Advantages / Disadvantages of semiconductor detectors

- Semiconductor detectors have a **high density** (compared to gas detector)
  - large energy loss in a short distance
  - diffusion effect is smaller than in gas detectors resulting in achievable position resolution of less then 10 µm

- **Low ionization energy** (few eV per e – hole pair) compared to
  - gas detectors (20 – 40 eV per e – ion pair) or
  - scintillators (400 – 1000 eV to create a photon)

- No internal amplification, i.e. small signal
  - with a few exceptions

- High cost per surface unit
  - not only Silicon itself
  - high number of readout channels
  - large power consumption, cooling
Elemental Semiconductor

- **Germanium:**
  - used in nuclear physics
  - needs cooling due to small band gap of 0.66 eV (usually done with liquid nitrogen at 77 K)

- **Silicon:**
  - can be operated at room temperature
  - synergies with micro electronics industry

- **Diamond (CVD or single crystal):**
  - allotrope of carbon
  - large band gap (requires no depletion zone)
  - very radiation hard
  - disadvantage: low signal and high cost
Compound semiconductors consist of
- two (binary semiconductors) or
- more than two

Depending on the column in the periodic system of elements one differentiates between
- IV – IV – (e.g. SiGe, SiC),
- III – V – (e.g. GaAs)
- II – VI compounds (CdTe, ZnSe)

Important III – V compounds:
- **GaAs**: faster and probably more radiation resistant than Si. Drawback is less experience in industry and higher costs.
  - GaP, GaSb, InP, InAs, InSb, InAlP

Important II – VI compounds:
- **CdTe**: high atomic number (48 + 52) hence very efficient to detect photons.
  - ZnS, ZnSe, ZnTe, CdS, Cd$_{1-x}$Zn$_x$Te, Cd$_{1-x}$Zn$_x$Se
Why Silicon

- Semiconductor with moderate bandgap (1.12 eV)
- Energy to create electron/hole pair (signal quanta) = 3.6 eV
  - (c.f. Argon gas = 15 eV)
  - high carrier yield
  - better energy resolution and high signal
    → no gain stage required

- High density and atomic number
  - higher specific energy loss
    → thinner detectors
    → reduced range of secondary particles
    → better spatial resolution

- High carrier mobility → Fast!
  - less than 30 ns to collect entire signal

- Large experience in industry with micro-chip technology

- High intrinsic radiation hardness
Example of column IV elemental semiconductor (2-dimensional projection):

Each atom has 4 closest neighbors, the 4 electrons in the outer shell are shared and form covalent bonds.

- At low temperature all electrons are bound
- At higher temperature thermal vibrations break some of the bonds → free e\(^{-}\) cause conductivity (electron conduction)
- The remaining open bonds attract other e\(^{-}\) → the “holes” change position (hole conduction)
In an isolated atom the electrons have only discrete energy levels. In solid state material the atomic levels merge to energy bands. In metals the conduction and the valence band overlap, whereas in isolators and semiconductors these levels are separated by an energy gap (band gap). In isolators this gap is large.
Fermi distribution function for different temperatures

$T_4 > T_3 > T_2 > T_1 > T_0 = 0 \text{ K}$

$T_0 = 0 \text{ K}$: saltus function
Intrinsic semi-conductor properties

- Dispersion relation
  \[ E(\vec{k}) = \frac{\hbar^2 k^2}{2m_e} = \frac{\hbar^2}{2m_e} (k_x^2 + k_y^2 + k_z^2) \]

- Density of states
  \[ g(E) = \frac{dN}{dE} = E^{1/2} \cdot \left( \frac{2m_e}{\hbar^2} \right)^{3/2} \frac{V}{2\pi^2} \]

- Fermi-Dirac distribution
  \[ f(E,T) = \frac{1}{e^{(E-\mu)/k_BT} + 1} \]

- Electron density
  \[ n = \frac{1}{V} \int_0^{E_{\text{max}}} g(E)f(E)dE \]
Drift velocity and mobility

