# PSI Praktikum 2017

http://www.physi.uni-heidelberg.de/~schoning/Vorlesungen/Poster_prak17.pdf

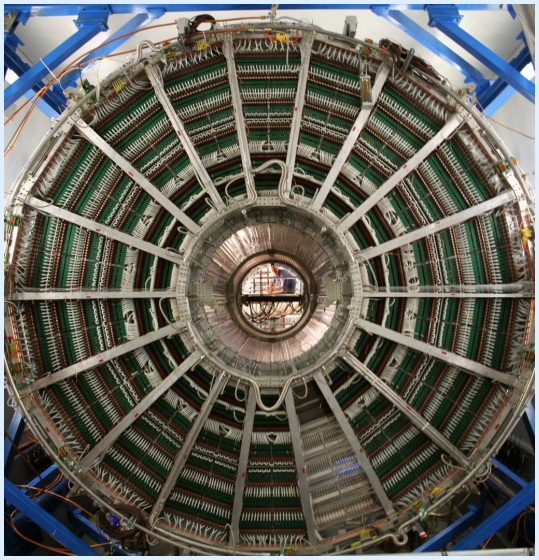
André Schöning

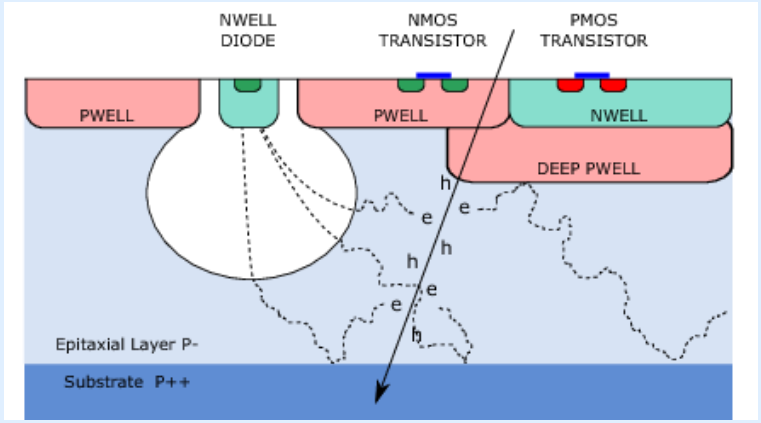
# For summer 2018

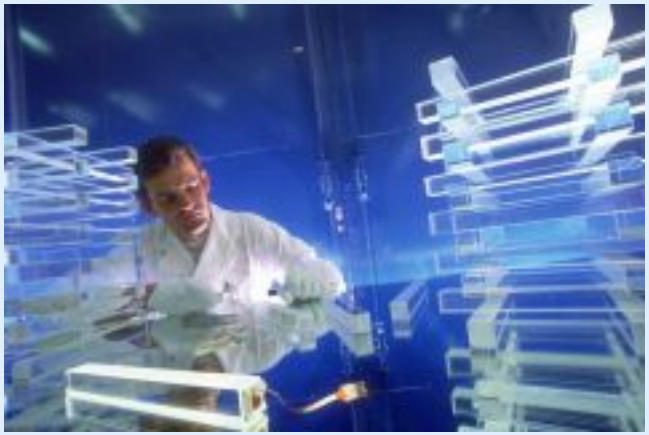
GSI and CERN have excellent programs for summer students!

GSI: https://theory.gsi.de/stud-pro/
CERN:
https://jobs.web.cern.ch/join-us/summer-student-programme-member-states

Applications are due typically in January / February (next in 2018)





# Semiconductor detectors - 1

Silvia Masciocchi,
GSI and University of Heidelberg

*SS2017, Heidelberg*
*May 24, 2017*

# Outline

- **Principle of operation of semiconductor detectors**
  - **Properties of semiconductors (band structure)**
  - **Intrinsic material**
  - **Extrinsic (doped) semiconductors**
  - **p-n junction**
- Signal generation
- Ionization yield and Fano factor

**TODAY**

- Energy measurement with semiconductor detectors
- Position measurement with semiconductor detectors
  - Micro-strip detectors
  - Silicon drift detectors
  - Pixels
- Charge-coupled devices (CCDs)
- Radiation damage

# Basics

**IONIZATION** as in gas detectors

→ Now in semiconductors = solid materials with crystalline structure (Si, Ge, GaAs)

→ electron-hole pairs (instead of electron-ion)

+ use microchip technology: structures with few micrometer precision can be produced at low cost. Read-out electronics can be directly bonded to the detectors

+ only a few eV per electron-hole pair → 10 times more charge produced (wrt gas) → better energy resolution

+ high density compared to gases → need only thin layers (greater stopping power)

– apart from silicon, the detectors need to be cooled (cryogenics)

– crystal lattices → radiation damage

# Applications

Main applications:

- γ spectroscopy with high energy resolution
- Energy measurement of charged particles (few MeV) and particle identification (PID) via dE/dx (multiple layers needed)
- Very high spatial resolution for tracking and vertexing

They will be discussed in detail in the next two lectures

A few dates:

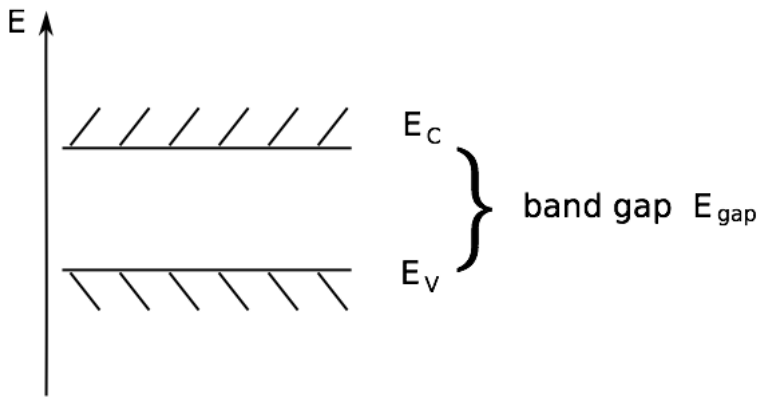
1930s – very first crystal detectors

1950s – first serious developments of particle detectors

1960s – energy measurement devices in commerce

# Principle of operation

- Detector operates as a solid state ionization chamber
- Charged particles create electron-hole pairs
- Place the crystal between two electrodes that set up an electric field → charge carriers drift and induce a signal




- Less than 1/3 of energy deposited goes into ionization. The rest goes into exciting lattice vibrations
- Effect: along track of primary ionizing particle plasma tube of electrons and holes with very high concentration ($10^{15}$ – $10^{17}$ $cm^{-3}$)
- Challenge: need to collect charge carriers before they recombine → very high purity semiconductor materials needed!!

# D-tour: band structure of electron levels

Solid → crystalline structure of atoms in a lattice, with covalent bonds.

The periodic arrangement of atoms in the crystal causes an overlap of electron wave-functions, which creates a "band" of energy states allowed for the outermost shell energy levels.

Electrons are fermions: the Pauli principle forbids to have more than electron in the same identical state and this produces a degeneracy in the outer atomic shell energy levels. This produces many discrete levels which are very close to each other, which appear as "bands"

The innermost energy levels are not modified, and the electrons remain associated to the respective lattice atoms.

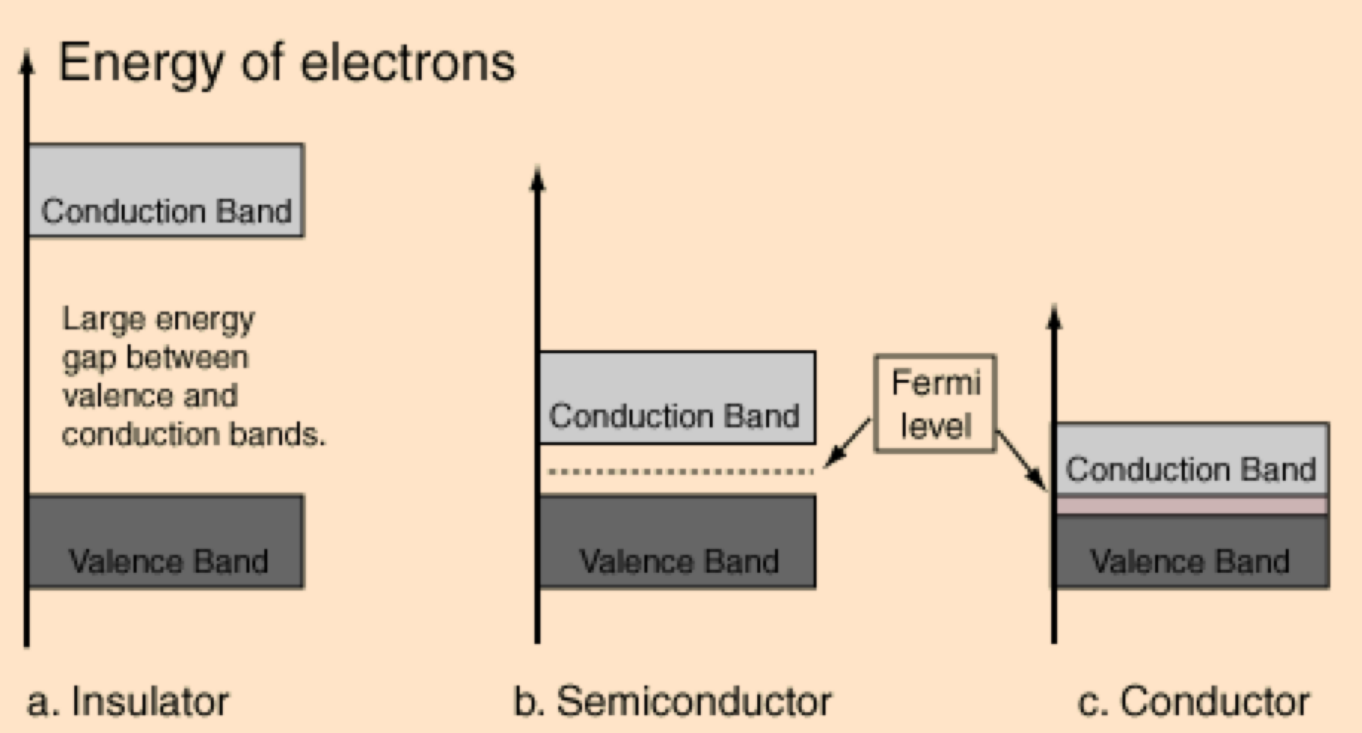
**CONDUCTION BAND**: electrons are detached from parent atoms and are free to roam about the whole crystal

**VALENCE BAND**: electrons are more tightly bound and remain associated to the respective lattice atom

**FORBIDDEN BAND**: in pure crystals, between the two bands above there are NO available energy levels

# Band theory of solids

The width of the energy bands and the energy gap is determined by the inter-atomic spacing. This depends on temperature and pressure.




