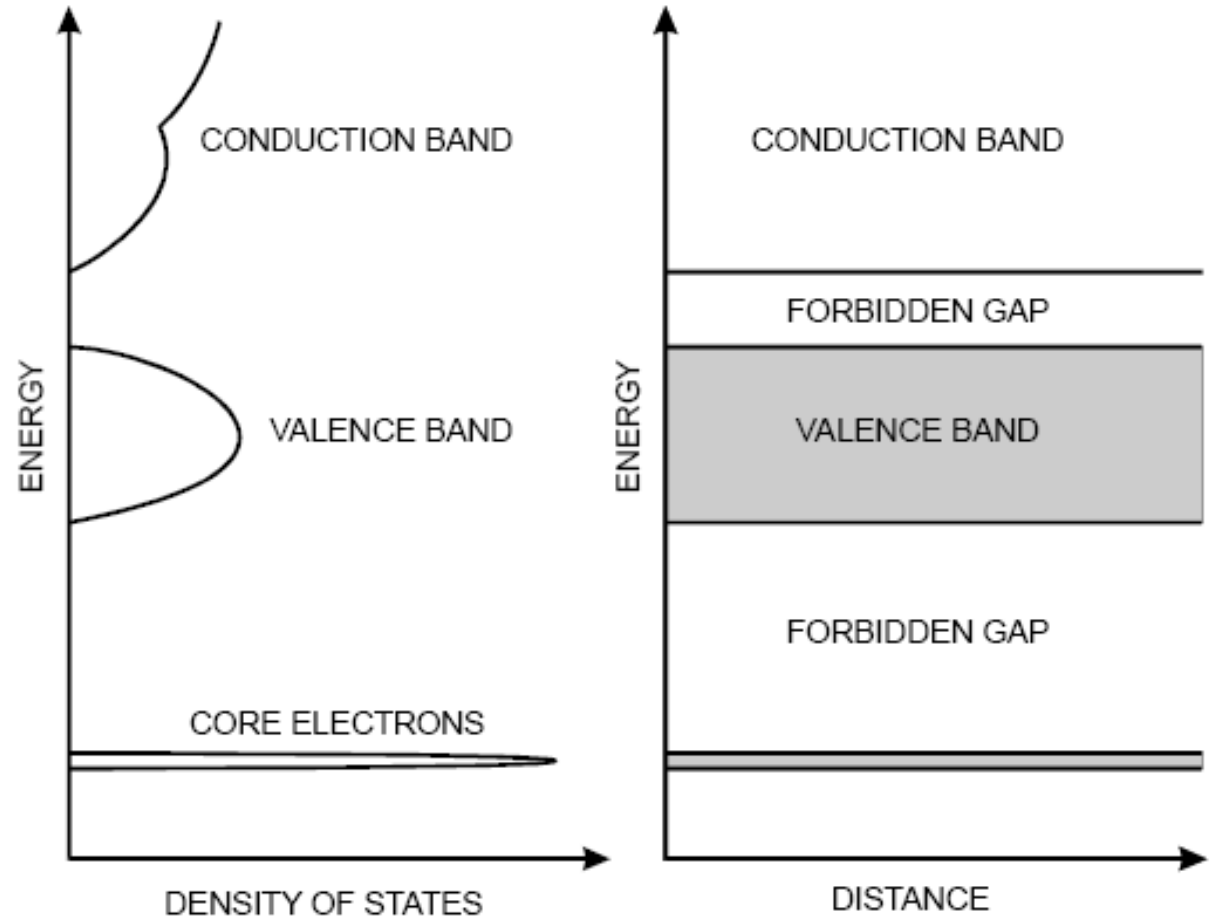
(b) Si (Indirect bandgap)

Energy Band Structure

Energy band structure

Typical band gaps
(valence – conduction band)

Ge	0.7 eV
GaAs	1.4 eV
Si	1.1 eV
Diamond	5.5 eV



Not all the dE/dx is used to ionize the semiconductor

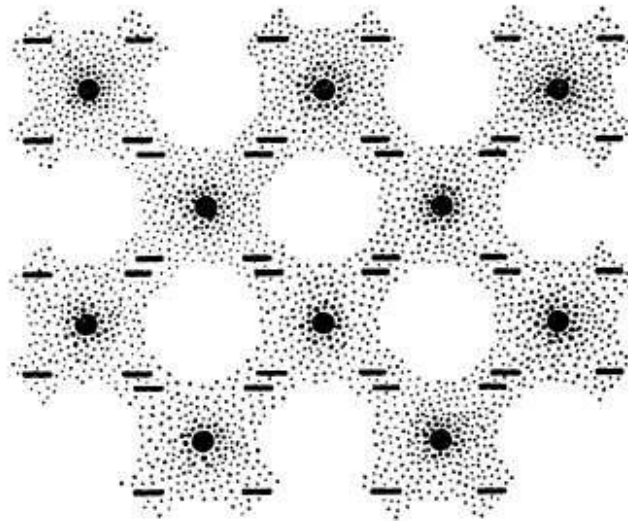
→ the amount of energy needed to create a e-hole pair in Si is 3.62 eV

Intrinsic Carriers

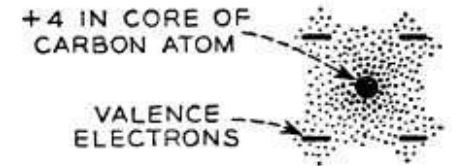
At 0° K all the electrons occupy the bonding states, thus fully occupy the valence band.

Applying an external E-field would result in no current as a moving electron must have more energy (vs stationary e^-) and there is no higher energy state available.

The charge must first be freed providing energy and then directed by an E-field

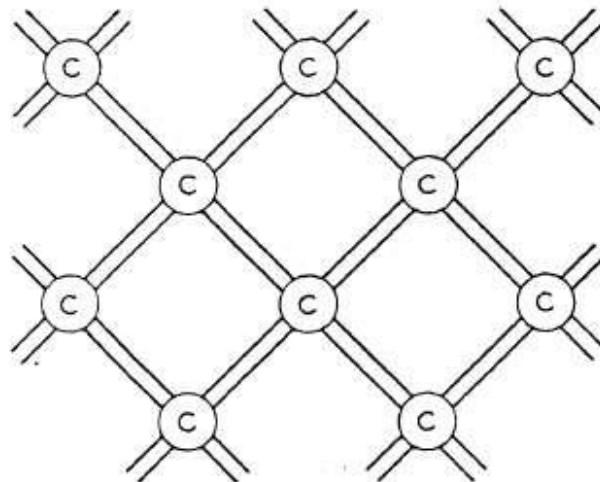


(a) ELECTRON PAIR BONDS



EACH ATOM, WITH THE CHARGE OF ITS SHARE OF VALENCE-BOND ELECTRONS, IS ELECTRICALLY NEUTRAL.

(b)



(c) PLANE DIAGRAM OF DIAMOND LATTICE WITH BONDS REPRESENTED BY LINES



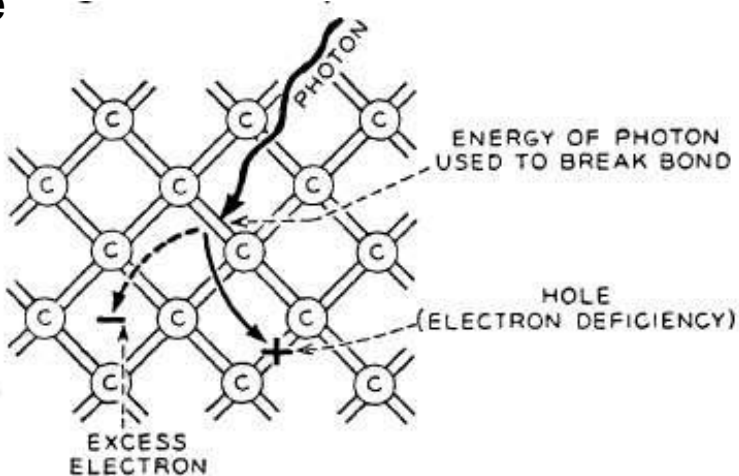
Assume a photon is absorbed by an electron and breaks the bond (e.g. through the photoelectric effect).

The e^- has now enough energy to freely move in the lattice (i.e. has jumped to the conduction band)

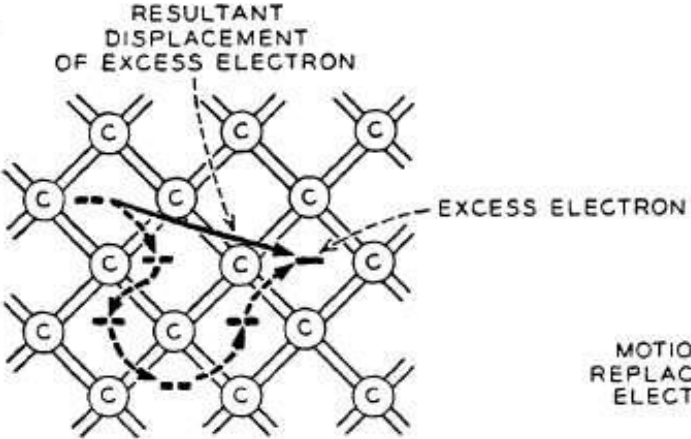
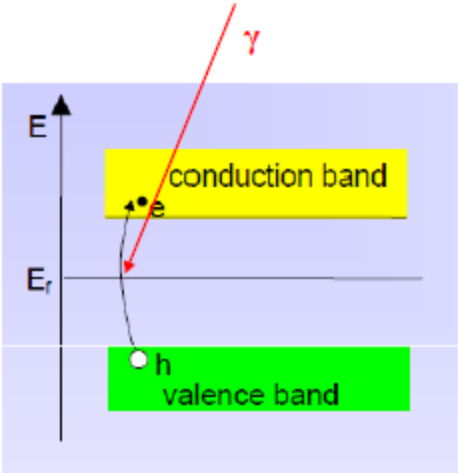
Conversely the vacancy left free by the e^- (the *hole*) can move (i.e. it can be filled by the e^- of a nearby atom)

We have then movement of two opposite charges, which can be directed by an E- field.

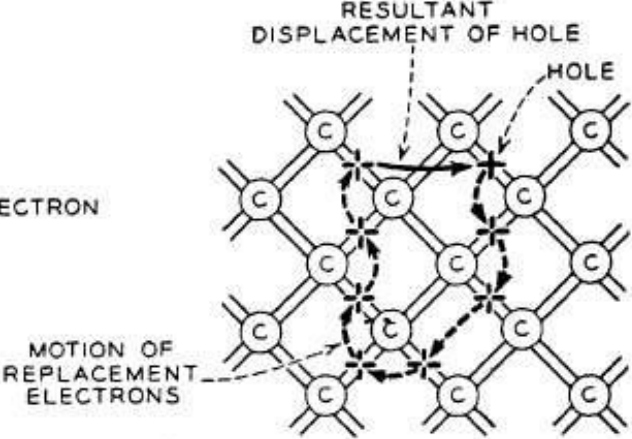
Let's now move out of 0° K. Thermal energy may send some e^- in the conduction band.



(a) PRODUCTION OF A HOLE-ELECTRON PAIR BY A PHOTON



(c) RANDOM MOTION OF AN EXCESS ELECTRON



(d) RANDOM MOTION OF A HOLE

Density of States

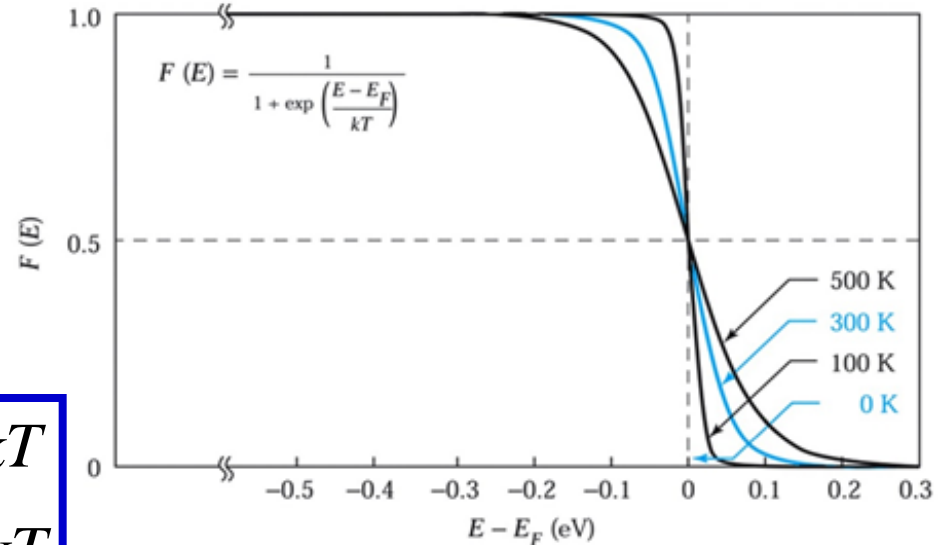
The probability of finding an electron in the conduction band is given by the Fermi-Dirac distribution

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

which can be approximated by the Boltzmann distribution if $kT > 3 E_F$
($kT \sim 0.026$ eV at 300^0 K)

$$f(E) \cong e^{-(E - E_F)/kT} \quad (E - E_F) > 3kT$$

$$f(E) \cong 1 - e^{-(E - E_F)/kT} \quad (E - E_F) < 3kT$$



Assume an intrinsic semiconductor (i.e. with # of impurities negligible compared to thermally generated carriers), the # of free electrons (n) can be calculated convoluting the density of states in the conduction band $N(E)$ with $f(E)$

$$n = \int_{E_{C=0}}^{E_{\text{top}}} N(E) f(E) dE$$

The density of states in the conduction band can be calculated as

$$N(E)dE = \frac{8\pi p^2 dp}{h^3} = 4\pi \left(\frac{2m_n}{h^2}\right)^{3/2} E^{1/2} dE \rightarrow N(E) = 4\pi \left(\frac{2m_n}{h^2}\right)^{3/2} E^{1/2}$$