Drift velocity
for electrons: \( \vec{v}_n = -\mu_n \vec{E} \)
and for holes: \( \vec{v}_p = -\mu_p \vec{E} \)

Mobility
for electrons: \( \mu_n = \frac{e \cdot \tau_n}{m_n} \)
and for holes: \( \mu_p = \frac{e \cdot \tau_p}{m_p} \)

\( e \) ... electron charge
\( E \) ... external electric field
\( m_n, m_p \) ... effective mass of e\(^-\) and holes
\( \tau_n, \tau_p \) ... mean free time between collisions
for e\(^-\) and holes (carrier lifetime)

Resistivity

Specific resistivity is a measure of silicon purity

\[
\rho = \frac{1}{e(\mu_n n_e + \mu_p n_h)}
\]

\( n_e, n_h \) … Charge carrier density for electrons and holes
\( \mu_n, \mu_p \) … Mobility for electrons and holes
\( e \) … Elementary charge

Carrier mobilities:
\( \mu_p(\text{Si}, 300\text{K}) \approx 450 \text{ cm}^2/\text{Vs} \)
\( \mu_n(\text{Si}, 300\text{K}) \approx 1450 \text{ cm}^2/\text{Vs} \)

The charge carrier concentration in pure silicon (i.e. intrinsic Si) for \( T = 300 \text{ K} \) is:
\( n_e = n_h \approx 1.45 \cdot 10^{10} \text{ cm}^{-3} \)

This yields an intrinsic resistivity of:
\( \rho \approx 230 \text{ k}\Omega\text{cm} \)
## Comparison of different semiconductor materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>Ge</th>
<th>GaAs</th>
<th>GaP</th>
<th>CdTe</th>
<th>Diamond*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number $Z$</td>
<td>14</td>
<td>32</td>
<td>31+33</td>
<td>31+15</td>
<td>48+52</td>
<td>6</td>
</tr>
<tr>
<td>Mass Number $A$ (amu)</td>
<td>28.086</td>
<td>72.61</td>
<td>69.72+74.92</td>
<td>69.72+30.97</td>
<td>112.4+127.6</td>
<td>12.011</td>
</tr>
<tr>
<td>Lattice constant $a$ (Å)</td>
<td>5.431</td>
<td>5.646</td>
<td>5.653</td>
<td>5.451</td>
<td>6.482</td>
<td>3.567</td>
</tr>
<tr>
<td>Density $\rho$ (g/cm³)</td>
<td>2.328</td>
<td>5.326</td>
<td>5.32</td>
<td>4.13</td>
<td>5.86</td>
<td>3.52</td>
</tr>
<tr>
<td>$E_g$ (eV) bei 300 K</td>
<td>1.11</td>
<td>0.66</td>
<td>1.42</td>
<td>2.26</td>
<td>1.44</td>
<td>5.47–5.6</td>
</tr>
<tr>
<td>$E_g$ (eV) bei 0 K</td>
<td>1.17</td>
<td>0.74</td>
<td>1.52</td>
<td>2.34</td>
<td>1.56</td>
<td>$\approx$ 6</td>
</tr>
<tr>
<td>rel. permittivity $\varepsilon_r = \varepsilon / \varepsilon_0$</td>
<td>11.9</td>
<td>16.0</td>
<td>12.8</td>
<td>11.1</td>
<td>10.9</td>
<td>5.7</td>
</tr>
<tr>
<td>Melting point (° C)</td>
<td>1415</td>
<td>938</td>
<td>1237</td>
<td>1477</td>
<td>1040</td>
<td>3527</td>
</tr>
<tr>
<td>eff. $e^-$-mass ($m_n/m_e$)</td>
<td>0.98, 0.19</td>
<td>1.64, 0.08</td>
<td>0.067</td>
<td>0.82</td>
<td>0.11</td>
<td>0.2</td>
</tr>
<tr>
<td>eff. hole mass$^+$ ($m_h/m_e$)</td>
<td>0.16</td>
<td>0.044</td>
<td>0.082</td>
<td>0.14</td>
<td>0.35</td>
<td>0.25</td>
</tr>
</tbody>
</table>