Bands determine the density of available energy states

# Band theory of solids

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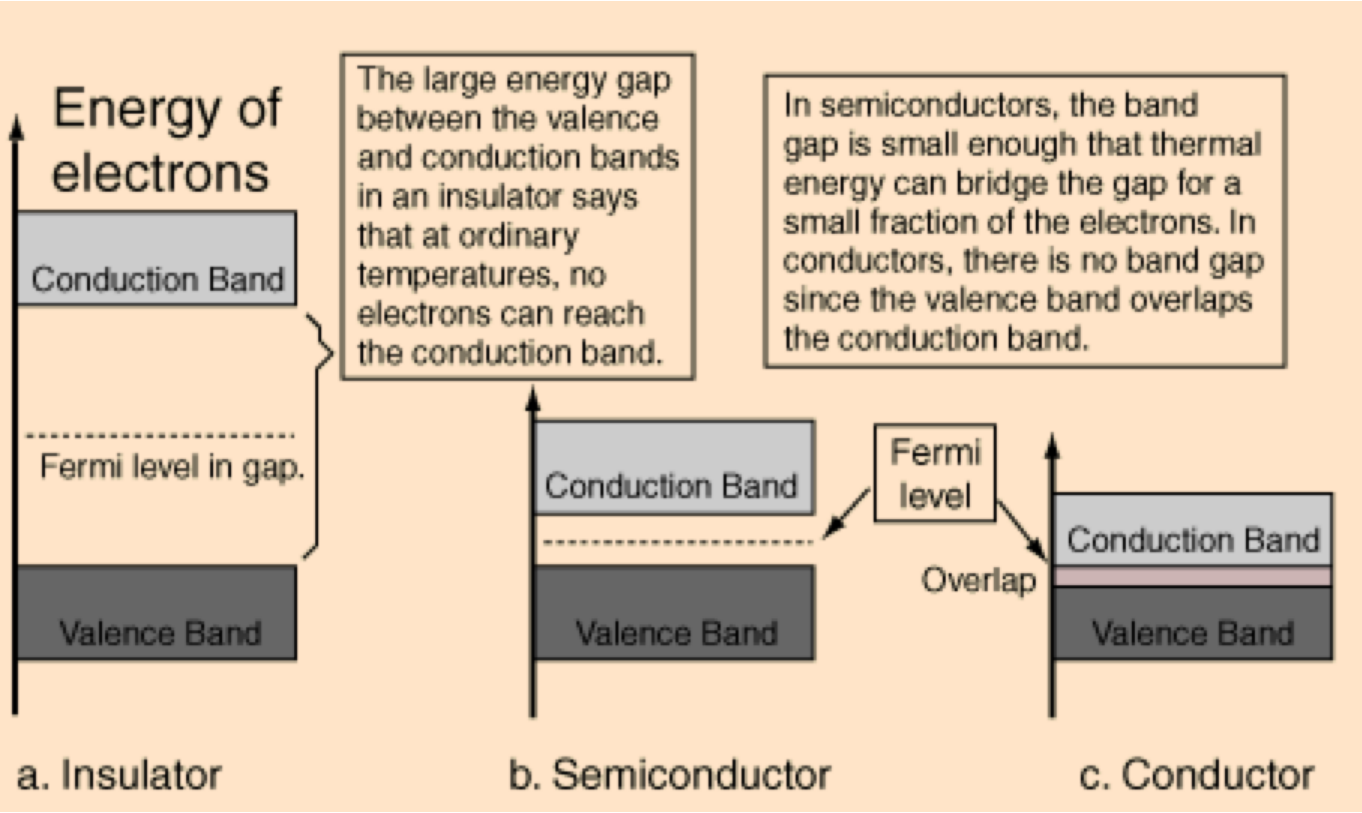



Bands determine the density of available energy states

# Fermi-Dirac distribution

At normal temperature, thermal energy might be enough to move an electron in the conduction band: in a semiconductor if sufficient, always in a metal, never in an insulator.

Electrons in a band can be described as particles in a box or in a potential well → Fermi gas model: density of states is

$$g(E) = \frac{g(\lambda)}{dE/d\lambda} = \frac{2m}{\hbar^2 \lambda} = \frac{(2m)^{3/2}}{2\pi^2 \hbar^3} \sqrt{E}$$

Number of electrons versus E → Fermi-Dirac probability distribution:

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

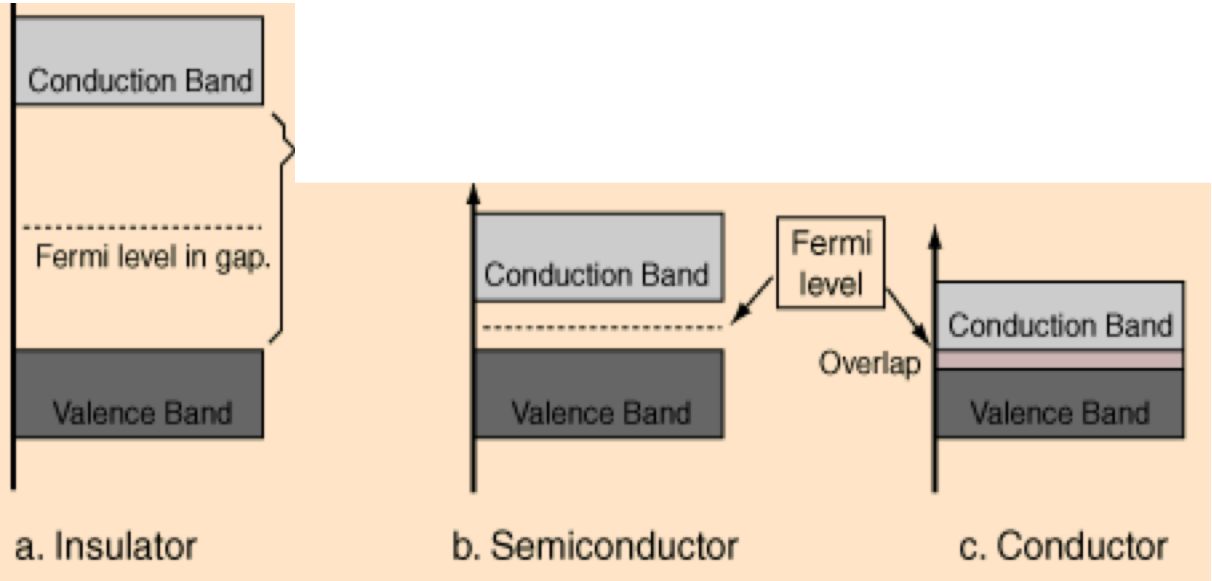
where $E_F$ is the so-called **Fermi energy**

Number of electrons per energy interval: n(E)dE = g(E) f(E) d(E)

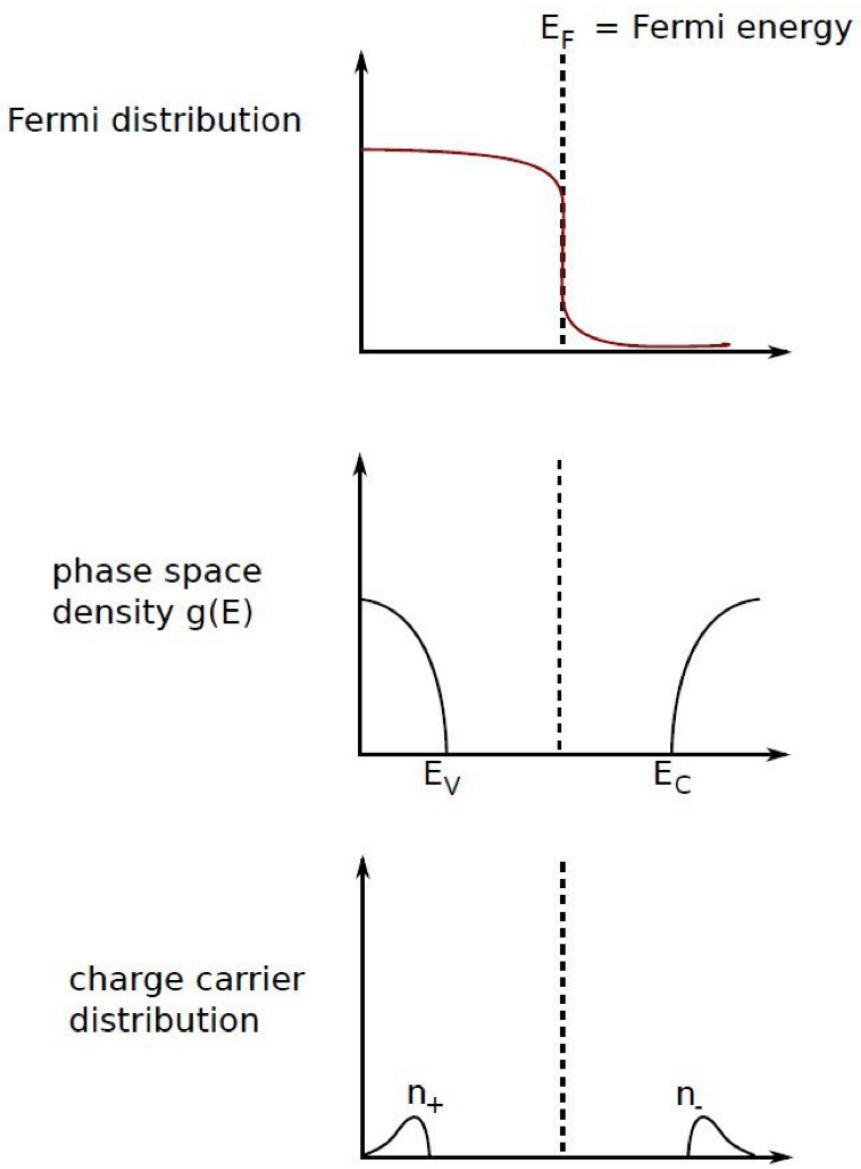
# Fermi energy and type of solid

The characteristics of a solid are determined by the location of the Fermi energy relative to the energy bands:

- Metal: $E_F$ below top of an energy band (V and C bands overlap)
- Insulator: $E_F$ at top of valence band and gap to next allowed band too large to be bridged by optical or thermal excitation, or electric force at normal E-field
- Semiconductor: gap is smaller, so that electrons can be excited across thermally or optically. $E_F$ between valence and conduction band



# Electron levels in semiconductors




## Fermi-Dirac probability distribution

$$f(E) \approx \exp[-(E - E_F)/kT] \qquad E > E_F$$
$$1 - f(E) \approx \exp[-(E_F - E)/kT] \qquad E < E_F$$