Intrinsic Carrier Concentration

Using the last 3 equations we can obtain the concentration of free charge carriers

$$n = \frac{2}{\sqrt{\pi}} N_C (KT)^{-3/2} \int_0^{\infty} E^{-1/2} e^{-(E-E_F)/kT} dE$$

with

$$N_C = 12(2\pi m_n kT / h^2)^{3/2}$$

(there are **12** free electrons in Si - 2s, 2p, 3s, 3p states – and only **2** in GaAs)

Let E_C be the energy at the bottom of the conduction band, the electron density n in the conduction band is given by

$$n_{Si} = \underbrace{12(2\pi m_n kT / h^2)^{3/2}}_{N_C} e^{-(E_C - E_F)/kT}$$

Effective density of states in the conduction band

$$N_C = 2.86 \times 10^{19} \text{ cm}^{-3}$$

and in the valence band

$$N_V = 2.66 \times 10^{19} \text{ cm}^{-3}$$

in Si at 300° K

Similarly we can obtain the density of *holes* p the valence band, with E_V the energy at the top of the valence band

$$p_{Si} = \underbrace{2(2\pi m_p kT / h^2)^{3/2}}_{N_V} e^{-(E_F - E_V)/kT}$$


(the effective number of *free holes* is **2** for both Si and GaAs)

The intrinsic carrier density is obtained by observing that at equilibrium #e = #holes = n_i

$$n \cdot p = n_i^2 = N_C \cdot N_V \cdot e^{-E_G/kT}$$

At room temperature (300⁰ K)

$$n_i = 9.65 \times 10^9 \text{ cm}^{-3}$$

$$e^{-43} \sim 2 \times 10^{-19}$$


($n_i = 2.25 \times 10^6 \text{ cm}^{-3}$ for GaAs)

This is **the law of mass action**, it is very useful in semiconductor device analysis.

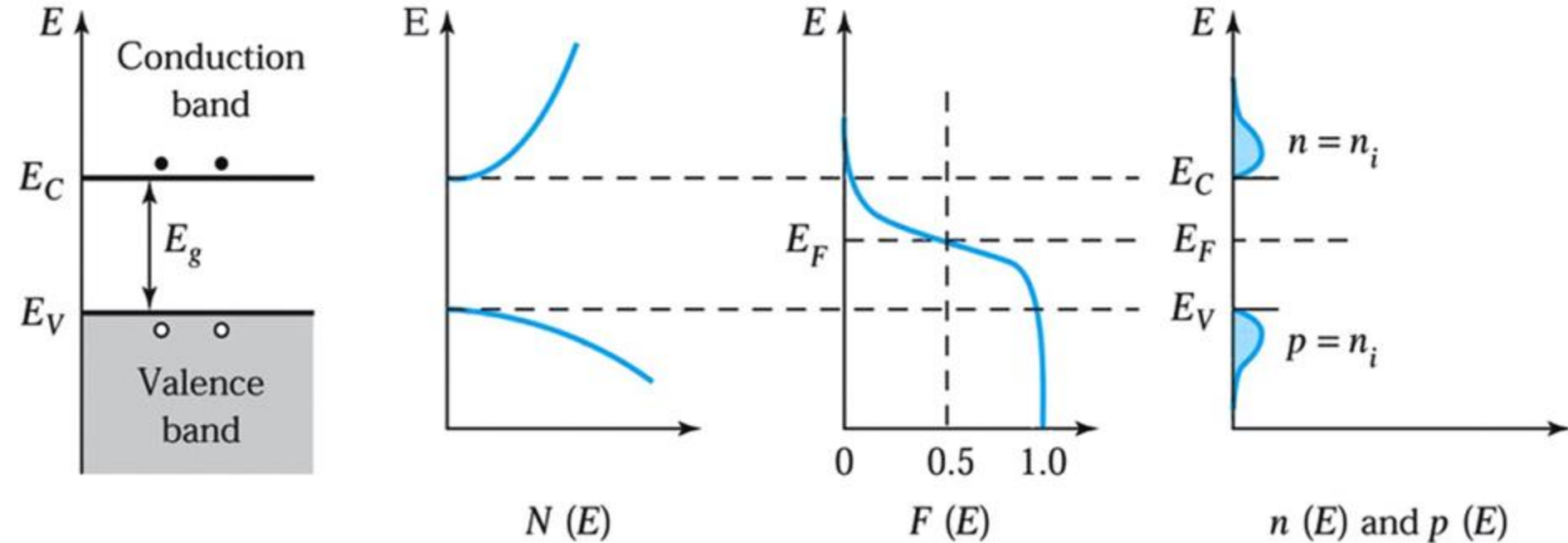
If one carrier type exceeds the equilibrium concentration, recombination will decrease the concentrations of both electrons and holes to maintain $n p = n_i^2$.

Finally we can calculate the value of the Fermi level, as the semiconductor must be electrically neutral. From the requirement $n = p$, we obtain

$$E_F = \frac{E_C - E_V}{2} + \frac{3kT}{4} \ln \left(\frac{m_p}{m_n} \right)$$

The ln term is negligible at room temperature (0.01 eV) → E_F is mid gap.

Summary Plot



schematic band diagram

density of states

Fermi distribution

carrier concentration

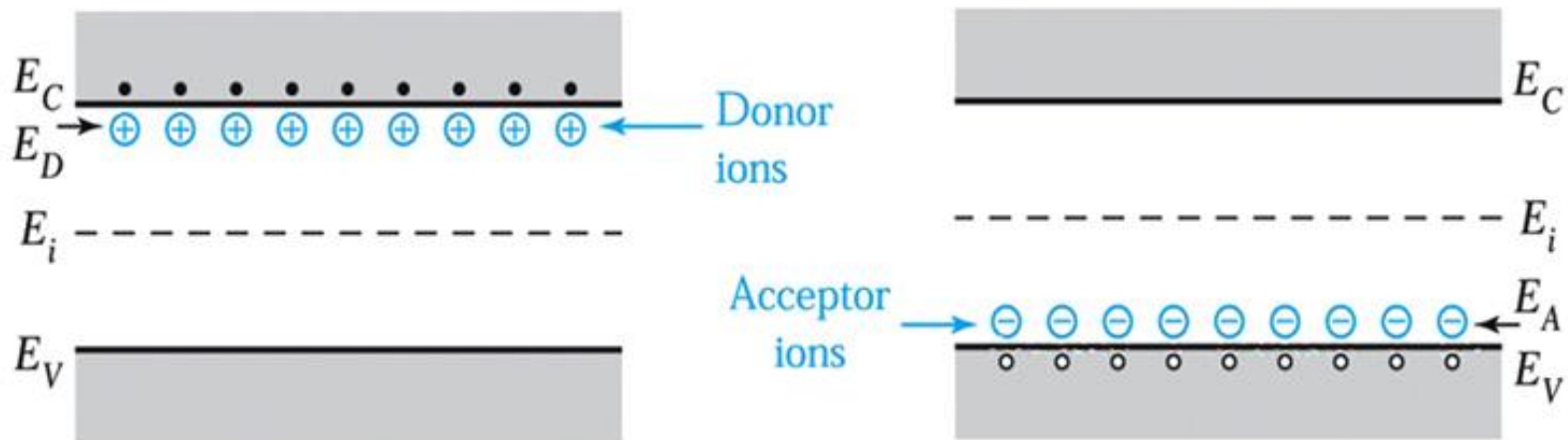
Doped (Extrinsic) Semiconductors

So far we have studied (ultra)pure intrinsic semiconductors :

$n = p$ holds only for intrinsic semiconductors.

In practice one cannot avoid impurities at the level of 10^{-12} or larger (it happens in the crystal growth process even if all precautions are taken), which corresponds to $> 10^{10}$ impurities per cm^3 . We can also add impurities (**dope the semiconductor**) by implanting atoms from the Group III (i.e. Boron) and/or V (i.e. Arsenic) \rightarrow **extrinsic semiconductor**. In this way, we can alter the behavior of intrinsic semiconductors and their energy band structure (E_F), i.e. add impurity energy levels.

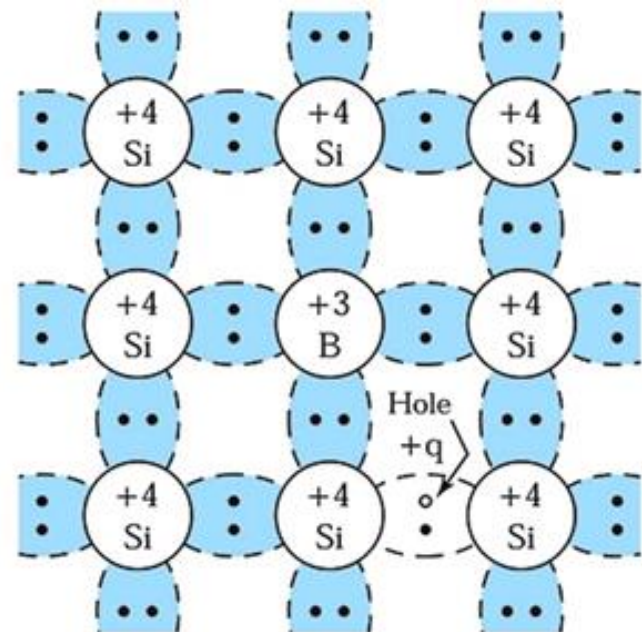
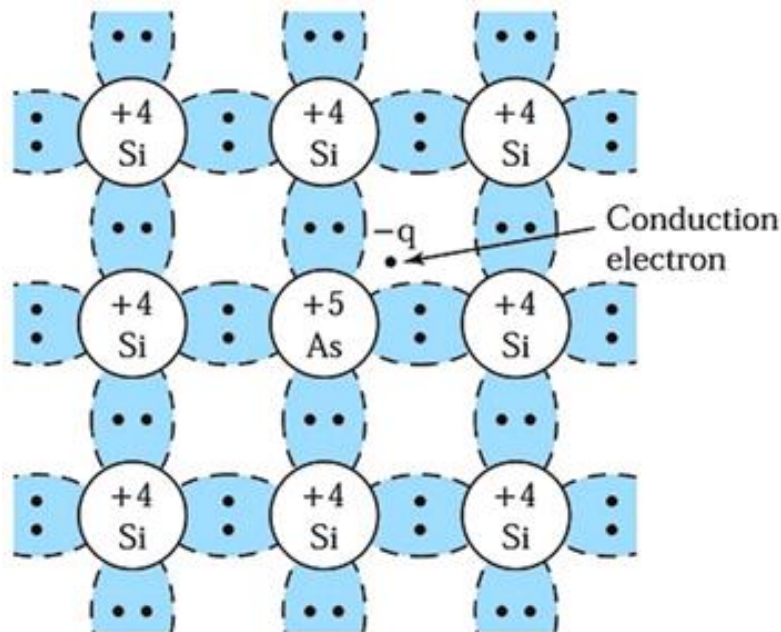
Impurities change the balance between n and p charge carriers.



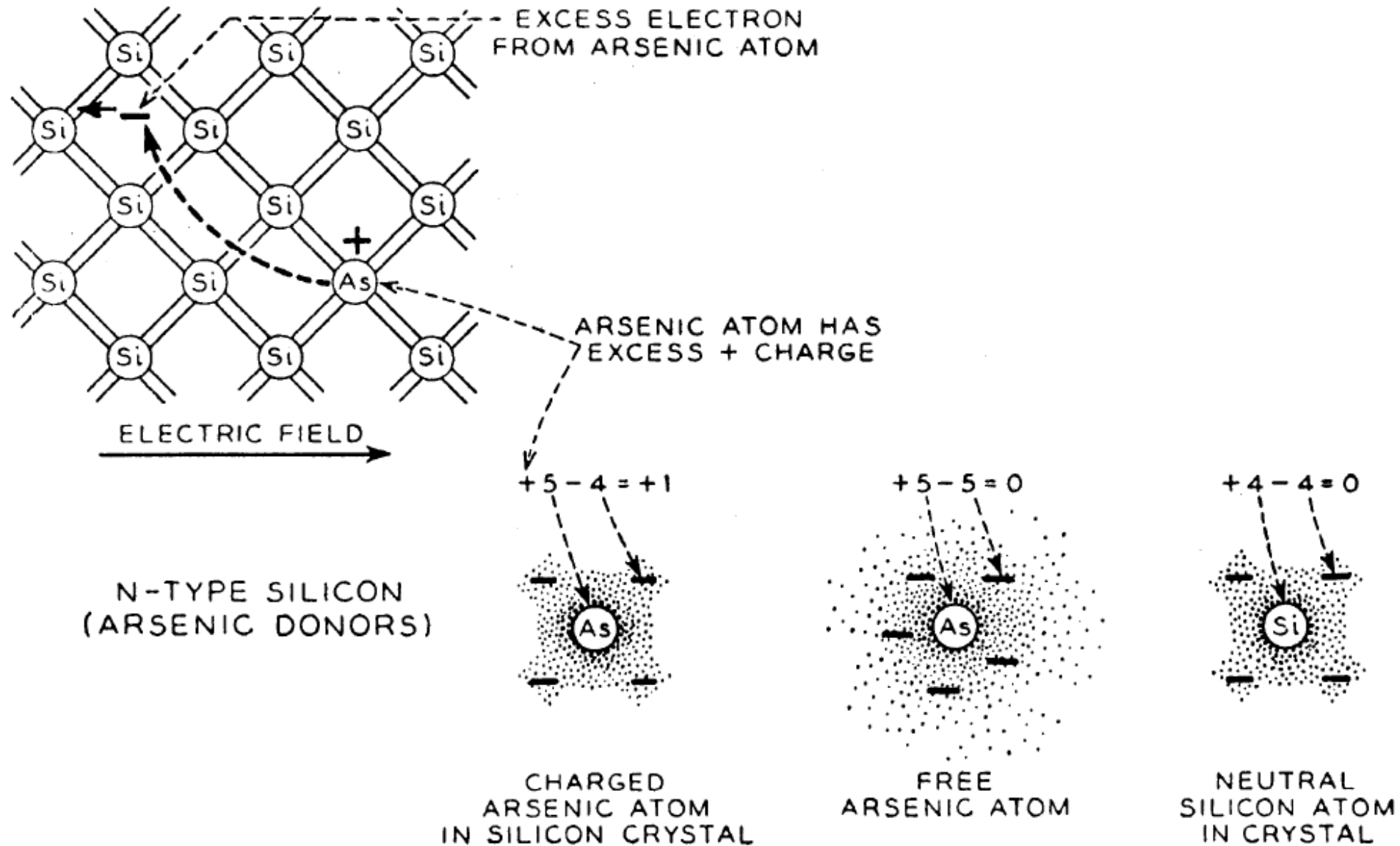
Selected impurities are intentionally used to control the charge carrier concentration for a given charge type, we defined *donors* those which can easily provide an extra e^- and *acceptors* those which can easily provide an extra *hole*.