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<th>Diamond*</th>
</tr>
</thead>
<tbody>
<tr>
<td>eff. density of states in conduction band $n_{CB}$ (cm$^{-3}$)</td>
<td>$3 \cdot 10^{19}$</td>
<td>$1 \cdot 10^{19}$</td>
<td>$4.7 \cdot 10^{17}$</td>
<td>$2 \cdot 10^{19}$</td>
<td>$\approx 10^{20}$</td>
<td></td>
</tr>
<tr>
<td>eff. density of states in valence band $n_{VB}$ (cm$^{-3}$)</td>
<td>$1 \cdot 10^{19}$</td>
<td>$6 \cdot 10^{18}$</td>
<td>$7 \cdot 10^{18}$</td>
<td>$2 \cdot 10^{19}$</td>
<td>$\approx 10^{19}$</td>
<td></td>
</tr>
<tr>
<td>Electron mobility $\mu_e$ bei 300 K (cm$^2$/Vs)</td>
<td>$\sim 1450$</td>
<td>3900</td>
<td>8500</td>
<td>$&lt; 300$</td>
<td>1050</td>
<td>1800</td>
</tr>
<tr>
<td>Hole mobility $\mu_h$ bei 300 K (cm$^2$/Vs)</td>
<td>$\sim 450$</td>
<td>1900</td>
<td>400</td>
<td>$&lt; 150$</td>
<td>100</td>
<td>1200</td>
</tr>
<tr>
<td>intrins. charge carrier density at 300 K (cm$^{-3}$)</td>
<td>$1.45 \cdot 10^{10}$</td>
<td>$2.4 \cdot 10^{13}$</td>
<td>$2 \cdot 10^{6}$</td>
<td>$2$</td>
<td>$\approx 10^{-27}$</td>
<td></td>
</tr>
<tr>
<td>intrins. resistivity at 300 K ((\Omega) cm)</td>
<td>$2.3 \cdot 10^{5}$</td>
<td>47</td>
<td>$\approx 10^{8}$</td>
<td>$\approx 10^{9}$</td>
<td>$\geq 10^{42}$</td>
<td></td>
</tr>
<tr>
<td>Breakdown field (V/cm)</td>
<td>$3 \cdot 10^{5}$</td>
<td>$\approx 10^{5}$</td>
<td>$4 \cdot 10^{5}$</td>
<td>$\approx 10^{6}$</td>
<td>3 $\cdot 10^{7}$</td>
<td></td>
</tr>
<tr>
<td>Mean $E$ to create an e$^-$-h$^+$ pair (eV), 300 K</td>
<td>3.62</td>
<td>2.9</td>
<td>4.2</td>
<td>$\approx 7$</td>
<td>4.43</td>
<td>13.25</td>
</tr>
</tbody>
</table>

Constructing a detector

One of the most important parameter of a detector is the **signal-to-noise-ratio** (SNR). A good detector should have a large SNR. However this leads to **two contradictory requirements**:

- Large signal
  - low ionization energy → small band gap
- Low noise
  - very few intrinsic charge carriers → large band gap

An optimal material should have $E_g \approx 6 \text{ eV}$

In this case the conduction band is almost empty at room temperature and the band gap is small enough to create a large number of $e^-h^+$ pairs through ionization.