## Density of available energy states

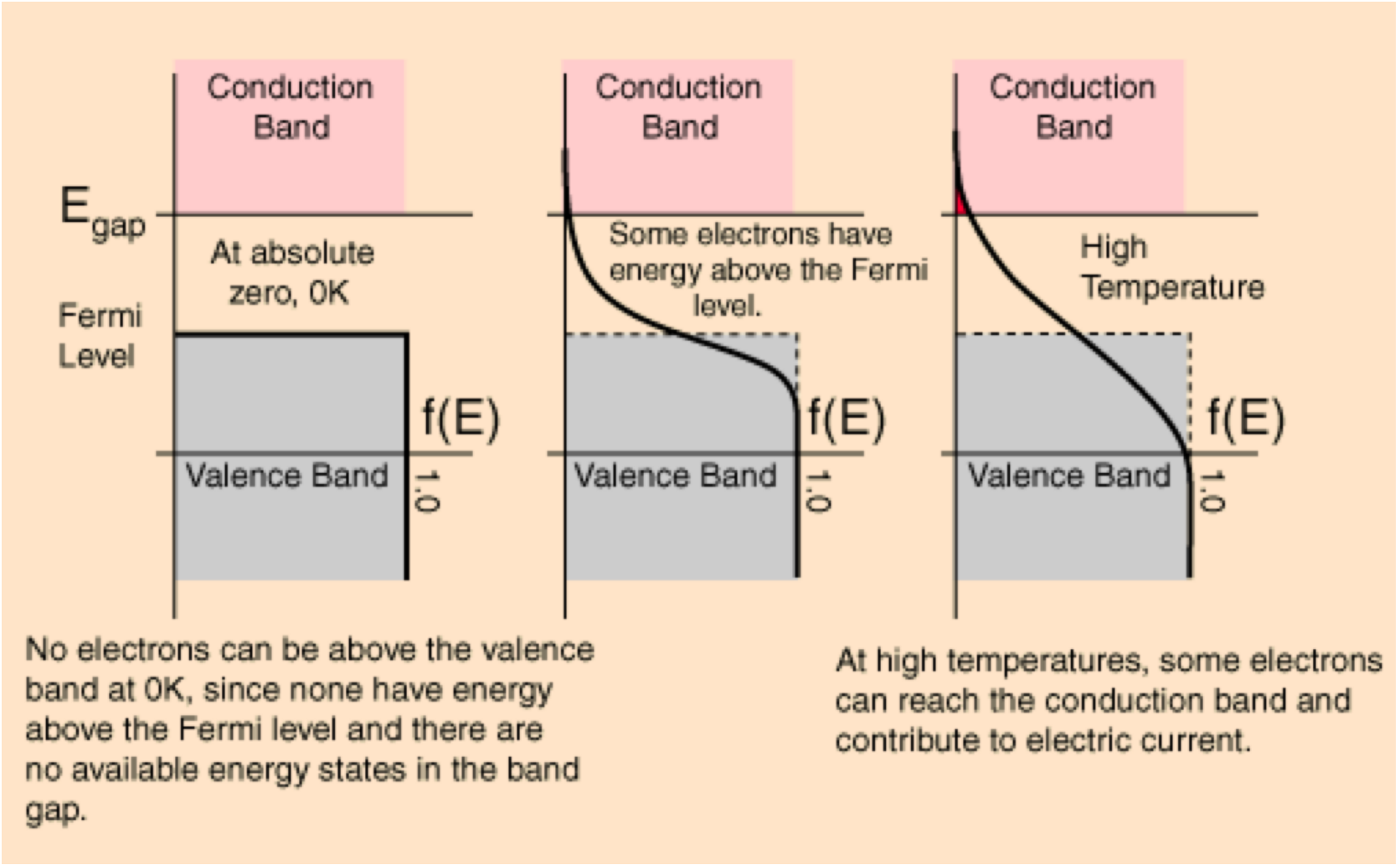
Fermi gas model

$$g_c(E) = \frac{(2m_n^*)^{3/2}}{2\pi^2\hbar^3}\sqrt{E - E_C} \qquad E > E_C$$
$$g_V(E) = \frac{(2m_p^*)^{3/2}}{2\pi^2\hbar^3}\sqrt{E_V - E} \qquad E < E_V$$

## Resulting distribution of charge carriers

$$n_-(E) = f \cdot g_C$$
$$n_+(E) = (1 - f) \cdot g_V$$

# Semiconductors: temperature dependence



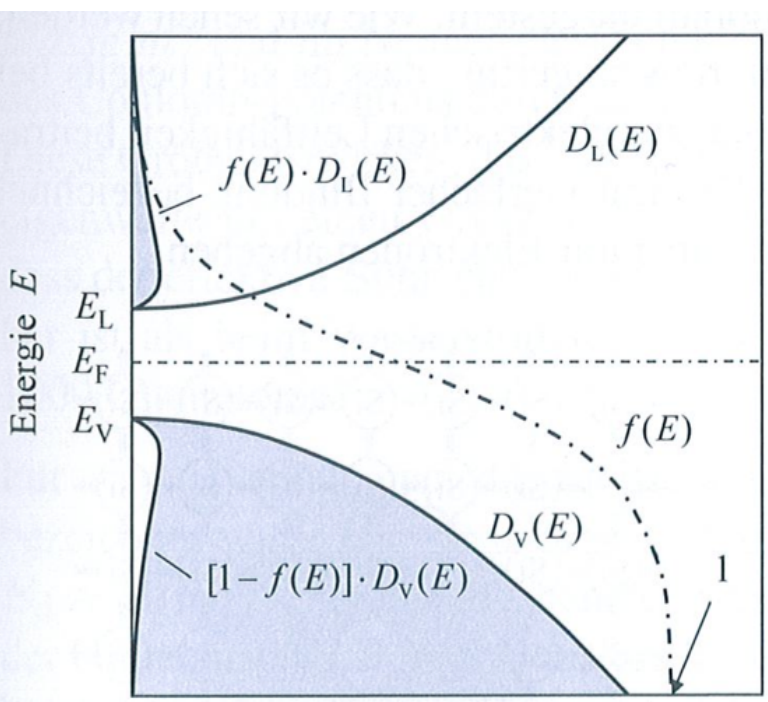

No electrons can be above the valence band at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.

At high temperatures, some electrons can reach the conduction band and contribute to electric current.

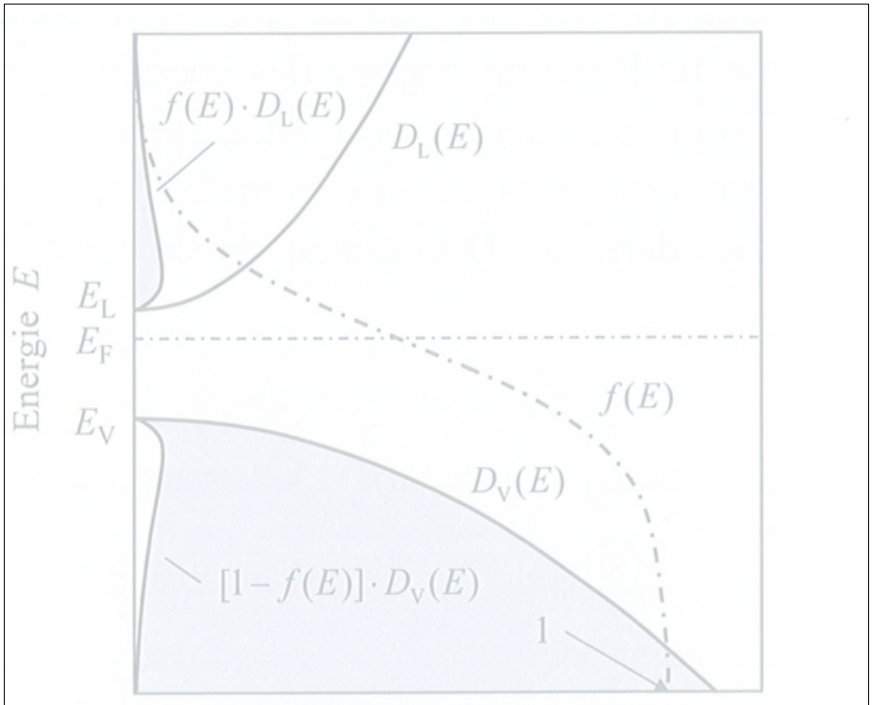
# Semiconductors and Fermi level

Festkörperphysik (p. 389)

Siegfried Hunklinger




(a) Zustandsdichte $D(E)$, Fermi-Funktion $f(E)$




(b) Zustandsdichte $D(E)$, Fermi-Funktion $f(E)$

**Bild 10.6:** Zustandsdichten $D(E)$ und Fermi-Funktion $f(E)$ im Valenz- und Leitungsband für $T > 0$. Die Elektronen sind hellblau, die Löcher weiß dargestellt. **a)** Halbleiter mit gleicher Zustandsdichte in Valenz- und Leitungsband, d.h. $\mathcal{N}_L = \mathcal{N}_V$, **b)** Halbleiter mit $\mathcal{N}_V > \mathcal{N}_L$, also mit der größeren Zahl von Zuständen an der Valenzbandkante.

# Charge carriers in semiconductors

- Intrinsic semiconductors: VERY PURE material, tetravalent

  Charge carriers are created by thermal or optical excitation of electrons to the conduction band: $N_- = N_+$

  - Difficult to produce large volumes of so pure materials.
  - Extremely low concentrations of charge carriers

- Extrinsic or doped semiconductors:

  Majority of charge carriers provided by impurity atoms at lattice sites of the crystal

  - Impurity atoms (pentavalent elements, donors) provide extra electrons → n-type (majority charge carriers: electrons)

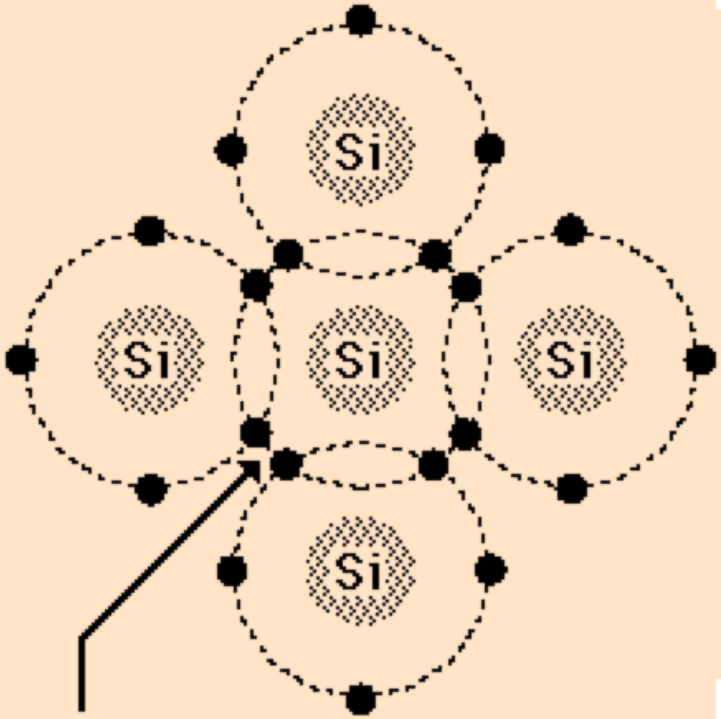
  OR

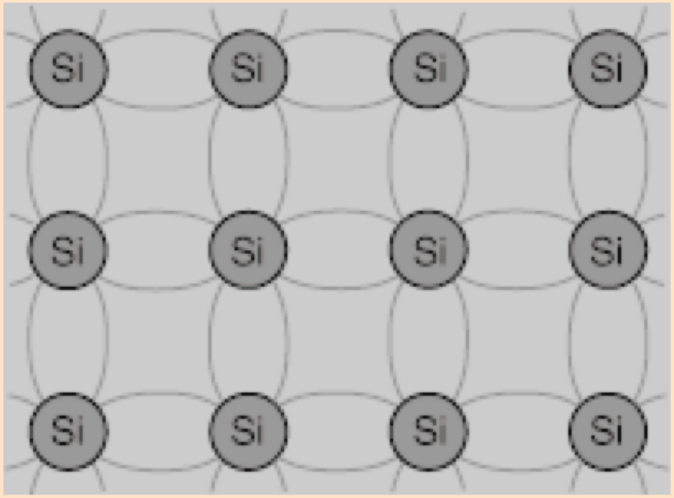
  - Impurity atoms (trivalent elements, acceptors) have insufficient number of electrons for the covalent bonds, free hole at impurity site, provide extra holes → p-type (majority charge carriers: holes)

# Intrinsic semiconductors

Crystalline lattice, of tetravalent elements (Si, Ge)

4 valence electrons → covalent bonds




| | $E_{gap}$ |
|---|---|
| Si | 1.12 eV |
| Ge | 0.66 eV |
| GaAs | 1.43 eV |

# Intrinsic semiconductors

At zero temperature, all electrons participate in covalent bons.