Since Si has 4 valence e^- in a covalent bond, if we insert a 5 e^- valence element (e.g. P, As) we saturate 4 e^- and leave one very weakly bonded (i.e. close to the valence band) \rightarrow we have a *donor impurity*.

Conversely if we insert a 3 e^- (e.g. B, Al) valence element a valence electron will be left without partner and try to capture an e^- from a neighbor atom, thus creating a hole \rightarrow we have an *acceptor impurity*.



Donors



The excess electron feels a Coulomb force reduced by the dielectric constant ϵ of the lattice ($\epsilon = 12$ for Si)

$$E_i(\text{lattice}) = E_i(\text{atom}) / \epsilon^2 \sim 0.01 \text{ eV}$$

This creates a donor level just ~ 0.01 eV below the conduction band giving sizeable ionization probability at room temperature

→ almost all of the donor electrons are in the conduction band at room temperature

In this case we can write

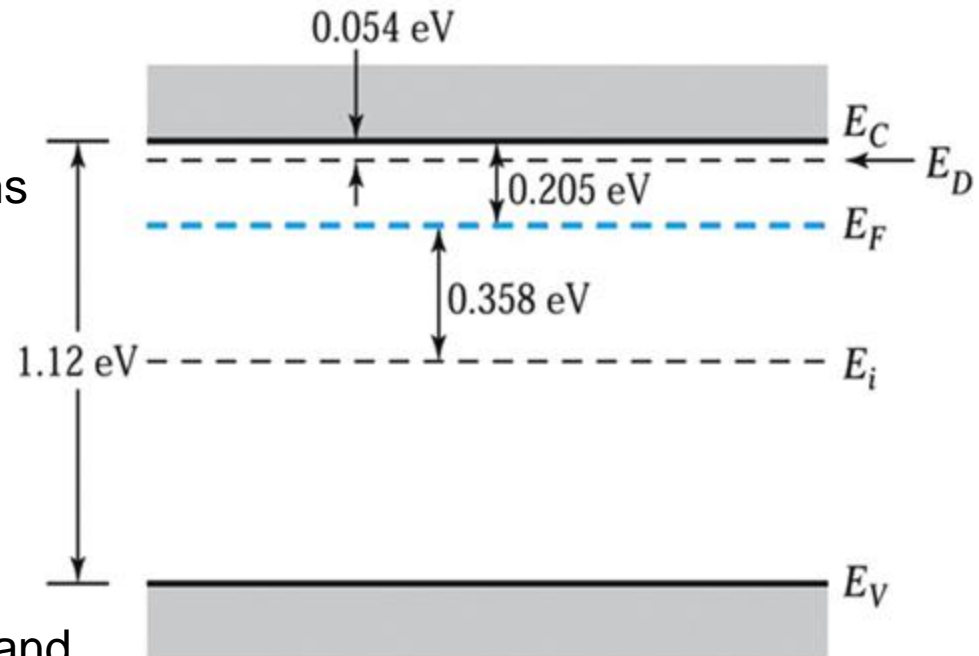
$$n = N_D$$

and obtain the Fermi energy level in terms of the effective density of states N_C and donor concentration N_D :

$$E_C - E_F = kT \ln(N_C / N_D)$$

$$\rightarrow E_F = E_C - kT \ln(N_C / N_D)$$

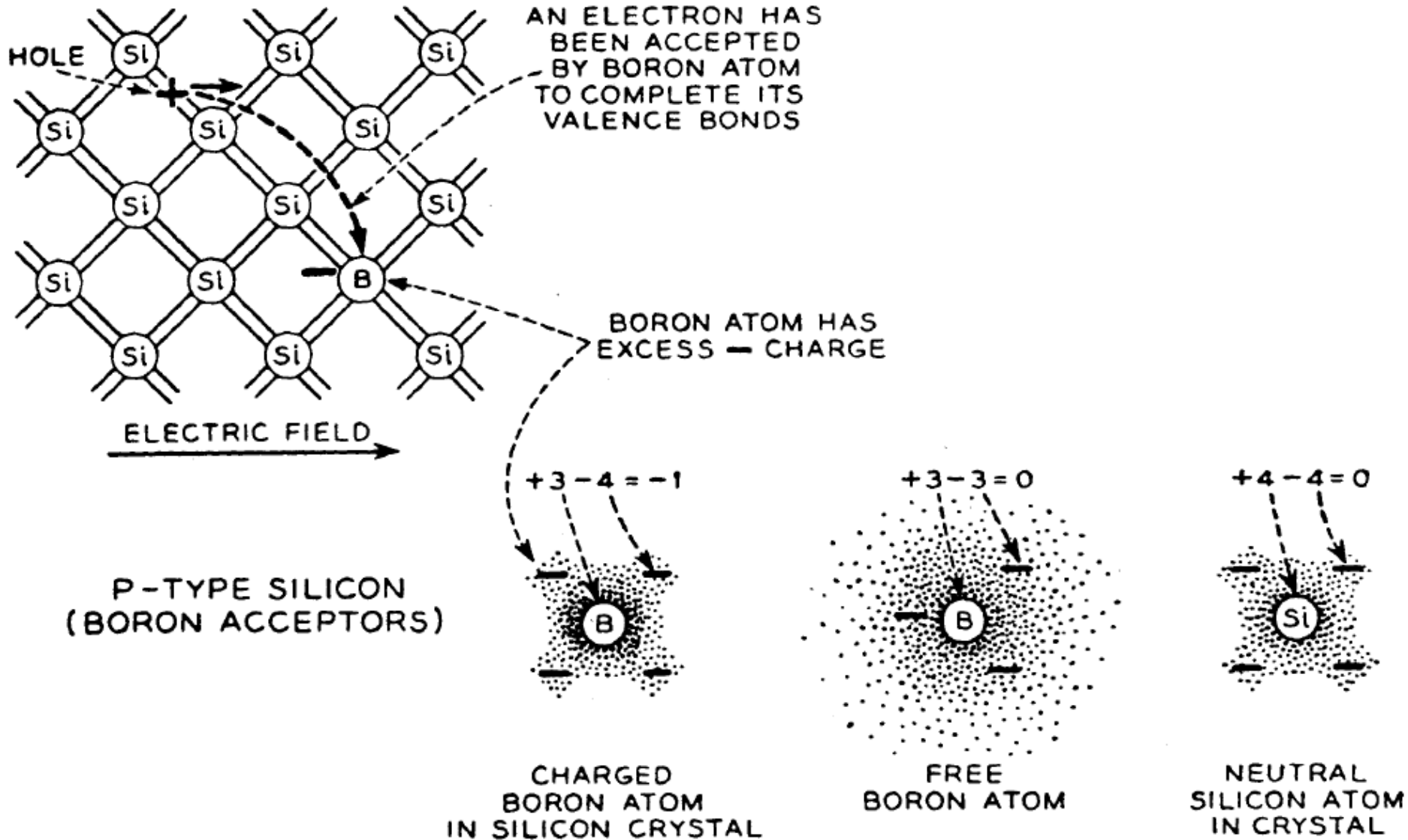
E_F has moved closer to the conduction band.



Majority charge carriers are e^- , and holes are minority carriers. This kind of doped Si is called n-type. Typical donor concentrations are $N_D \sim 10^{12}$ donors / cm^3 .

In case of a heavily doped n-type Si, it is called n⁺-type.

Acceptors



Similar considerations can be done in case of the acceptors impurities, in this case the level of the acceptors will be close to the valence band and will allow (at minimal energy cost) the migration of holes in the valence band (i.e. the valence electrons can easily jump in the acceptor level leaving holes in the valence band free to move).

→ almost all of the acceptor holes are in the valence band at room temperature

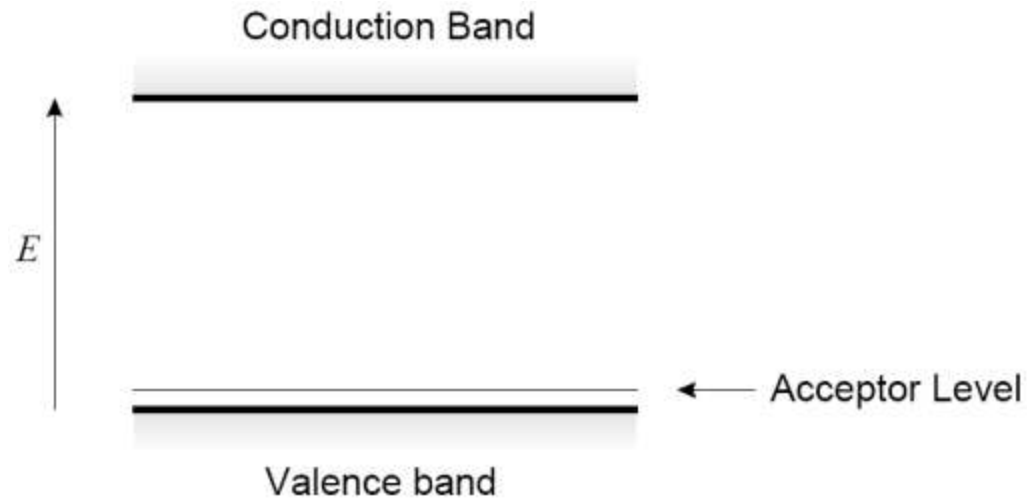
In this case we can write

$$\rho = N_A$$

and obtain the Fermi energy level in terms of the effective density of states N_V and acceptor concentration N_A :

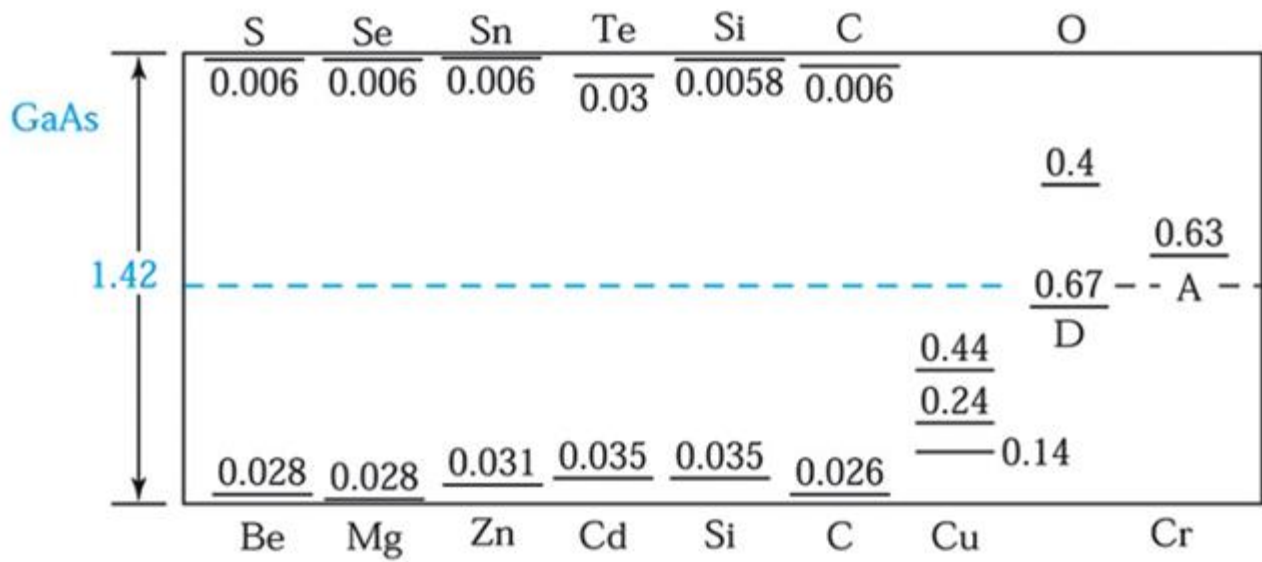
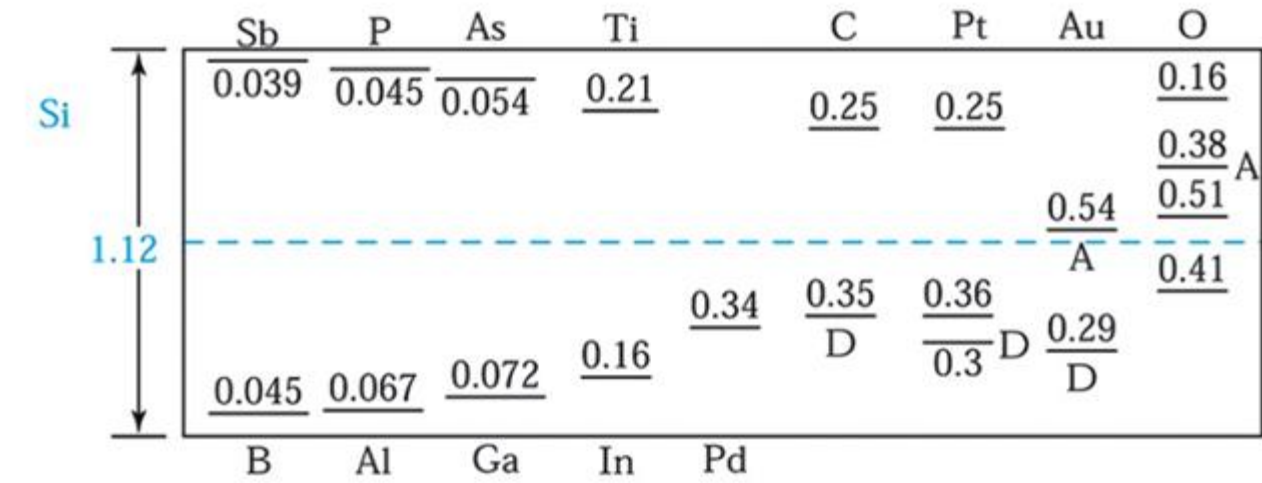
$$E_F - E_V = kT \ln(N_V / N_D)$$

$$\rightarrow E_F = E_V + kT \ln(N_V / N_A)$$



E_F has moved closer to the valence band.