Such a material exist, it is **Diamond**. However even even artificial diamonds (e.g. CVD diamonds) are too expensive for large area detectors.
Constructing a detector

Let’s make a simple calculation for silicon:
• mean ionization energy $I_0 = 3.62$ eV.
• mean energy loss per flight path of a mip $dE/dx = 3.87$ MeV/cm

Assuming a detector with a thickness of $d = 300 \, \mu m$ and an area of $A = 1 \, cm^2$
• Signal of a mip in such a detector:

$$\frac{dE/dx \cdot d}{I_0} = \frac{3.87 \cdot 10^6 \, eV/cm \cdot 0.03\, cm}{3.62\, eV} \approx 3.2 \cdot 10^4 e^- h^+ - pairs$$

• Intrinsic charge carrier in the same volume ($T = 300 \, K$)

$$n_i \cdot d \cdot A = 1.45 \cdot 10^{10}\, cm^{-3} \cdot 0.03\, cm \cdot 1\, cm^2 \approx 4.35 \cdot 10^8 e^- h^+ - pairs$$

Result: the number of thermal created e-h+-pairs (noise is four orders of magnitude larger than the signal.

We have to remove the charge carriers
→ depletion zone in inverse biased pn junctions
A pn junction consists of n and p doped substrates:

- Doping is the **replacement of a small number of atoms** in the lattice by atoms of **neighboring columns** from the periodic table.

- These doping atoms create **energy levels within the band gap** and therefore alter the conductivity.

**Definitions:**

- An un-doped semiconductor is called an **intrinsic semiconductor**
  - For each conduction electron exists the corresponding hole.

- A doped semiconductor is called an **extrinsic semiconductor**.
  - Extrinsic semiconductors have a abundance of electrons or holes.
Doping: n- and p-type silicon

**n-type:**
- Dopants: Elements with 5 valence electrons, e.g. Phosphorus
- Donators
- Electron abundance

**p-type:**
- Dopants: Elements with 3 valence electrons, e.g. Aluminum
- Acceptors
- Electron shortage
Doping with an element 5 atom (e.g. P, As, Sb). The 5th valence electrons is weakly bound.

The doping atom is called **donor**

The released conduction electron leaves a positively charged ion
The energy level of the donor is just below the edge of the conduction band. At room temperature most electrons are raised to the conduction band. The Fermi level $E_F$ moves up.
Doping with an element 3 atom (e.g. B, Al, Ga, In). One valence bond remains open. This open bond attracts electrons from the neighbor atoms.

The doping atom is called **acceptor**. The acceptor atom in the lattice is negatively charged.
The energy level of the acceptor is just above the edge of the valence band. At room temperature most levels are occupied by electrons leaving holes in the valence band. The Fermi level $E_F$ moves down.
Donor and acceptor levels in Si and GaAs

Measured ionization energies for doping atoms in Si and GaAs.

Levels **above band gap middle** are donors and are measured from the edge of the conduction band (exceptions denoted D).

Levels **below band gap middle** are acceptors and are measured from the edge of the valence band (exceptions denoted A).

Creating a pn junction

At the interface of an n-type and p-type semiconductor the difference in the Fermi levels cause diffusion of excessive carries to the other material until thermal equilibrium is reached. At this point the Fermi level is equal. The remaining ions create a space charge region and an electric field stopping further diffusion. The stable space charge region is free of charge carries and is called the depletion zone.
Electrical characteristics of pn junctions

pn junction scheme

acceptor and donator concentration

space charge density

concentration of free charge carriers

electric field

electric potential

\( \Theta \) ... acceptor  \( + \) ... empty hole
\( \Theta \) ... donator  \( - \) ... conduction electron
Operation of a pn-junction with forward bias

Applying an external voltage $V$ with the anode to $p$ and the cathode to $n$ e- and holes are refilled to the depletion zone. The depletion zone becomes narrower (forward biasing)

Consequences:
- The potential barrier becomes smaller by $eV$
- Diffusion across the junction becomes easier
- The current across the junction increases significantly.
Operation a pn-junction with reverse bias

Applying an external voltage $V$ with the cathode to p and the anode to n $e^{-}$ and holes are pulled out of the depletion zone. The **depletion zone becomes larger** (reverse biasing).