At non-zero temperature: thermal energy can excite a valence electron into the conduction band. A hole = positive charge remains in the valence band

Under the action of an E-field: the electron can move in the conduction band. In the valence band, other electrons can fill the hole → effective movement of holes (electric current)

Intrinsic **charge carrier** concentration:

$$n_i = \sqrt{N_C N_V} \cdot \exp\left(-\frac{E_g}{2kT}\right) = A\,T^{3/2} \exp\left(-\frac{E_g}{2kT}\right)$$

At T = 300 K, $n_i = 2.5 \times 10^{13}$ cm$^{-3}$ in Germanium

$n_i = 1.5 \times 10^{10}$ cm$^{-3}$ in Silicon

wrt $10^{22}$ atoms cm$^{-3}$

**VERY LOW CONCENTRATIONS !!!**

# Charge carrier densities

Density of electrons in the conduction band:

$$n = \int n_{-}\, dE = \int_{E_c}^{\infty} f\, g_c\, dE = N_c \exp[-(E_c - E_F)/kT]$$

And correspondingly density of holes in the valence band:

$$p = \int n_{+}\, dE = \int_{-\infty}^{E_v} (1-f)\, g_v\, dE = N_v \exp[-(E_F - E_v)/kT]$$

$N_c$, $N_v$: effective density of states at edge of conduction and valence bands

$$N_{c,v} = 2\left(\frac{m^*_{n,p}\, k\, T}{2\pi\hbar^2}\right)^{3/2}$$ with effective masses m* of electrons and holes

→ much weaker T-dependence than exponential (looks like only levels at $E_c$ and $E_v$ are present, not broad bands)

Electric current has 2 components: movement of free electrons in conduction band and movement of holes in the valence band

# Charge carrier densities

For intrinsic semiconductors:

$$E_c - E_F = E_F - E_v \quad \Rightarrow \quad n_i = p_i$$

$$np = N_c N_v \exp\left(-\frac{(E_c - E_v)}{kT}\right) = n_i^2$$

Product of n and p at a given T has fixed value, characterized by effective masses and band gap

→ often called: LAW OF MASS ACTION

Electric current has 2 components: movement of free electrons in conduction band and movement of holes in the valence band

# Mobility of charge carriers

The electrical behavior is determined by the mobility of charge carriers:

- Drift velocity: $v_D = \mu E$ - $\mu$ mobility
- Specific resistance: $\rho$ ($\Omega$m)
- Resistance $R = \rho\, l / A$, with length l and area A transverse to E

As in gases: random thermal motion + drift in electric field

In intrinsic semiconductors:

- $\mu \simeq$ const. for $E < 10^3$ V/cm
- $\mu \propto 1/\sqrt{E}$ for $10^3$ V/cm $< E <$ $10^4$ V/cm
- $\mu \propto 1/E$ for $E > 10^4$ V/cm $\rightarrow$ $v_D = \mu \cdot E$ is CONSTANT !!

Saturates at about $10^7$ cm/µs (similar to gases / trade off between energy acquired and collisions with the lattice here)

**$\rightarrow$ fast collection of charges: 10 ns for 100 µm drift**

**$\rightarrow$ $v_h \simeq 0.3 - 0.5\, v_e$ (very different from gases!)**

$I = e \cdot n_i (\mu_e + \mu_h) E = \sigma E \rightarrow$ conductivity: $\sigma = 1/\rho$ $\rho$: resistivity

# Properties of intrinsic Si and Ge

| | | Si | Ge |
|---|---|---|---|
| Atomic number | | 14 | 32 |
| Atomic weight | u | 28.09 | 72.60 |
| Stable isotope mass numbers | | 28-29-30 | 70-72-73-74-76 |
| Density (300 K) | $g/cm^3$ | 2.33 | 5.32 |
| Atoms/$cm^3$ | $cm^{-3}$ | $4.96 \cdot 10^{22}$ | $4.41 \cdot 10^{22}$ |
| Dielectric constant | | 12 | 16 |
| Forbidden energy gap (300 K) | eV | 1.115 | 0.665 |
| Forbidden energy gap (0 K) | eV | 1.165 | 0.746 |
| Intrinsic carrier density (300 K) | $cm^{-3}$ | $1.5 \cdot 10^{10}$ | $2.4 \cdot 10^{13}$ |
| Intrinsic resistivity (300 K) | $\Omega$cm | $2.3 \cdot 10^5$ | 47 |
| Electron mobility (300 K) | $cm^2/Vs$ | 1350 | 3900 |
| Hole mobility (300 K) | $cm^2/Vs$ | 480 | 1900 |
| Electron mobility (77 K) | $cm^2/Vs$ | $2.1 \cdot 10^4$ | $3.6 \cdot 10^4$ |
| Hole mobility (77 K) | $cm^2/Vs$ | $1.1 \cdot 10^4$ | $4.2 \cdot 10^4$ |
| Energy per electron-hole pair (300 K) | eV | 3.62 | |
| Energy per electron-hole pair (77 K) | eV | 3.76 | 2.96 |

Source: G. Bertolini an A. Coche (eds.), Semiconductor Detectors, Elsevier-North Holland, Amsterdam, 1968

# Recombination and trapping

Relatively rare: **direct recombination**: an electron falls from the conduction to the valence band to fill a hole → produces a photon.
It is a rare process, with long lifetime (the exact energy is needed)

**IMPURITIES** in the crystal lattice can produce: (ALWAYS present!!)

RECOMBINATION CENTERS: additional levels in the forbidden gap can capture electrons from the conduction band, or holes from the valence band → reduction of the mean time a charge carrier remains free

TRAPPING: of only electrons or holes, for some time

→ If the release time of the charge carriers is longer than the collection time in the detector, these processes produce a **LOSS OF CHARGE**

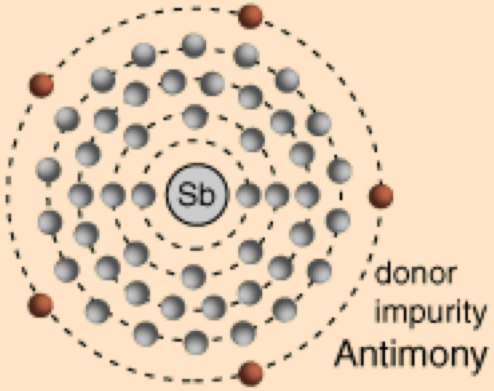
**STRUCTURAL DEFECTS** include point defects (vacancies, positions in between lattice) and dislocations (displacement of a full line of atoms). Produced during growth of crystal or by thermal shock, plastic deformation, stress and radiation damage.

# Doping of semiconductors

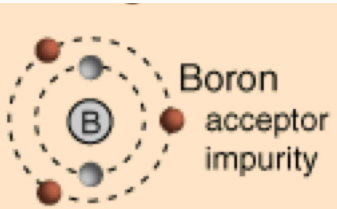
n-type
pentavalent impurities

p-type
trivalent impurities

Antimony
Arsenic
Phosphorous




Boron
Aluminum
Gallium

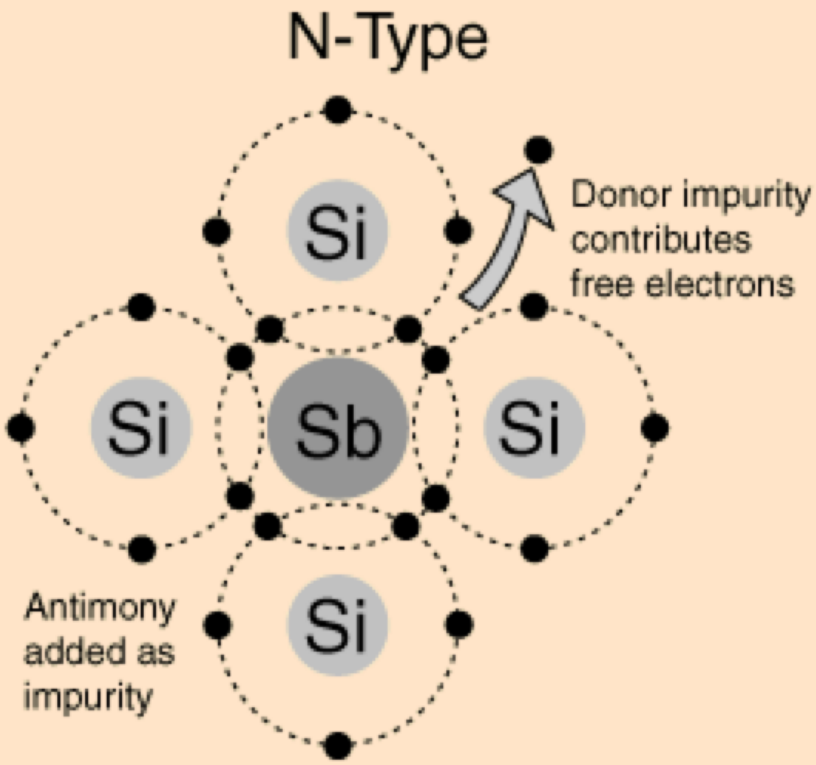



Sb
As
P

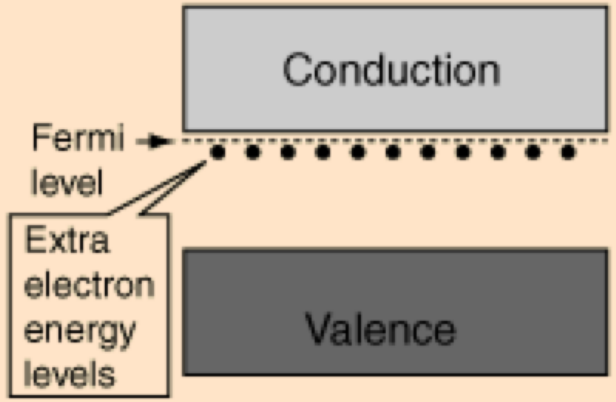
B
Al
Ga
In

**Extra electrons (n) and holes (p) respectively enhance the conductivity of the material!**

# n-type



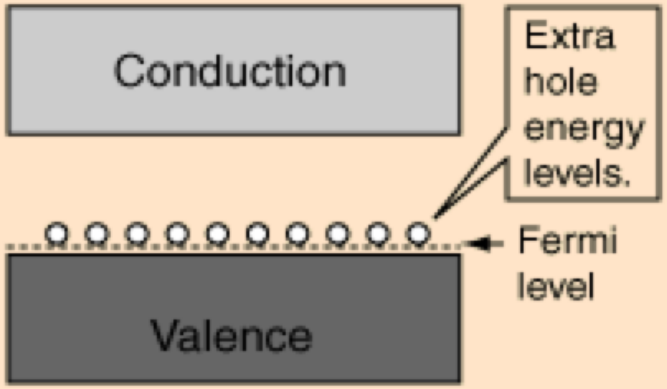

The addition of pentavalent impurities such as antimony, arsenic or phosphorous contributes free electrons, greatly increasing the conductivity of the intrinsic semiconductor. Phosphorous may be added by diffusion of phosphine gas (PH3).