Majority charge carriers are **holes**, and **e^-** are **minority carriers**. This kind of doped Si is called **p-type**. Typical acceptor concentrations are $N_A \sim 10^{15}$ acceptor / cm^3 . In case of a heavily doped p-type Si, it is called **p⁺-type**.



Measured ionization energies (in eV) for various impurities in Si and GaAs

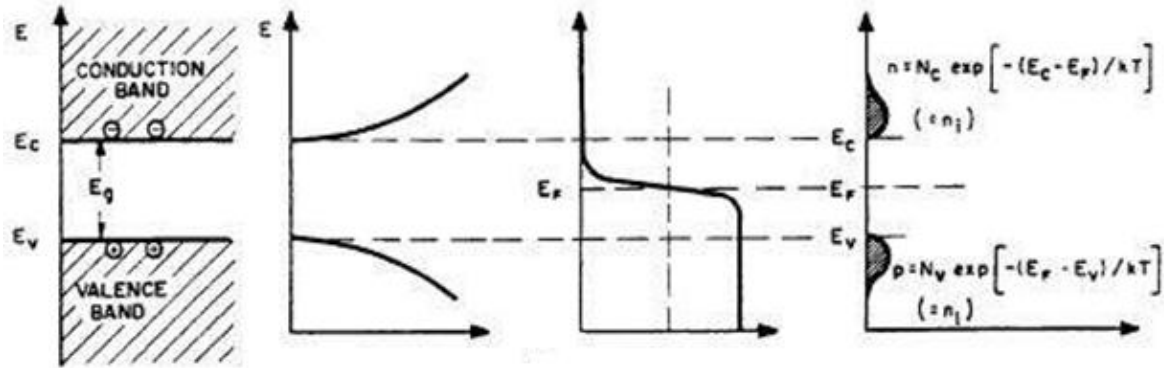
band diagram

density of states

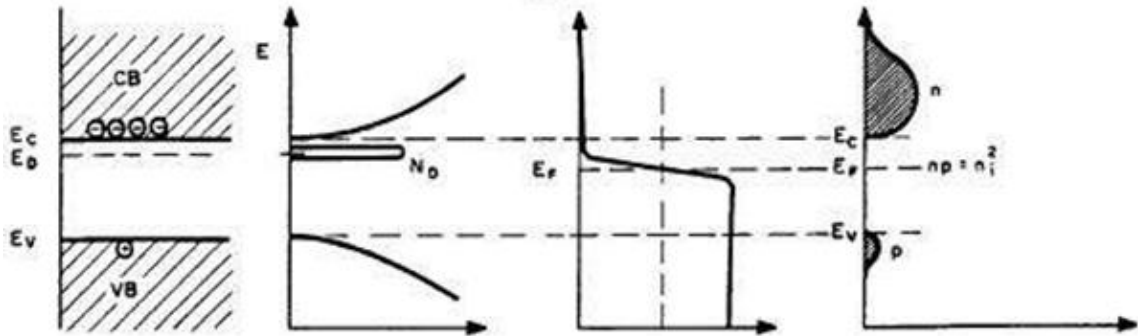
Fermi distribution

carrier concentration

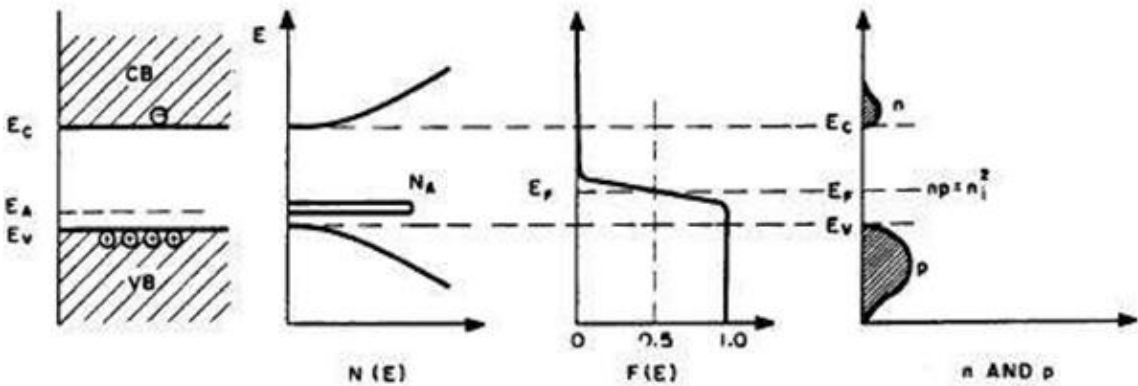
intrinsic



n - type



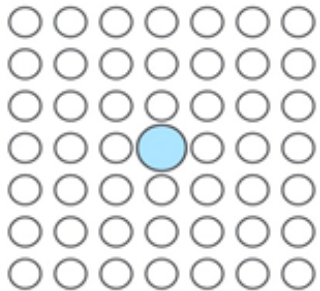
p - type



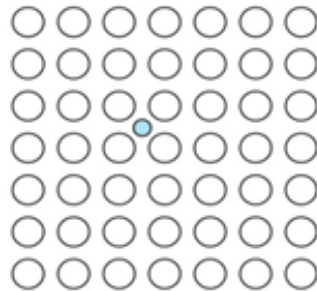
Crystal Defects

Crystal defect can occur during the Si wafer production (impurities)
or generated later by radiation damage
will change the properties of the pn junctions
(\rightarrow increase of leakage current and dark count rate)

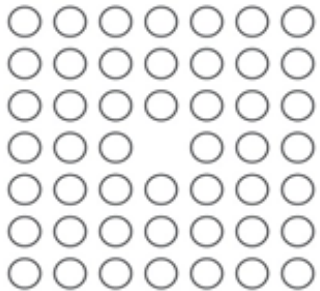
point defects



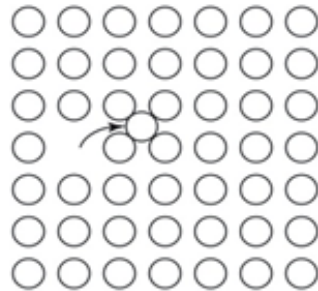
substitutional impurity



interstitial impurity

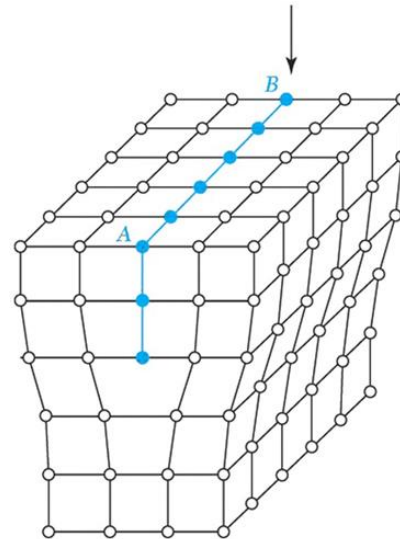


lattice vacancy

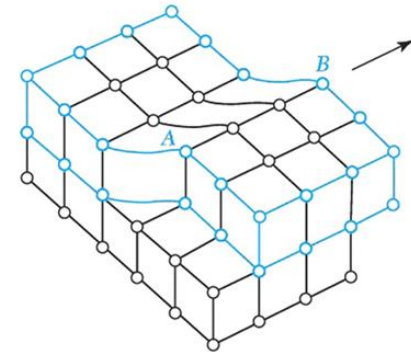


Frenkel-type defect

line defects



edge dislocation



screw dislocation

pn Junction (The Diode)

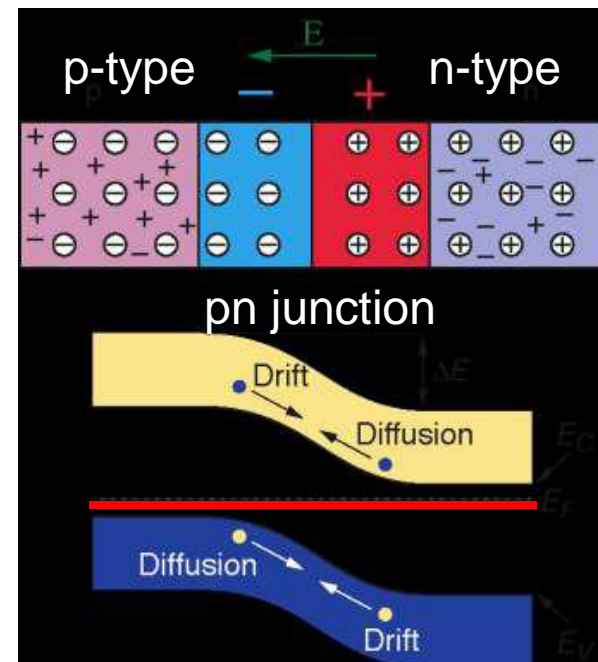
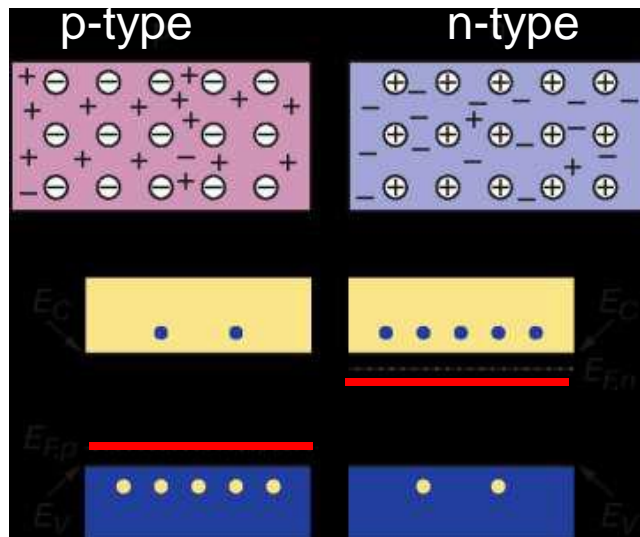
Let's join a n-type and a p-type semiconductor.