**Consequences:**
- The potential barrier becomes higher by $eV$
- Diffusion across the junction is suppressed.
- The current across the junction is very small ("leakage current")

➢ This is the way we operate our semiconductor detector!
Width of the depletion zone

Effective doping concentration in typical silicon detector with p⁺-n junction

- \( N_a = 10^{15} \text{ cm}^{-3} \) in p⁺ region
- \( N_d = 10^{12} \text{ cm}^{-3} \) in n bulk

without external voltage:

\[
W_p = 0.02 \, \mu m \\
W_n = 23 \, \mu m
\]

Applying a reverse bias voltage of 100 V:

\[
W_p = 0.4 \, \mu m \\
W_n = 363 \, \mu m
\]

Width of depletion zone in n bulk:

\[
W \approx \sqrt{2\varepsilon_0 \varepsilon_r \mu \rho |V|}
\]

\[
\rho = \frac{1}{e \mu N_{eff}}
\]

with the following:

- \( V \) ... External voltage
- \( \rho \) ... specific resistivity
- \( \mu \) ... mobility of majority charge carriers
- \( N_{eff} \) ... effective doping concentration
Measurements with Si-detectors

Si-detector

Si-detector with slit cover

detector principle

Energy loss measurement of $\alpha$-particles in air
Different Fermi energies adjust to on contact. Thin metal film on Si surface produces space charge, an effective barrier (contact potential) and depleted zone free of carriers. Apply reverse bias to increase depletion depth.

Possible:
depletion depth $\sim 300\mu m$
dead layer $d_d \leq 1\mu$
$V \sim 0.5 \text{ V/} \mu$
Over-bias reduces $d_d$
Principle of microstrip detector

- Surface of a Microstrip detector bonding pads

- Diagram showing the internal structure and signal timing for a microstrip detector.
Germanium detector

Interaction in a Ge crystal:

- **Photo effect** (low $\gamma$-ray energy)
- Compton scattering (medium $\gamma$-ray energy)
- Pair production $e^+e^-$ (high $\gamma$-ray energy)

Number of electron-hole pairs for 1 MeV, $N = 10^6 / 3 = 3 \times 10^5$

Energy resolution $= \sqrt{N}/N = 0.0018 \rightarrow 1.8 \text{ keV} \times \sqrt{E_\gamma}$
**Interaction in a Ge crystal:**

- **Photo effect** (low $\gamma$-ray energy)
- **Compton scattering** (medium $\gamma$-ray energy)
- Pair production $e^+e^-$ (high $\gamma$-ray energy)
Compton suppressed Germanium detector

Interaction in a Ge crystal:
- **Photo effect** (low $\gamma$-ray energy)
- **Compton scattering** (medium $\gamma$-ray energy)
- Pair production $e^+e^-$ (high $\gamma$-ray energy)

peak-to-total ratio
- unsuppressed $P/T \sim 0.15$
- Compton suppressed $P/T \sim 0.6$
Gamma-ray spectrum of a radioactive decay

\( \gamma_1 \), 0.30 MeV
\( \gamma_2 \), 2.1 MeV

\( \beta^+ \), 0.83 MeV

Stable Daughter, \( {}^{A(Z-1)} \)

\( 511 \text{ keV} \)

\( \gamma_1 + \gamma_2 \)

\( \gamma_2 \)

\( \gamma_1 \)

\( Pb X-ray \)

\( BSc \)

\( 511 \text{ keV} \)

\( DE \gamma_2 \)

\( SE \gamma_2 \)

\( CE \gamma_2 \)
EUROBALL (Legnaro / Strasbourg)

15 seven-fold Cluster detectors

30 coaxial detectors

26 four-fold Clover detectors
Making a High Purity Germanium detector

Coaxial Ge detectors

The hard part: Don’t spoil purity of the Ge crystal
(HPGe $10^{10}$ imp./cm$^3$; e.g. 1ng Cu = $10^{13}$ atoms and
$10^9$ Cu atoms per cm$^3$ already deteriorates FWHM
[L. Van Goethem et al., NIM A240 (1985) 365])