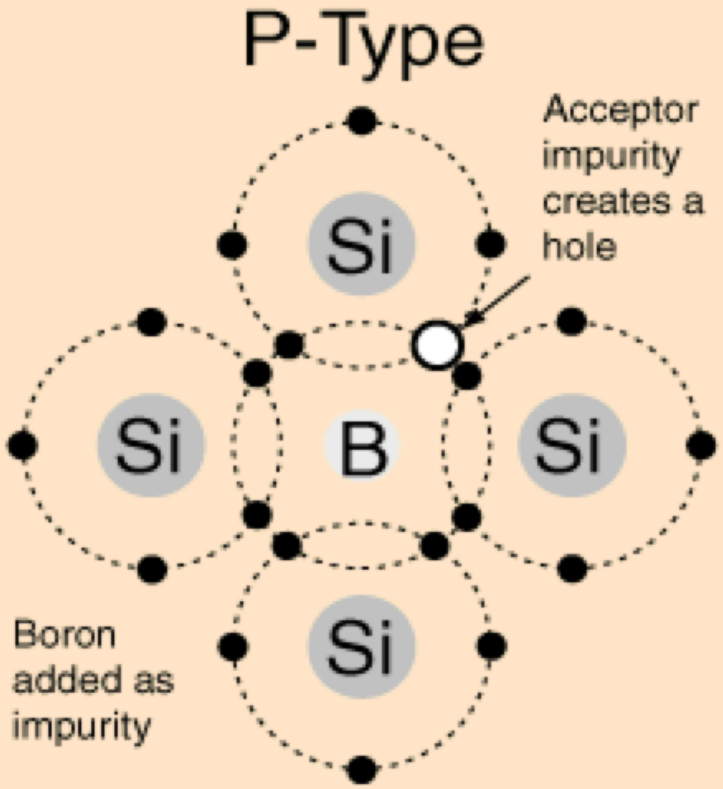



Majority charge carriers: electrons
Minority charge carriers: holes

# p-type

The addition of trivalent impurities such as boron, aluminum or gallium to an intrinsic semiconductor creates deficiencies of valence electrons,called "holes". It is typical to use $B_2H_6$ diborane gas to diffuse boron into the silicon material.




Majority charge carriers: holes
Minority charge carriers: electrons

# Additional levels from doping elements

Festkörperphysik (p. 392)
Siegfried Hunklinger

n-type / donors

p-type / acceptors

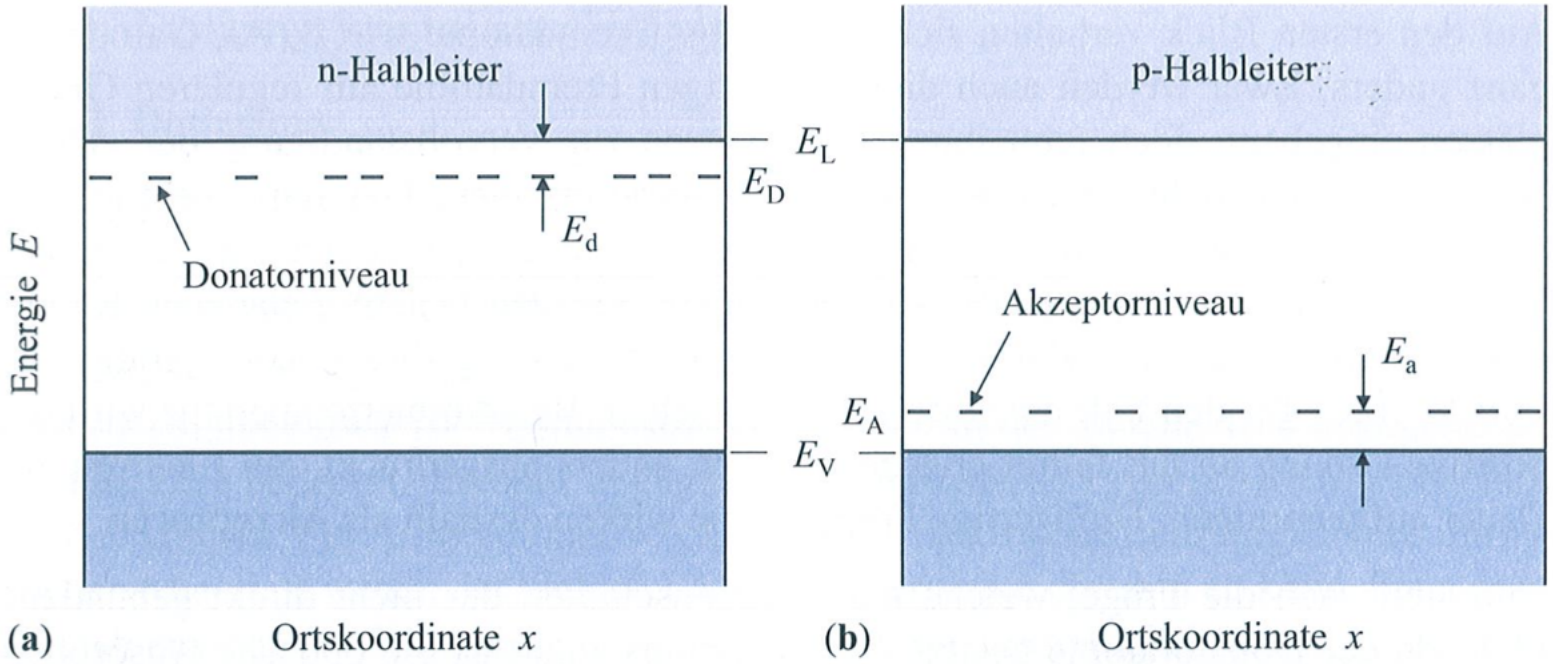



**Bild 10.8:** Störstellenniveaus in Halbleitern. **a)** Der Grundzustand $E_D$ der Donatoren liegt unmittelbar unter der Leitungsbandkante $E_L$, ihre Ionisierungsenergie ist $E_d$. **b)** Der Grundzustand $E_A$ der Akzeptoren befindet sich knapp über der Valenzbandkante $E_V$, $E_a$ ist die Ionisierungsenergie der Löcher.

# Additional levels from doping elements

Festkörperphysik (p. 394)
Siegfried Hunklinger

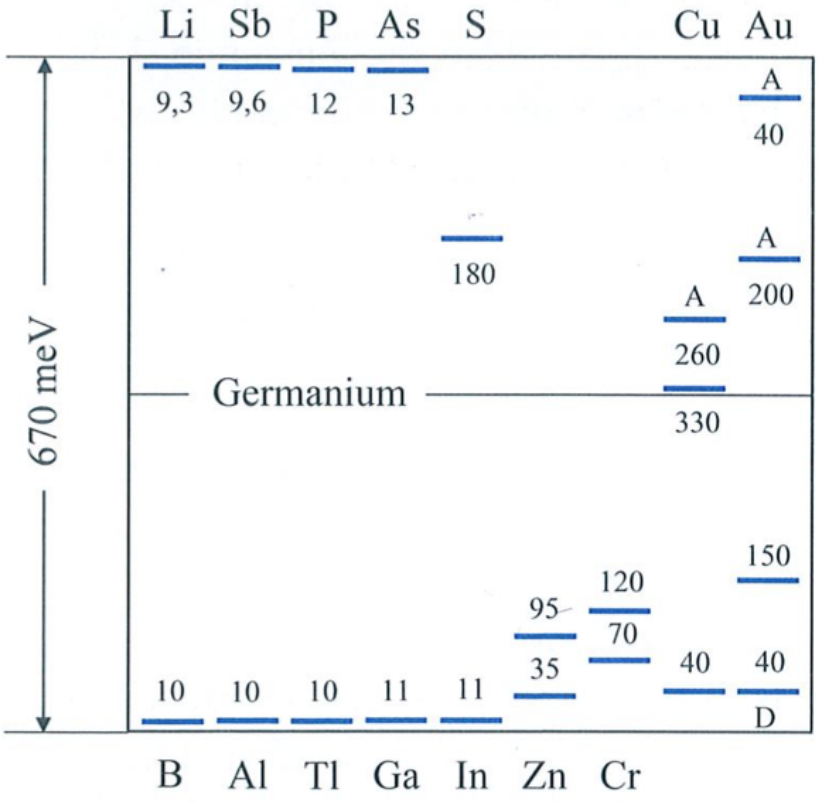
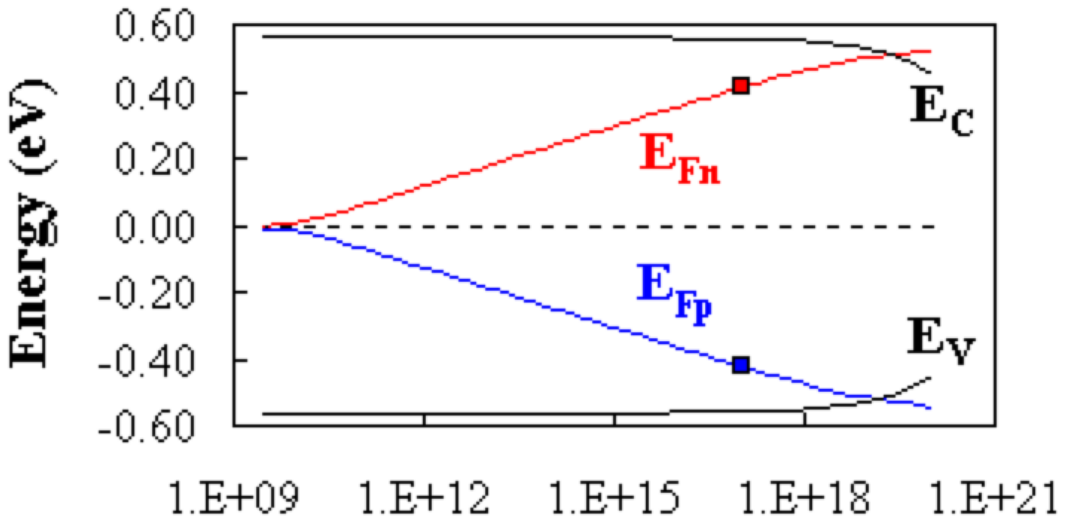



**Bild 10.10:** Störstellenniveaus in Germanium. Die Zahlen geben den Abstand von der nächstgelegenen Bandkante an. Die Buchstaben A und D stehen für *Akzeptor* bzw. *Donator*, wenn sich die Zuordnung der Zustände nicht unmittelbar aus ihrer Lage ergibt. (Nach S.M. Sze, *Physics of Semiconductor Devices*, Wiley, New York 1981).