Before the junction is formed

p-type: contains a large concentration of **acceptors** (holes) with few electrons, and the Fermi level E_F is near the valence band edge

n-type: contains a large concentration of **donors** (electrons) with few holes, and the Fermi level E_F is near the conduction band edge

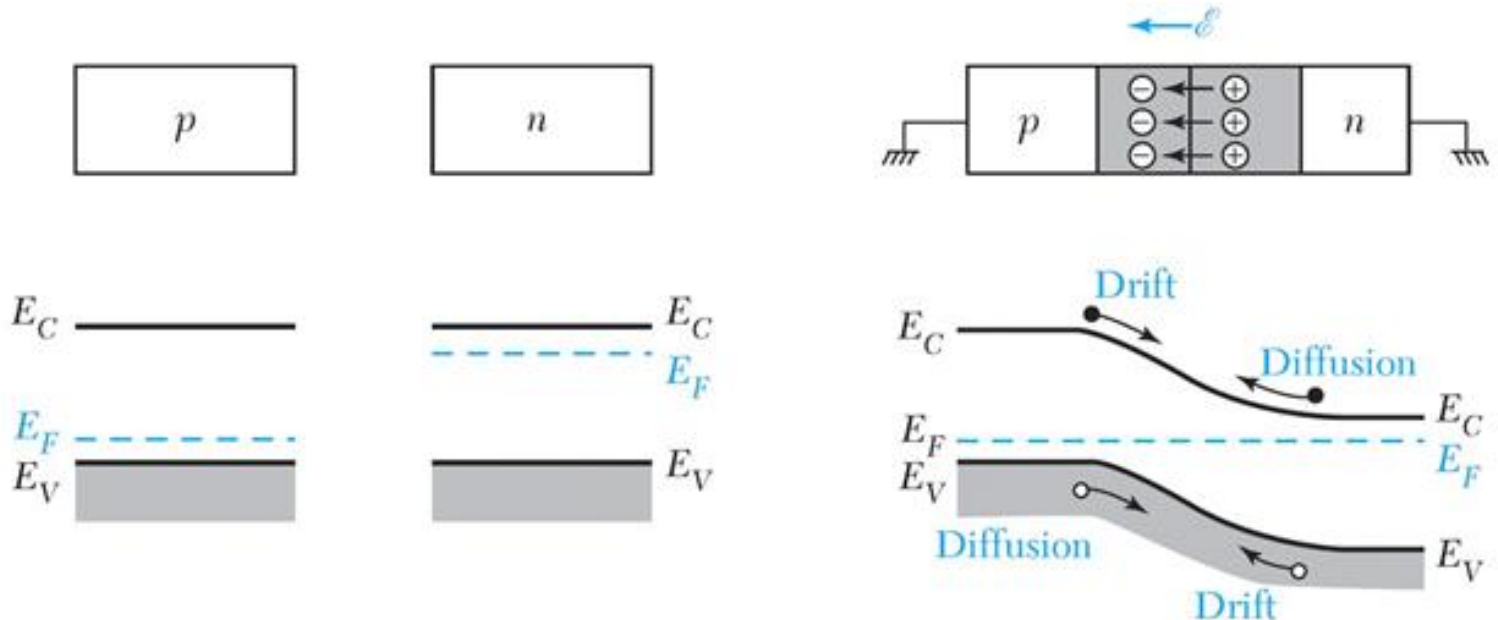
The large carrier concentration gradients at the junction (difference in Fermi levels) cause carrier diffusion into the other material: holes from the *p*-side diffuse into the *n*-side and electrons from the *n*-side diffuse into the *p*-side.



As holes leave the p -side, some of the negative acceptor ions N_A^- near the junction are left uncompensated (they are fixed in the lattice, while the holes can move), since only a fraction of majority carriers recombine on the other side.

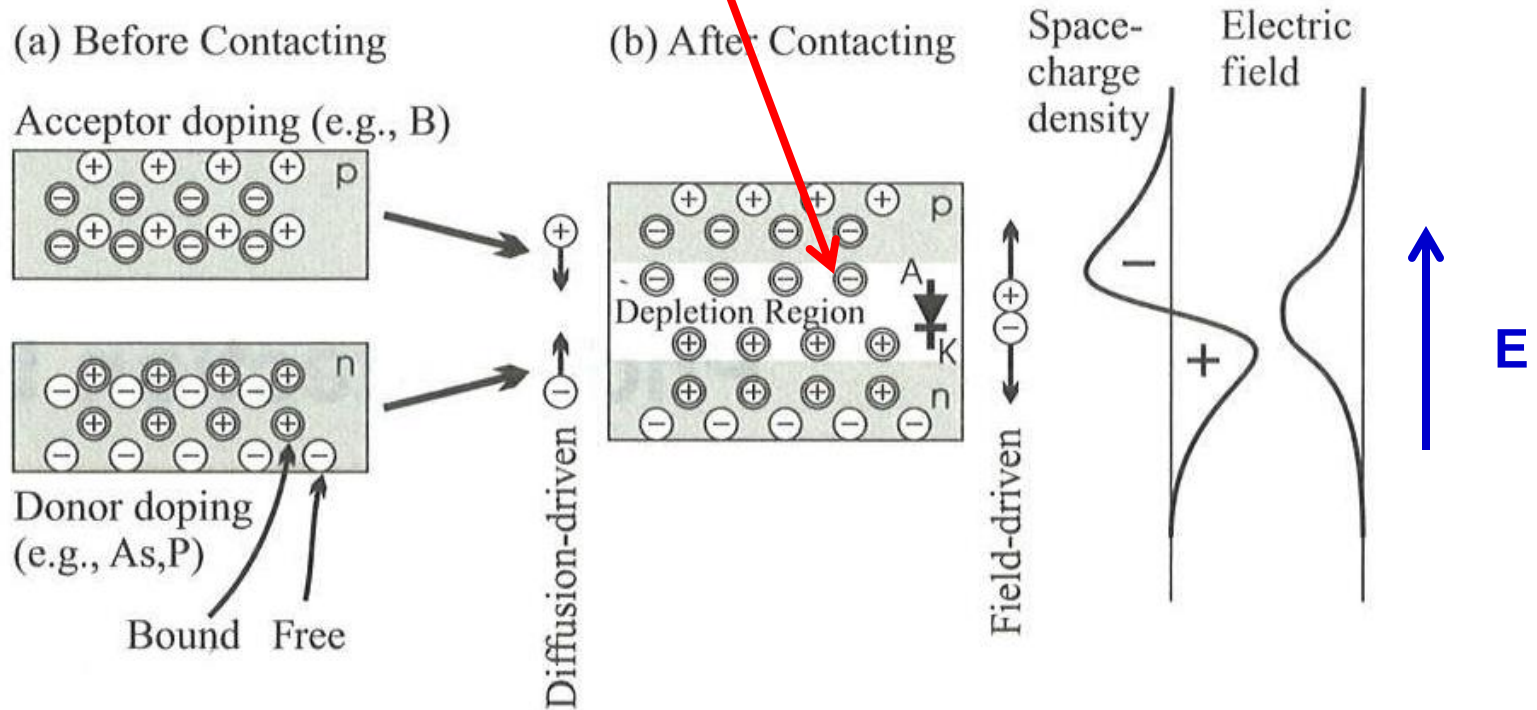
Similarly, some of the positive donor ions N_D^+ near the junction are left uncompensated, as electrons leave the n -side.

- a negative space charge forms near the p -side, and a positive space charge forms near the n -side
- the space charge generates an electric field directed from the n -side to the p -side, in the direction opposite to the diffusion current
- the electric field stops further diffusion.
this region is characterized by a built-in voltage V_{bi} , which is quite small $V_{bi} \sim 1$ V



pn Junction

This leaves a *charge free zone* or *depletion zone*, where acceptor and donor ions are left without their reversely charged free carriers.



Applying an external voltage (V_{bias}) of the same sign as V_{bi} will increase the depth of the depletion zone. In this case the junction is *reversely biased*.

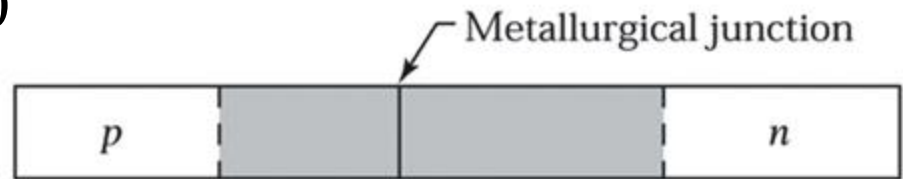
Equilibrium Fermi Levels

At thermal equilibrium the drift current caused by the electric field (space charge) cancels exactly the diffusion current due to the gradient concentration (Fermi levels).

$$J_p = J_p(\text{drift}) + J_p(\text{diffusion}) = 0$$

$$\Rightarrow \frac{dE_F}{dx} = 0$$

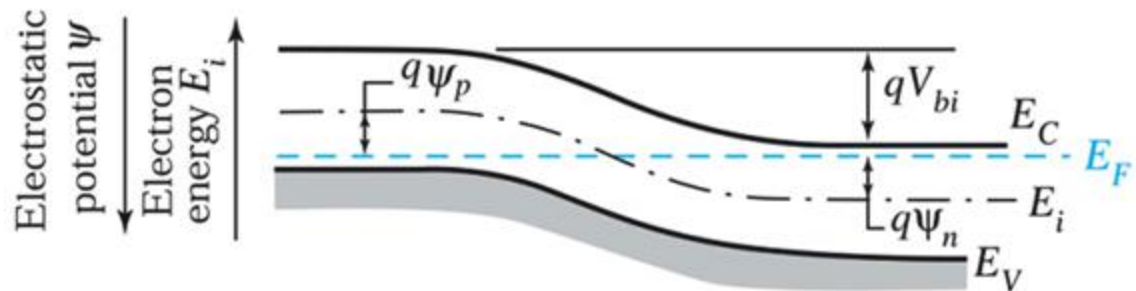
$$J_n = J_n(\text{drift}) + J_n(\text{diffusion}) = 0$$



At the junction the Fermi levels must equalize, and stay constant throughout the sample.

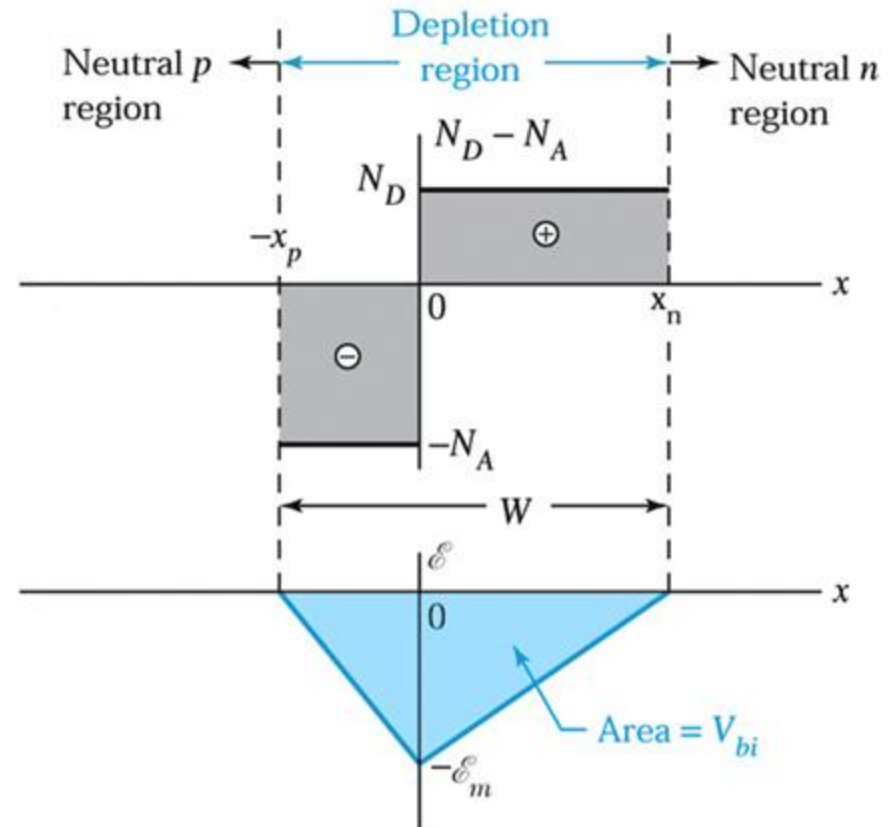
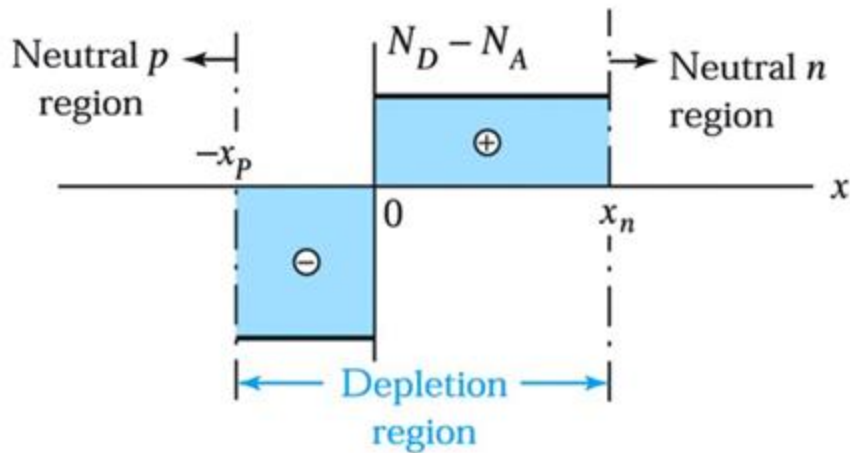
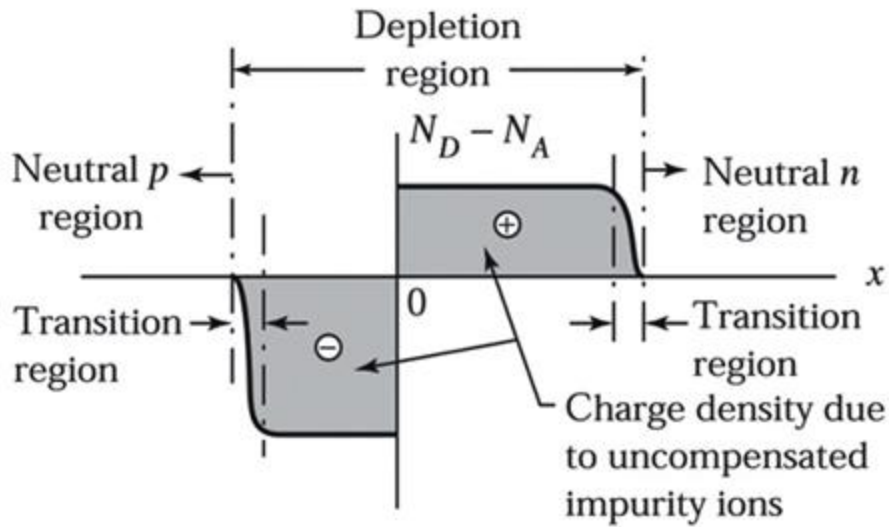
The built in voltage V_{bi} is given by

$$V_{bi} = \frac{kT}{q} \ln \left(\frac{N_A N_D}{n_i^2} \right)$$



(to prove all this we would need to study the carrier transport phenomena in a semiconductor as diffusion, drift, space-charge effects, etc. solve Poisson equations)

Space Charge and Electric Field



Depletion Region

The reversely biased pn junction is the building block of silicon sensors, it builds-up an electric field that can be used to extract the signal charge and suppresses the noise resulting from the leakage current.