# Fermi level in doped semiconductors




fermiden.xls - fermiden.gif

**Fig.2.7.1** *Fermi energy of n-type and p-type silicon as a function of doping density at 300 K. Shown are the conduction and valence band edges, $E_C$ and $E_V$, the intrinsic energy $E_i$, the Fermi energy for n-type material, $E_{Fn}$, and for p-type material, $E_{Fp}$.*

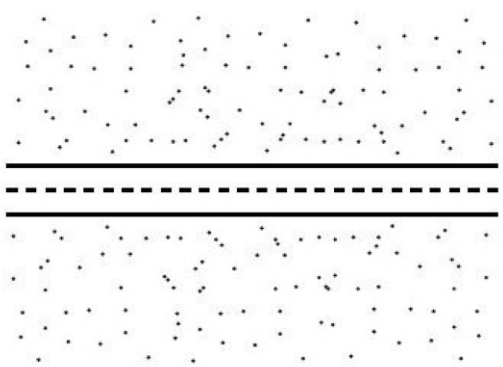
# Intrinsic and extrinsic (or doped) semiconductors

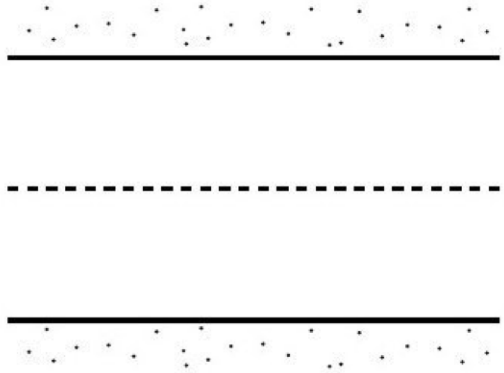
Intrinsic: the smaller the band gap, the larger the number of charge carriers

$$n = \int n_{-}\, dE$$

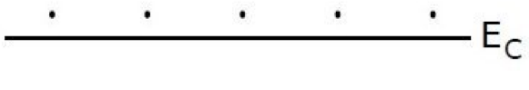
$$p = \int n_{+}\, dE$$

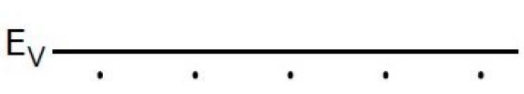
$$n = p$$





## Doped semiconductors:


n- doped


p- doped

At T=0 → not conducting

At T>0 → Electrons conducting

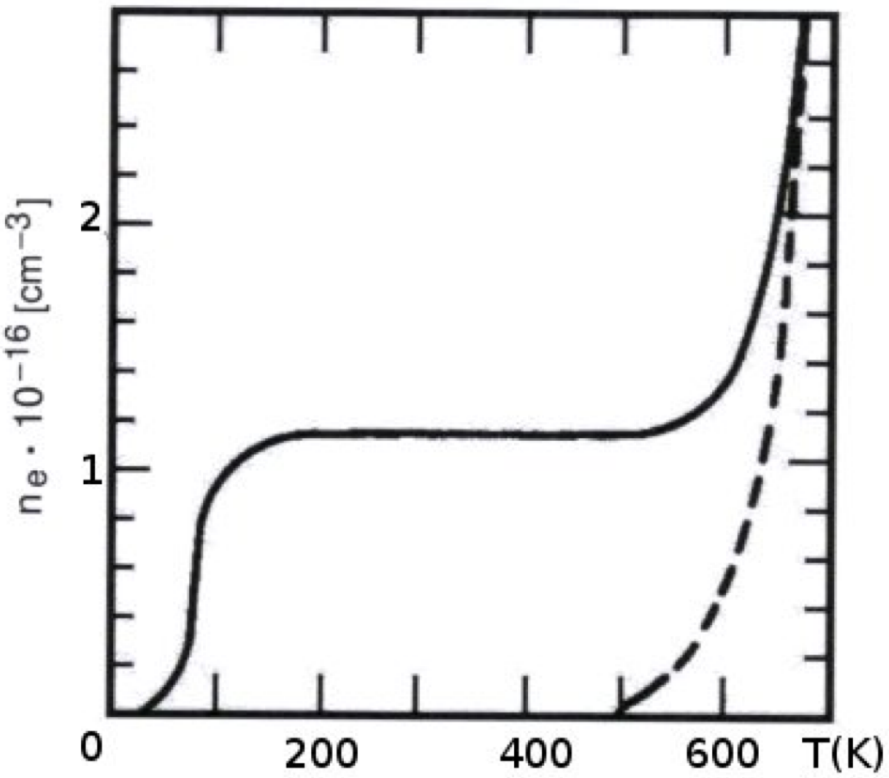
Holes conducting

# Intrinsic and extrinsic (or doped) semiconductors

Electron density in the conduction band:

- - - - In pure silicon

——— In silicon doped with As (n-type, $10^{16}/cm^3$)



# Charge carrier densities - 1

Donor atom is either neutral or ionized: $N_D = N_D^0 + N_D^+$

Same for acceptors: $N_A = N_A^0 + N_A^-$

Charged states determined by: $N_D^+ = N_D\,(1 - f(E_D))$

$N_A^- = N_A\, f(E_A)$

Condition of charge neutrality: $n + N_A^- = p + N_D^+$

(see intrinsic semiconductors): $n = N_c \exp[-(E_c - E_F)/kT]$

$p = N_v \exp[-(E_F - E_v)/kT]$

With $N_c$, $N_v$ effective density of states at the edge of the respective bands.

# Charge carrier densities - 2

- n-type material (donors): Fermi energy at room temperature is close to $E_D \rightarrow kT \approx E_c - E_D = E_d$ and $\exp[-E_d/kT] \approx 1$

  Charge carriers dominantly electrons of the donors. Nearly all donors ionized

  $n \simeq N_D \approx \text{const} \gg n_i$

- p-type material (acceptors): similar, now for the positively charged holes of acceptors

Typical dopant concentration: $\geqslant 10^{13}$ atoms/cm$^3$ (in Si: $5 \cdot 10^{23}$/cm$^3$)

Strong doping: $n^+$ or $p^+$ $\approx 10^{20}$ atoms/cm$^3$

Equilibrium between densities electrons and holes: holds the law of mass action:

$$n \cdot p = n_i p_i = A \cdot T^3 \exp\left(-\frac{E_{gap}}{kT}\right)$$

Increase of one type of carrier concentrantion → reduction of the other due to recombination

# Example

Silicon at 300 K:

$n_i = p_i = 10^{10}$ cm$^{-3}$

$n = 10^{17}$ cm$^{-3}$ $\rightarrow$ $p = 10^{3}$ cm$^{-3}$

The conductivity is determined by the majority carriers (electrons in n-doped, holes in p-doped).

Role of minority carriers is negligible: $n \simeq N_D$

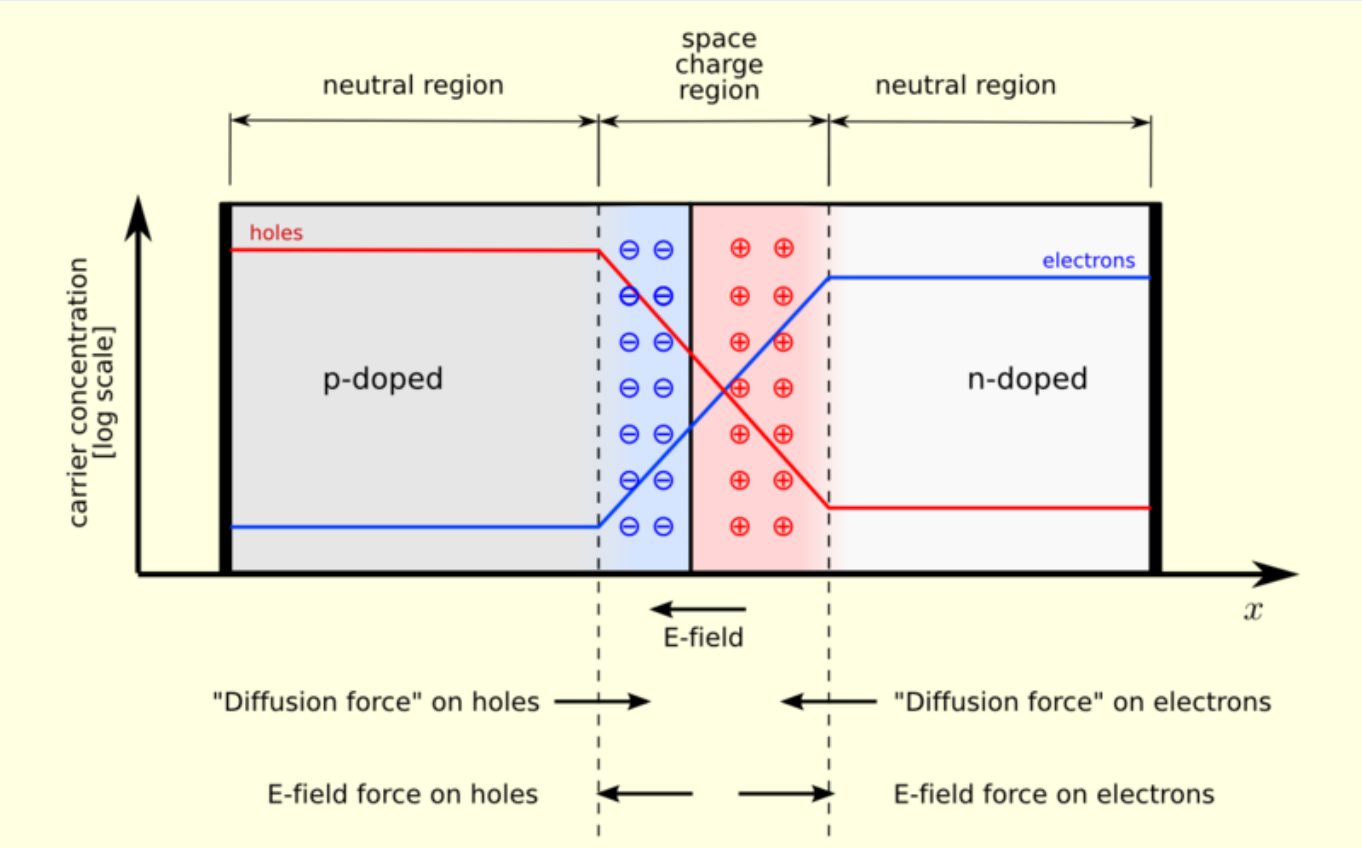
$$p \simeq \frac{n_i p_i}{N_D} = \frac{n_i^2}{N_D}$$

$$\frac{1}{\rho} = \sigma = e \cdot N_D \cdot \mu_e$$

Typical values: pure Si $\rightarrow$ 2.3 x $10^5$ Ωcm

Si p-type $10^{13}$ cm$^{-3}$ $\rightarrow$ 500 Ωcm

# p-n junction


space
charge
region
neutral region
neutral region
holes
electrons
p-doped
n-doped
carrier concentration
[log scale]
x
E-field
"Diffusion force" on holes
"Diffusion force" on electrons
E-field force on holes
E-field force on electrons

# p-n junction

- Bring p and n materials “into contact” (in reality, done otherwise) → thermodynamic equilibrium
- Electrons diffuse from n to p semiconductor, and holes from p to n
- At the boundary there will be a zone with few free charge carriers (electrons and holes) → depletion layer
- Fixed charges are left behind (ionized donors and acceptors) → space charge

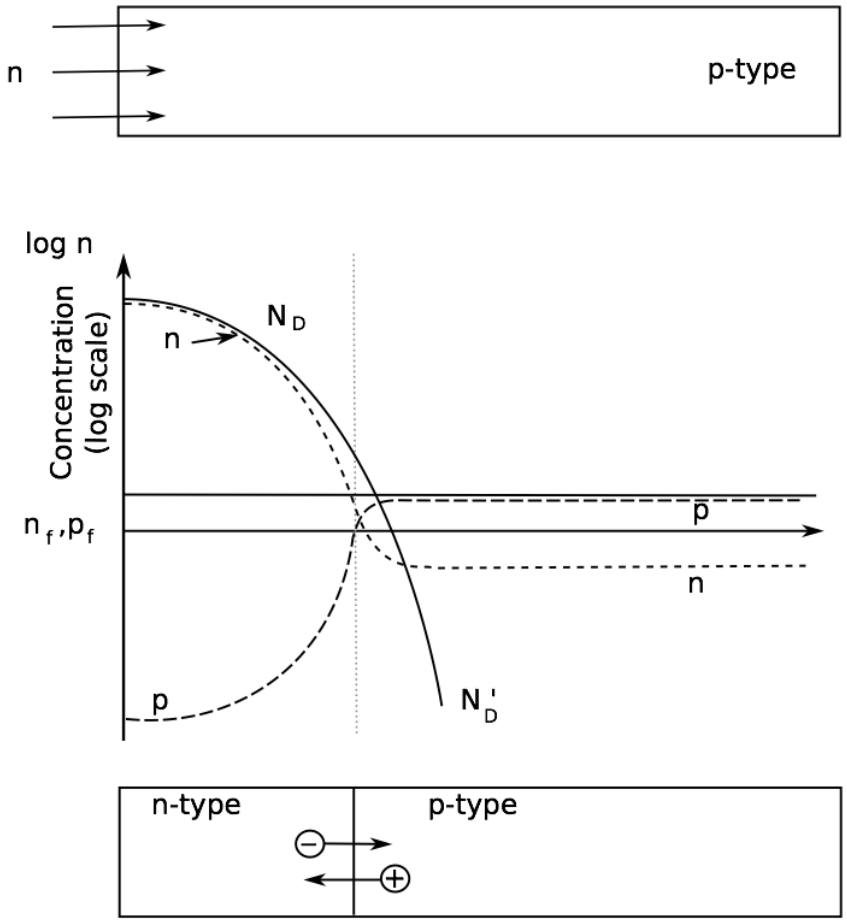
  E-field builds up and counteracts the diffusion, which stops eventually with $n \approx N_D$ and $p \approx N_A$
- Difference between Fermi energies on both sides gives:

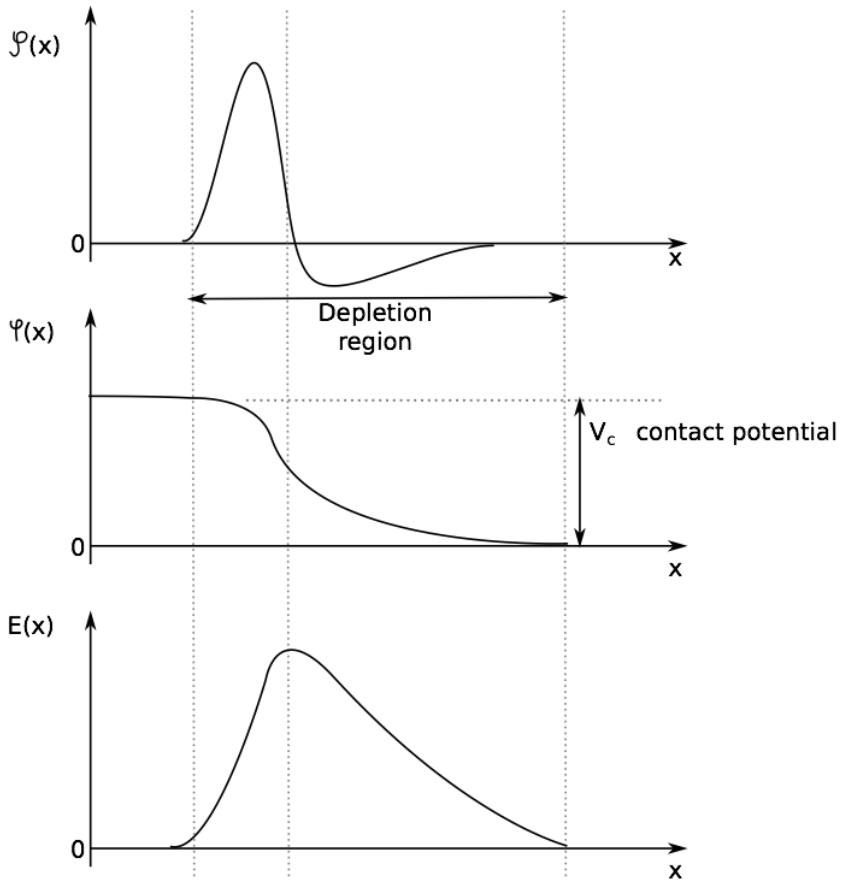
$$e V_D = E_c - kT \ln \frac{N_c}{N_D} - E_v - kT \ln \frac{N_v}{N_A}$$

$$= E_{gap} - kT \ln \frac{N_c N_v}{N_D N_A}$$

$V_D$ = diffusion or contact potential

# p-n junction



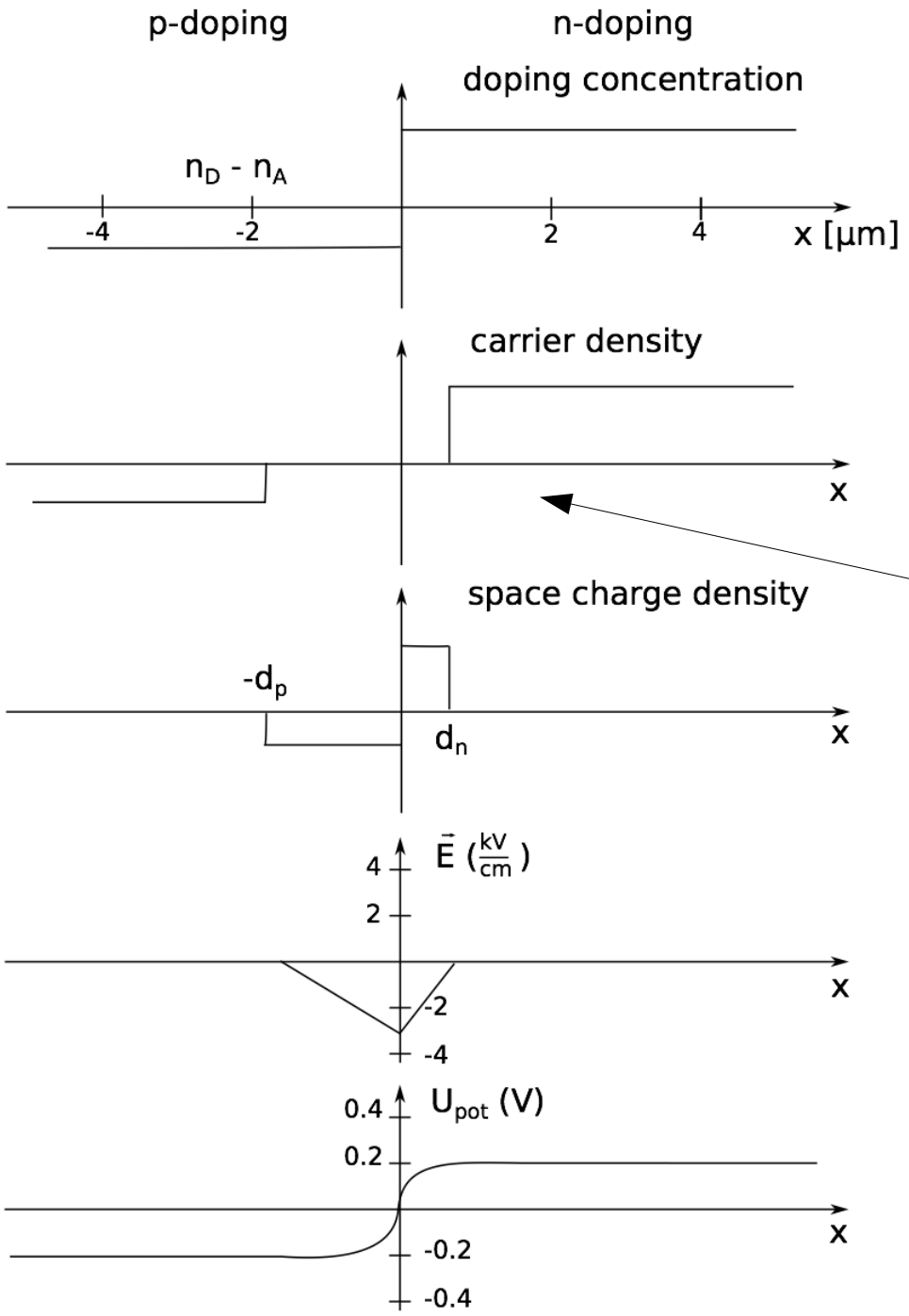




$$\text{n-region} \qquad \rho = e(N_D^+ - n_n(x) + p_n(x))$$

$$\text{p-region} \qquad \rho = -e(N_A^- + n_p(x) - p_p(x))$$

density of majority carriers $n_n, p_p$ $\gg$ density of minority carriers $n_p, p_n$