In the transition pn region, some of the majority carriers on one side diffuse in the opposite side due to the concentration difference and recombine with the majority carriers on the other side, leaving a **charge free** zone (**depletion zone**, where acceptor and donor ions are left without their reversely charged free carriers).

Only ionization in the depletion region can be detected, since there are no free charges (background).

The width $W = x_p + x_n$ of the depletion zone can be calculated noting that the overall space charge neutrality of the semiconductor requires (space charge per unit area)

$$N_A x_p = N_D x_n$$

with the electric fields for each region given by (1-D Poisson equation)

$$E(x) = -q / \epsilon_{Si} \cdot N_A (x + x_p) \quad -x_p \leq x < 0$$

$$E(x) = q / \epsilon_{Si} \cdot N_D (x - x_n) \quad 0 < x_n \leq x$$

maximum E field at $x = 0$ $E_{\max} = q / \epsilon_{Si} \cdot N_D x_n = q / \epsilon_{Si} \cdot N_A x_p$

Depletion Region with Bias

Integrating these equations over the depletion region gives the *built-in* potential V_{bi} :

$$V_{bi} = E_{\max} W / 2$$

Combining all these equations we can obtain W

$$W = \sqrt{\frac{2\epsilon_{Si}}{q} \left(\frac{N_A + N_D}{N_A N_D} \right) V_{bi}}$$

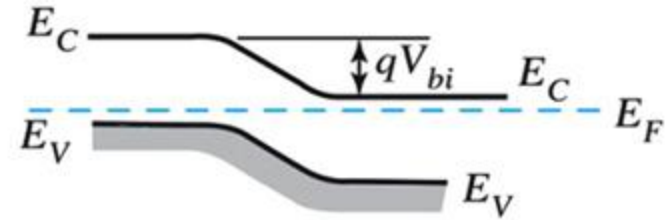
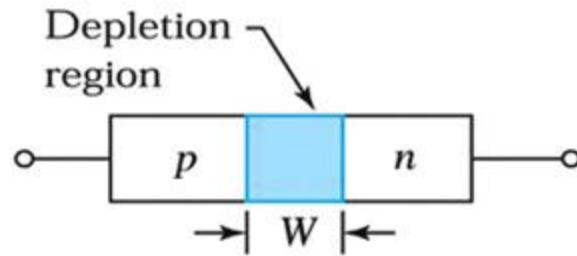
Under the effect of an external voltage (V_{bias}) W will change as

$$W = \sqrt{\frac{2\epsilon_{Si}}{q} \left(\frac{N_A + N_D}{N_A N_D} \right) (V_{bias} + V_{bi})}$$

Applying an external voltage of

- the same sign as V_{bi} will increase the depth of the depletion region (*reversely biased*) reaching **full depletion** of the material
- the opposite sign as V_{bi} will decrease the depth of the depletion region (*forward biased*)
if $V_{bias} > |V_{bi}|$ the *pn* junction conducts (rectifying diode)

unbiased

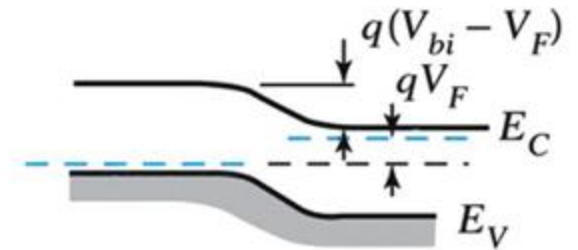
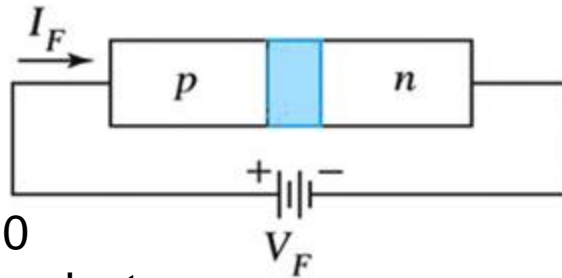


forward biased

the depletion region decreases

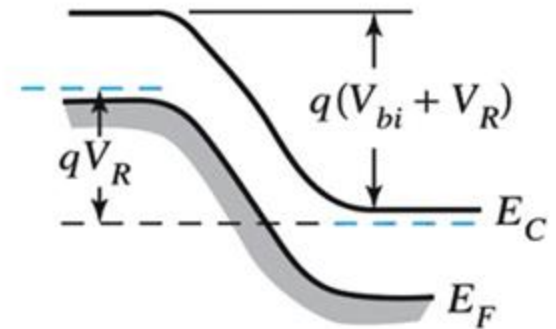
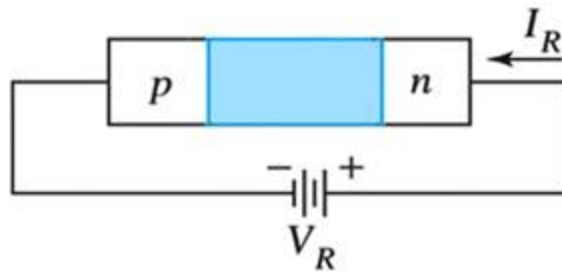
if $V_{bias} > |V_{bi}| = 0 \rightarrow W = 0$