# p-n junction




Potential and space charge related by Poisson equation:

$$\frac{\partial^2 V(x)}{\partial x^2} = -\frac{\rho(x)}{\epsilon \epsilon_0}$$

Approximation: free charge carriers in depletion layer set to concentration =0

Schottky model:

$$\rho(x) = \begin{cases} 0 & \text{for} \quad x < -d_p \\ -eN_A & -d_p < x < 0 \\ +eN_D & 0 < x < d_n \\ 0 & d_n < x \end{cases}$$

# p-n junction

To determine the thickness of depletion layer $d_p$ and $d_n$: integrate Poisson equation in pieces:

n-doped region

$$\frac{\partial^2 V(x)}{\partial x^2} = -\frac{eN_D}{\epsilon\epsilon_0}$$

$$E_x = -\frac{\partial V}{\partial x} = -\frac{e}{\epsilon\epsilon_0} N_D (d_n - x)$$

$$V(x) = V_n(\infty) - \frac{e}{2\epsilon\epsilon_0} N_D (d_n - x)^2$$

P-doped region: equivalently

Impose condition of neutrality: $N_D\, d_n = N_A\, d_p$

And of continuity of potential V(x) at x=0

$$\frac{e}{2\epsilon\epsilon_0}(N_D d_n^2 + N_A d_p^2) = V_n(\infty) - V_p(-\infty) = V_D$$

# p-n junction

From above, we deduce:

$$d_n = \sqrt{\frac{2\epsilon\epsilon_0 V_D}{e}\frac{N_A/N_D}{N_A+N_D}} \qquad d_p = \sqrt{\frac{2\epsilon\epsilon_0 V_D}{e}\frac{N_D/N_A}{N_A+N_D}}$$

Example: $eV_D \simeq E_{gap} \simeq 1\ eV$
$N_A \simeq N_D \simeq 10^{14}\ cm^{-3}$

$\Big\}$ $d_n \simeq d_p \simeq 1\ \mu m$
$E \simeq 10^6\ V/m$

Extremely small!!

Watch another problem: capacitance load on electronics: $C = \frac{\epsilon A}{d}$

To achieve large width on one side chose ASYMMETRIC DOPING !!

Example: $N_D = 10^{12}\ cm^{-3}$ and $N_A = 10^{16}\ cm^{-3}$ (need very pure material to start with)

# p-n junction: external field

Most of the voltage drop U occurs in the depletion layer (very few free carriers, large ρ): $V_n(\infty) - V_p(\infty) = V_d - U$

Chose sign such that positive U is opposite to diffusion (or contact) potential

**FORWARD BIAS: U>0**

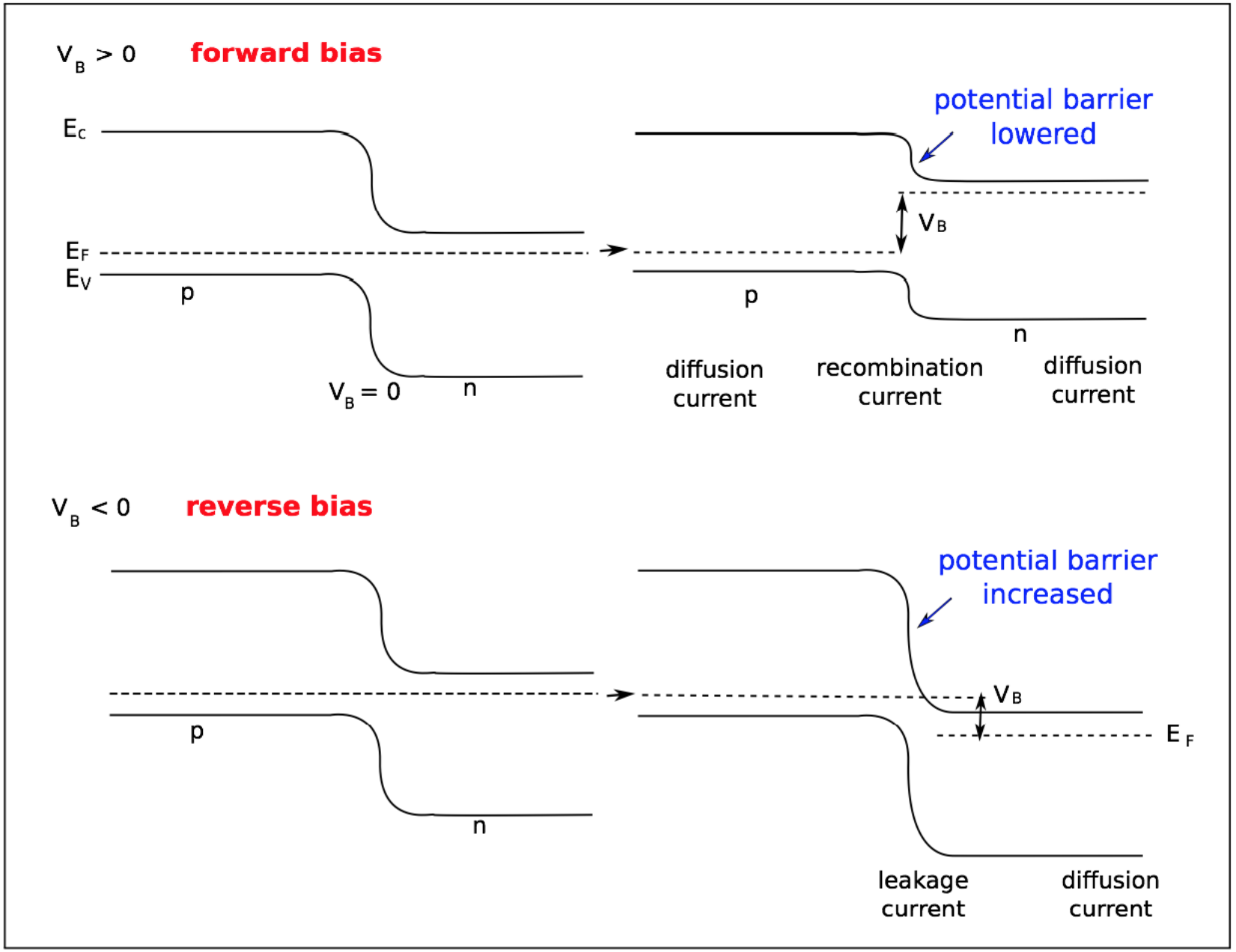
- Holes diffuse in n-direction, electrons diffuse in p-direction, potential barrier is lowered
- Majority carriers recombine in depletion region: “recombination current”
- Or penetrate to the other side “diffusion current”
- Depletion zone narrows:

$$d_n(U) = d_n(0)\sqrt{1-U/V_D} \qquad d_p(U) = d_p(0)\sqrt{1-U/V_D}$$

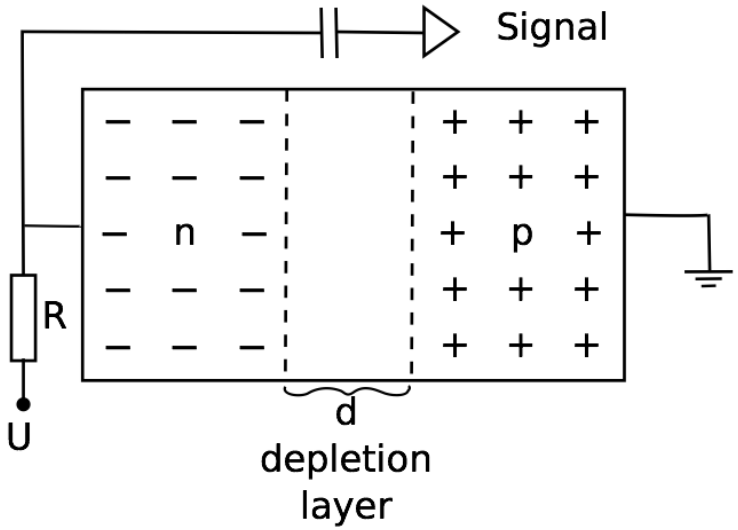
**REVERSE BIAS: U<0**

- Electron-hole pairs generated in or near the depletion layer by thermal processes (or ionization) are separated: “leakage current”
- Depletion zone becomes wider (at 300 V order of 1 mm)

# p-n junction: external field

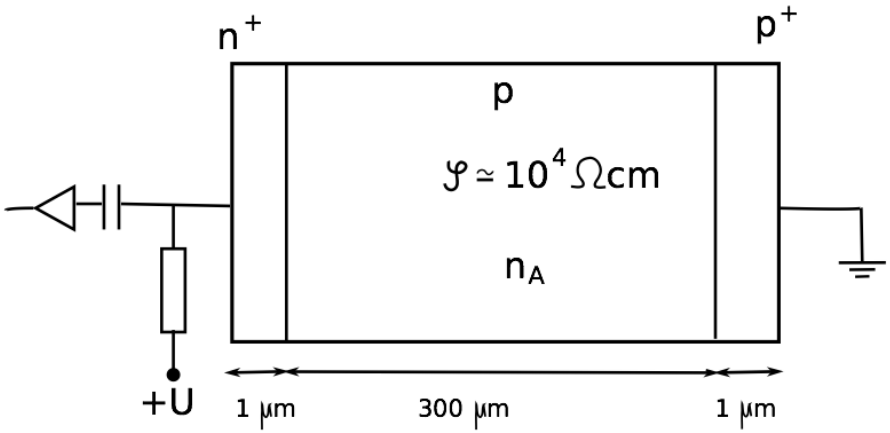


# p-n semiconductor detector




$+++$, $---$: free charge carriers

typical realization:




$p^+$, $n^+$: very highly doped, conducting

$$d_p + d_n \cong d_p \cong \sqrt{\frac{2\epsilon\epsilon_0}{e}\frac{U}{N_A}}$$

since $N_A \ll N_D$, $V_D \ll U$

with $N_A \cong 10^{15}\ \mathrm{cm}^{-3} \Rightarrow$

$$U = \frac{e}{2\epsilon\epsilon_0} N_A d_p^2 \cong 100\ \mathrm{V}$$

$$|E| = \frac{100\ \mathrm{V}}{300 \cdot 10^{-6}\ \mathrm{m}} = 3 \cdot 10^5\ \mathrm{V/m}$$

(safe; spark limit at $10^7$ V/m)

# Overview semiconductor detectors

- **Principle of operation of semiconductor detectors**
  - **Properties of semiconductors (band structure)**
  - **Intrinsic material**
  - **Extrinsic (doped) semiconductors**
  - **p-n junction**

**TODAY**

- Signal generation
- Ionization yield and Fano factor

**NEXT WEEK**
**May 31**

- Energy measurement with semiconductor detectors
- Position measurement with semiconductor detectors
  - Micro-strip detectors
  - Silicon drift detectors
  - Pixels

**JUNE 14 !!!**

- Charge-coupled devices (CCDs)
- Radiation damage