if $V_{bias} > |V_{bi}|$ the diode conducts

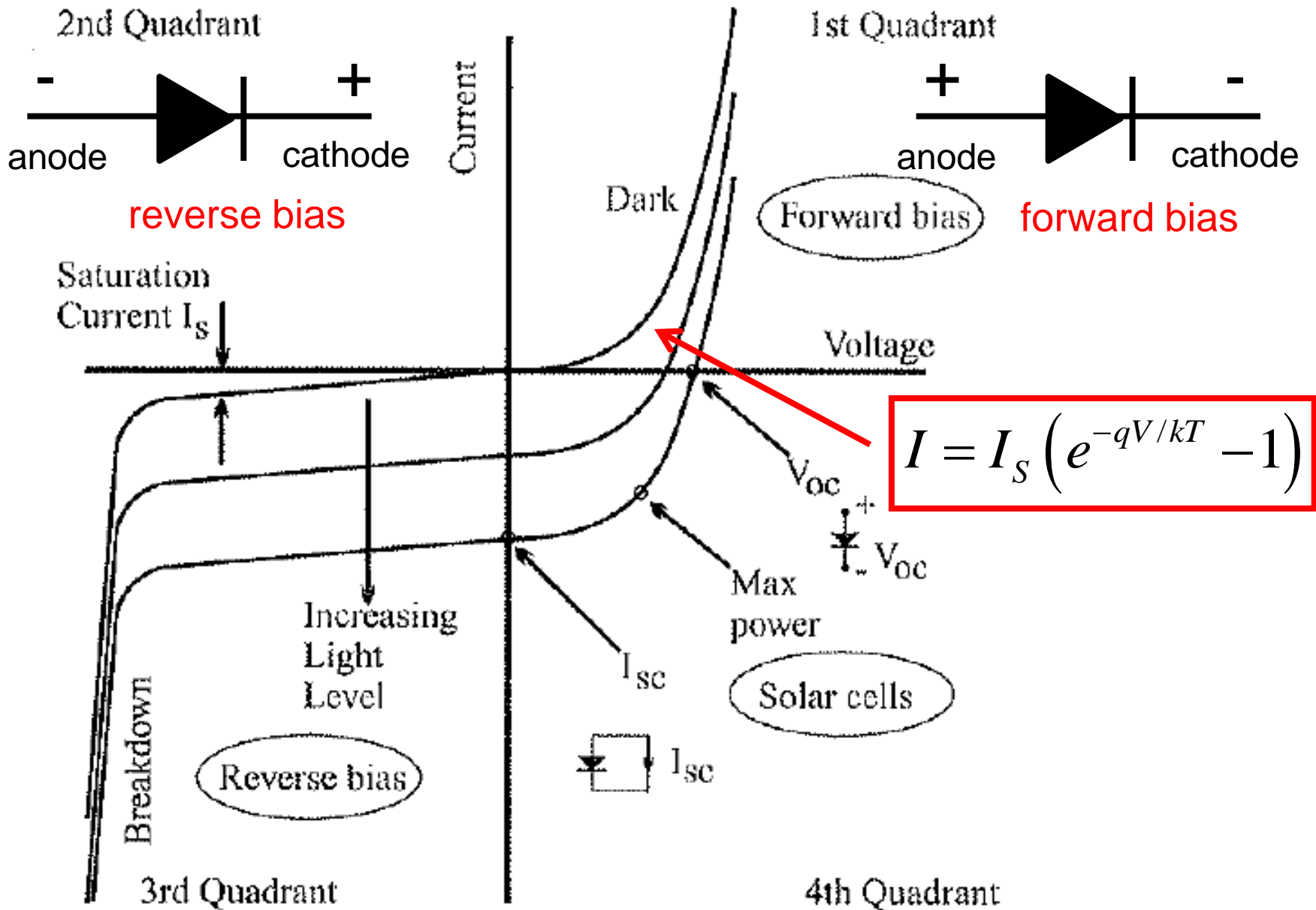


reversely biased

the depletion region increases



Current – Voltage Curve

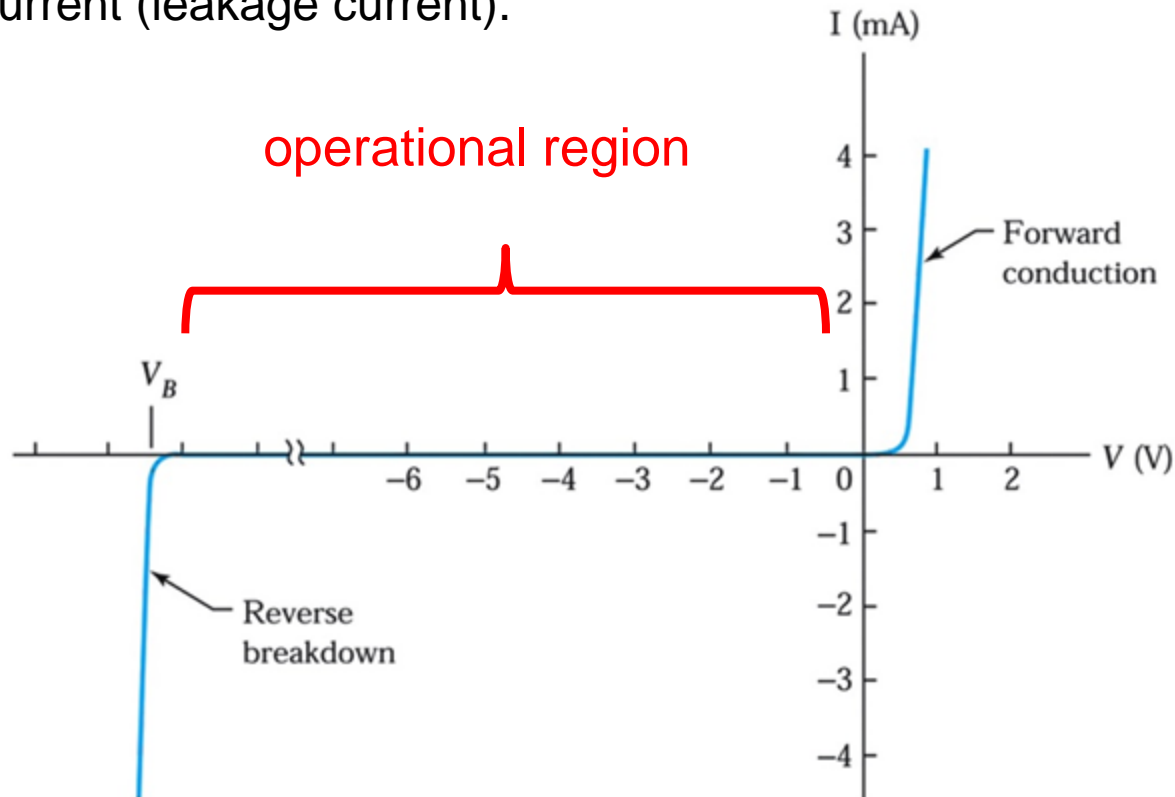


Current – Voltage Characteristics

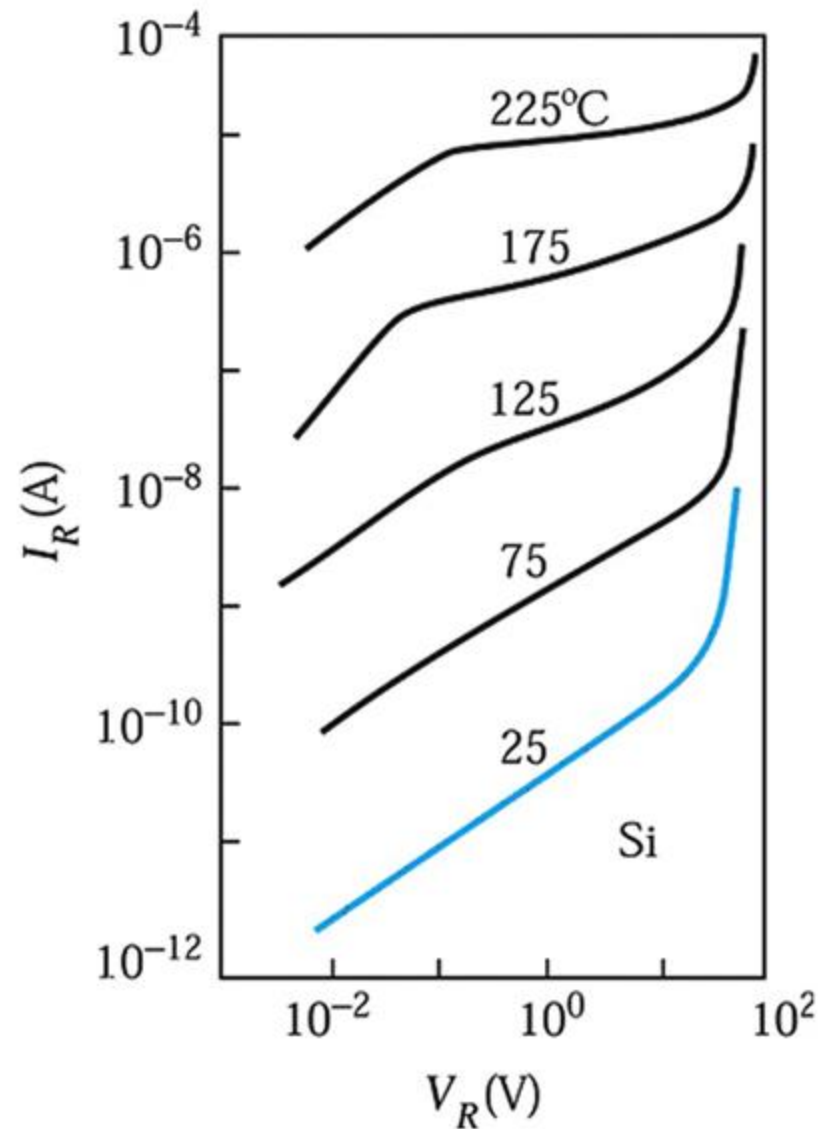
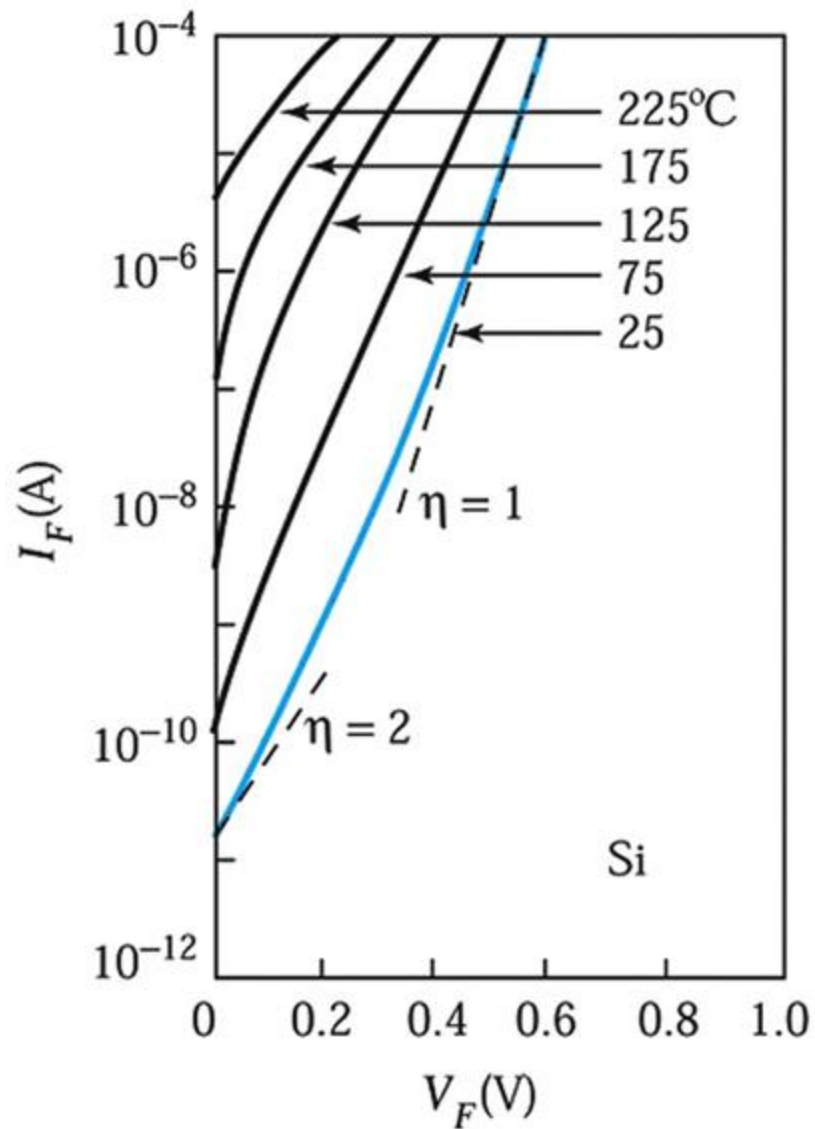
Exponential current increase in forward bias.

Avalanche current increase when reverse breakdown is reached (with possible device damage if current is not limited).

Large operational region (with different depletion depths up to full depletion) with very small current (leakage current).



Temperature Characteristics



One-Sided Abrupt Junction

In silicon sensors the diodes are *asymmetric*, i.e. there is a low-doped bulk material (e.g. $N_D \sim 10^{12} / \text{cm}^3$) on which high concentration shallow p^+ (acceptor) implants are deposited (e.g. $N_A \sim 10^{15} / \text{cm}^3$).

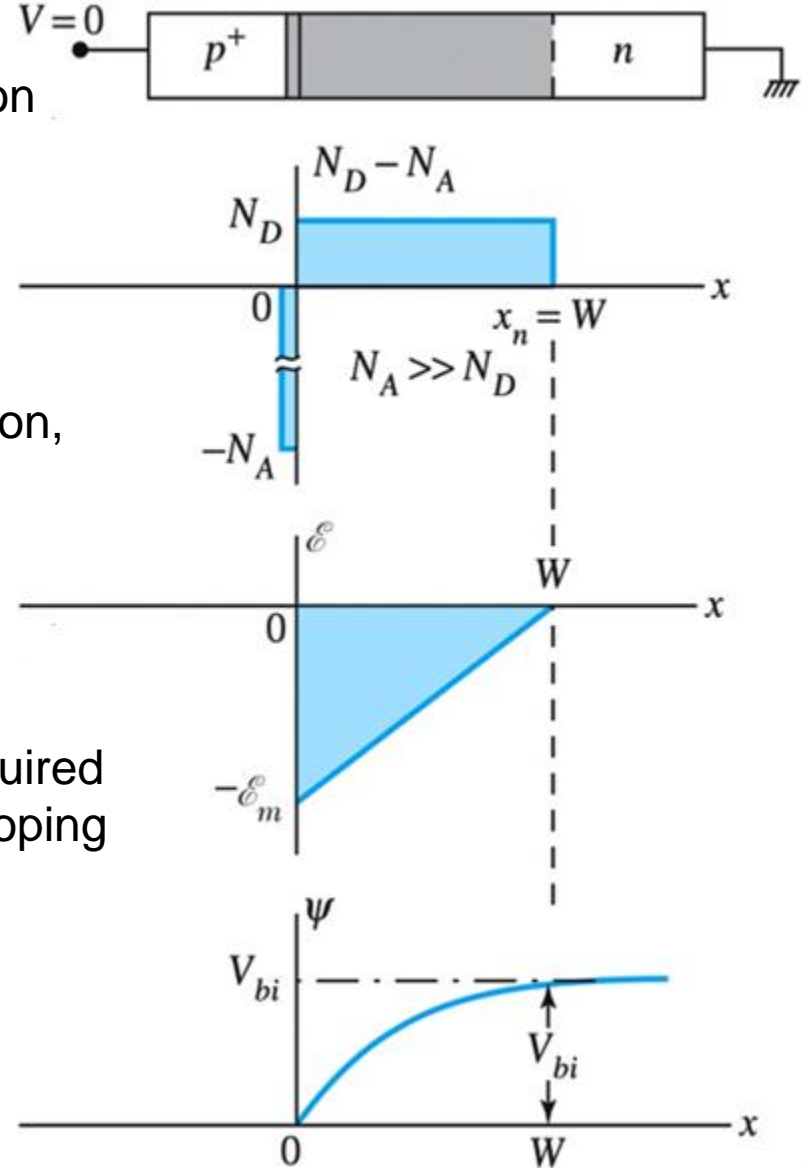
This generates a one-sided abrupt pn junction. Most used are n-type bulk silicon substrates.

Neglecting V_{bi} and neglecting the $1/N_A$ contribution, the width W of the depletion zone is

$$W \approx x_n \approx \sqrt{\frac{2\epsilon_{Si}}{qN_D} V_{bias}}$$

The full depletion voltage V_{depl} is the voltage required to fully deplete the detector. It depends on the doping concentration of the bulk material and $V_{depl} \propto d^2$

If $V > V_{depl}$ the sensor is *overdepleted* and a constant voltage ($V - V_{depl}$) is added to each point of the device.

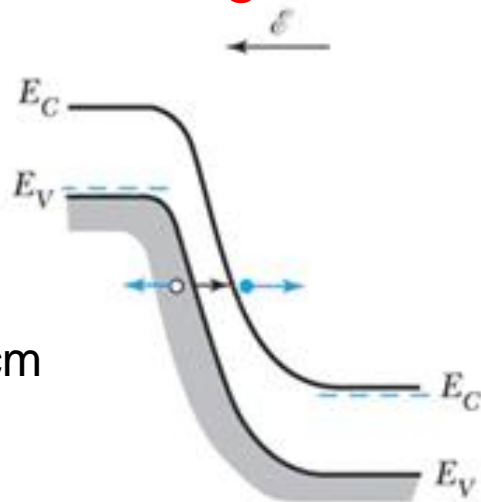


Breakdown

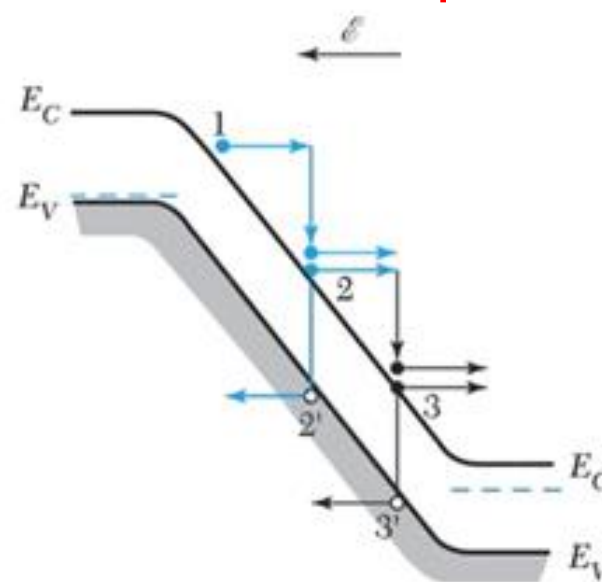
When a sufficiently large reverse voltage is applied to a pn junction, the junction breaks down and conducts a very large current. To avoid damage (like overheating) one must limit the current.

There are two important breakdown mechanisms

tunneling



avalanche multiplication

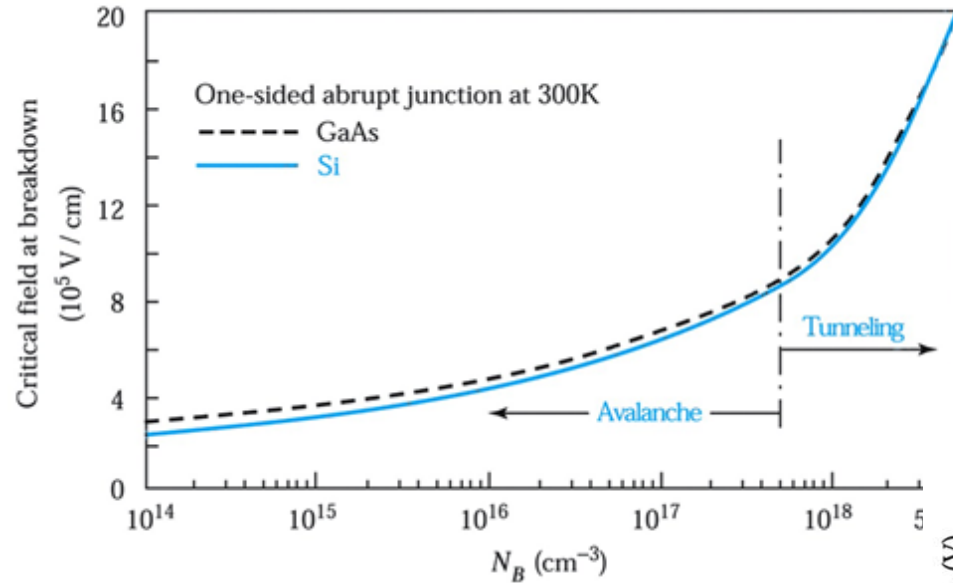


Avalanche multiplication occurs when a free electron gains enough kinetic energy that can break lattice bonds on collisions with an atom creating an electron-hole pair.

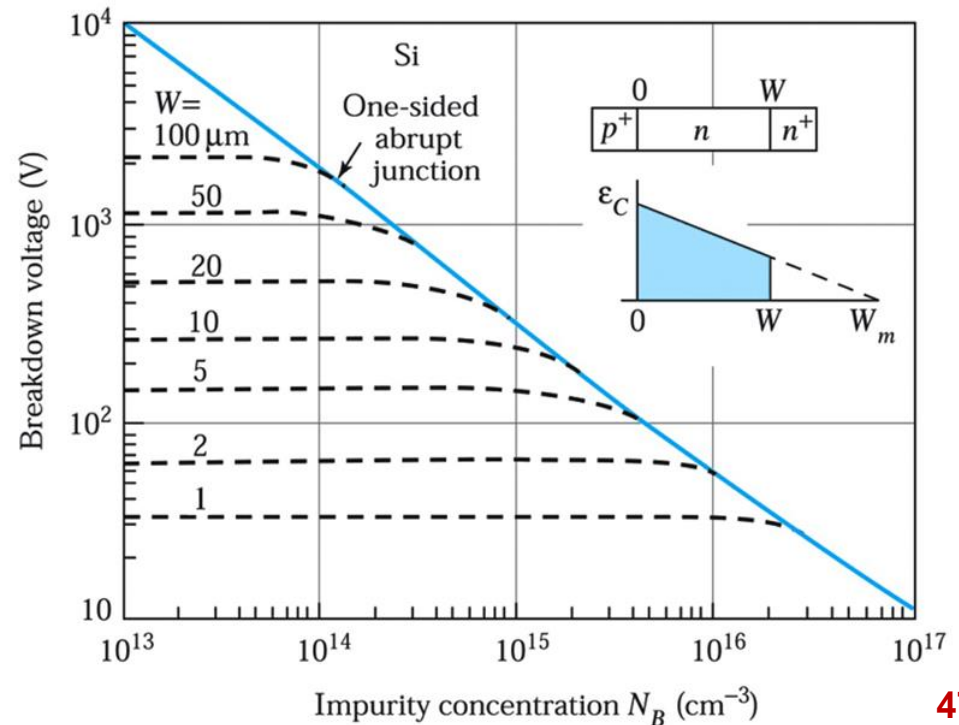
And the newly created electron-hole in turn continue the process ...

Breakdown

critical field at breakdown vs background doping N_B
 (N_B impurity concentration in the lightly doped region)



breakdown voltage
 $p^+ - \pi - n^+$ or $p^+ - v - n^+$



Junction Capacitance

The depleted junction volume is free of mobile charges and thus forms a capacitor with capacitance C , (i.e. a parallel plate capacitor of area A and thickness W):

$$C = \epsilon_{Si} \frac{A}{W} = A \sqrt{\frac{\epsilon q N_B}{2(V_{bias} + V_{bi})}}$$

→ capacitance decreases with the applied voltage V_{bias} .

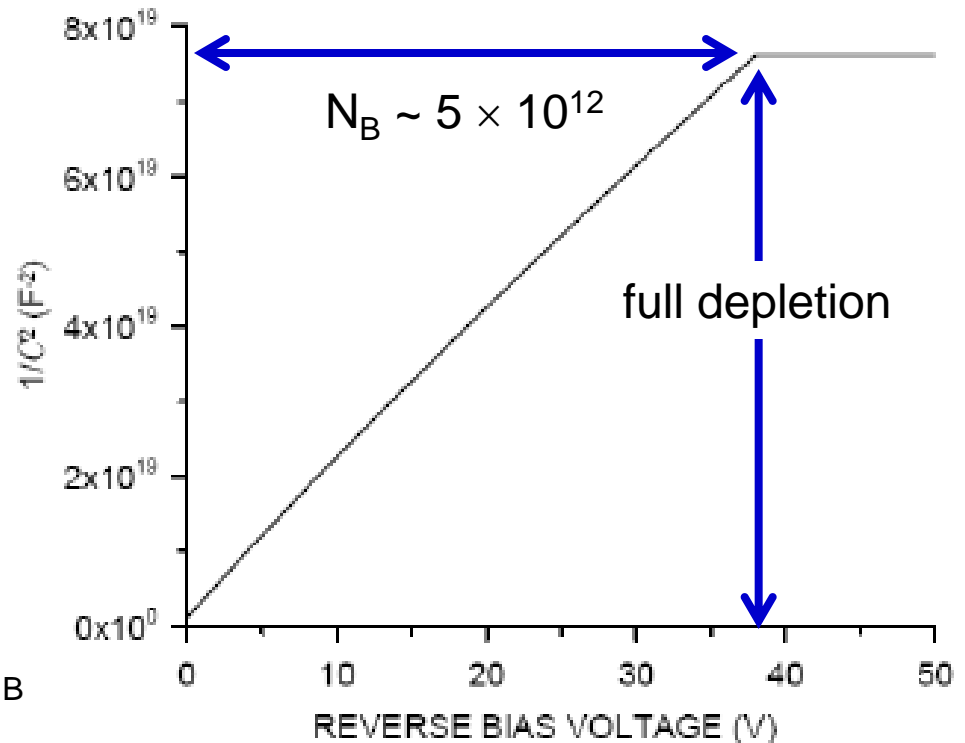
The capacitance per unit area for a typical Si detector is

$$\frac{C}{A} = \frac{\epsilon_{Si}}{W} \approx 1 [\text{pF/cm}] \frac{1}{W}$$

which favors highly segmented diodes.

The ratio C / A vs V_{bias} allows us to

- 1) determine the full depletion voltage
- 2) measure the doping concentration N_B



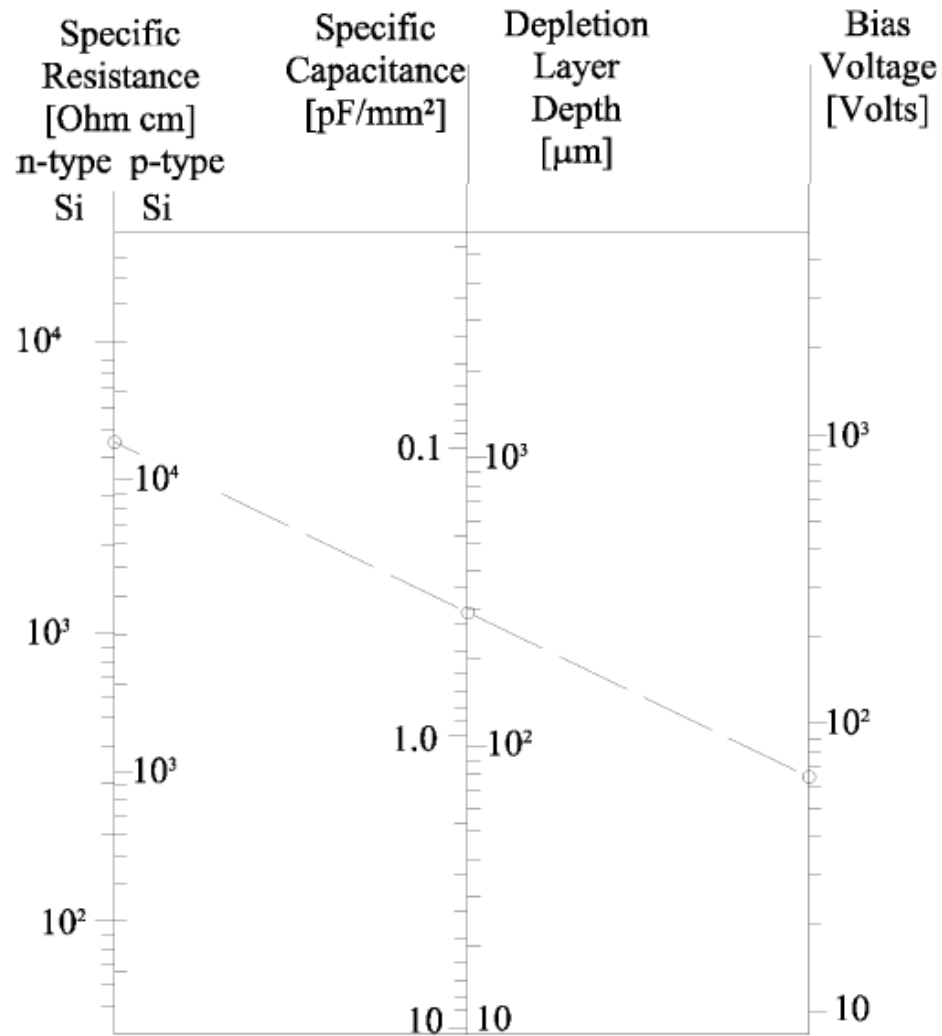
Basic Semiconductor Properties

Basic properties of some semiconductors.

Only few of them have been used as detector material.

semi-conductor	density (g/cm ³)	band gap (eV)	intrinsic carrier conc. (cm ⁻³)	average Z	w _{e,h} (eV)	mobility cm ² /Vs e h	(min.) carrier life time
Si	2.3	1.12	$1.45 \cdot 10^{10}$	14	3.61	1415 480	~ ms
Ge	5.3	0.66	$2.4 \cdot 10^{13}$	32	2.96	3900 1800	250 μs
GaAs	5.4	1.42	$1.8 \cdot 10^6$	32	4.35	8800 320	1-10 ns
CdTe	6.1	1.44	10^7	50	4.43	1050 100	0.1-2 μs
CdZnTe	5.8	~1.6	10^7	49.1	4.6	~1000 50-80	~ μs
CdS	4.8	2.42		48 / 16	6.3	340 50	
HgI ₂	6.3	2.13		62	4.2	100 4	~ μs
InAs	5.7	0.36		49 / 33		33000 460	
InP	4.8	1.35	$1.3 \cdot 10^7$	49 / 15		4600 150	
ZnS	4.1	3.68		30 / 16	8.23	165 5	
PbS	7.6	0.41		82 / 16		6000 4000	
Diamond	3.5	5.48	$<10^3$	6	13.1	1800 1200	~1 ns

A Useful Nomogram



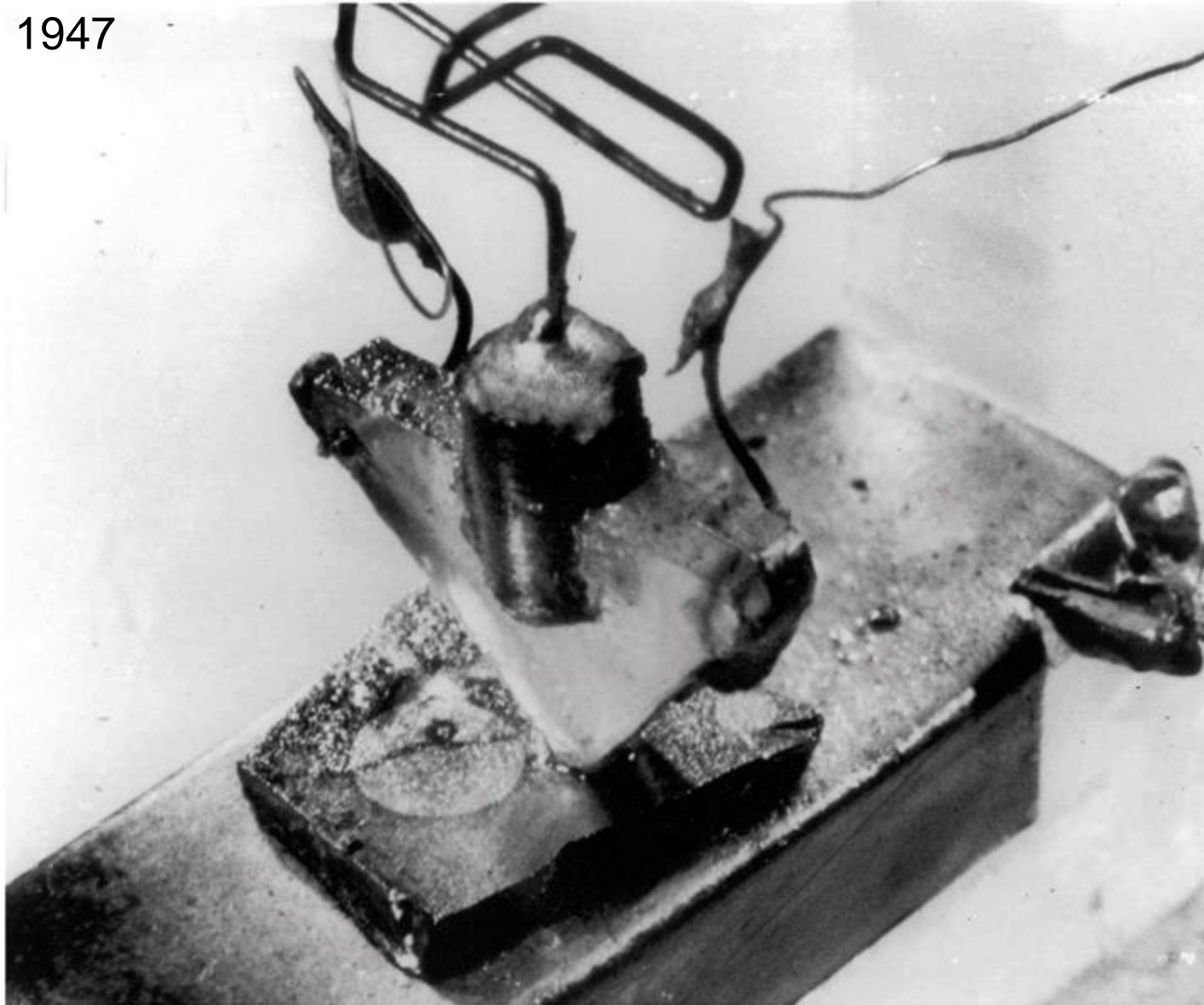
Relation between key parameters for silicon junction detector operation.

Any straight line correlates the values of different parameters.

(for different semiconductors these values will change, but the structure stays)

First Transistor

1947



1956

J. Bardeen
W. Shockley
W. Brattain