Experimental Techiques in Particle Physics

Semiconductor Detectors

Lecture 7, 2020-12-08

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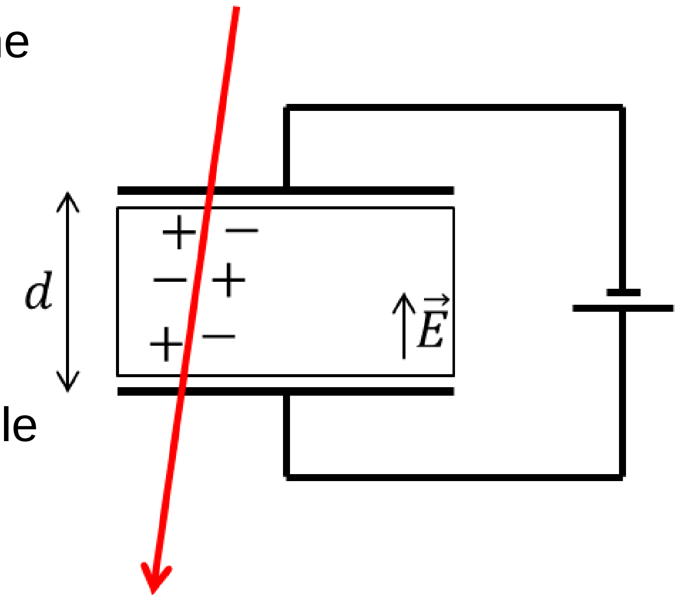
Basics of Semiconductor Detectors

- **Semiconductor detectors are essentially ionization chambers with semiconductors as a counting material.**
- Because of the large number of atoms per volume there will be a high number of interactions along the track of impinging particles.
- Because of their high density compared to gas detectors they can absorb (stop) particles of high energies.
- Due to the lower energy to produce an electron-hole pair compared to electron-ion pairs in gases the produced ionization along the track will be higher.
- With an applied electric field across the detector the produced electrons and holes can be collected and measured.



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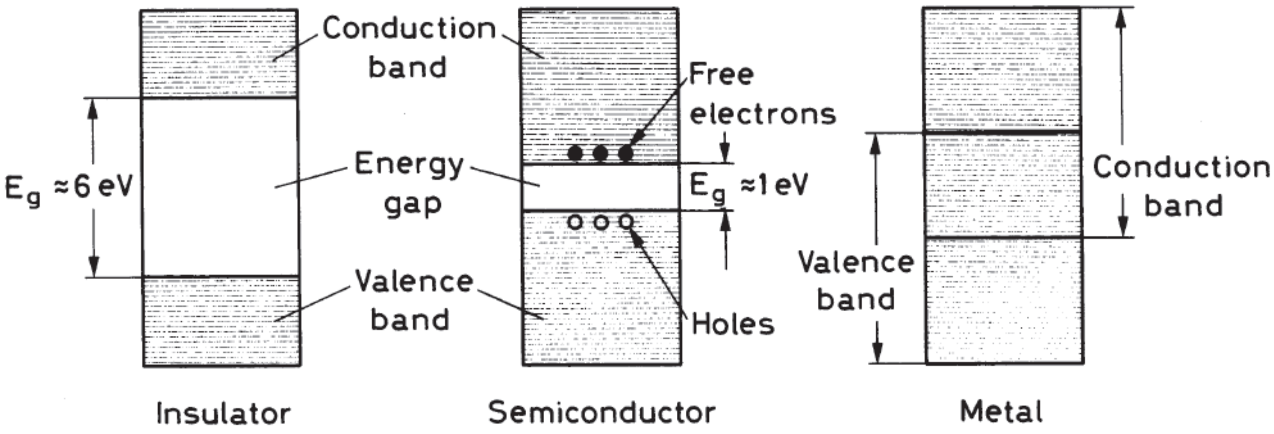
Energy Band Structure (I)

- Semiconductors are crystalline materials whose outer shell energy levels show a band structure.
- The basic structure consist of a valence band, a conduction band and a „forbidden“ energy gap in between.
- The energy bands are essentially regions of many discrete levels that are so closed to each other that they can be treated as a continuum whereas in the band gap no energy level at all exists.



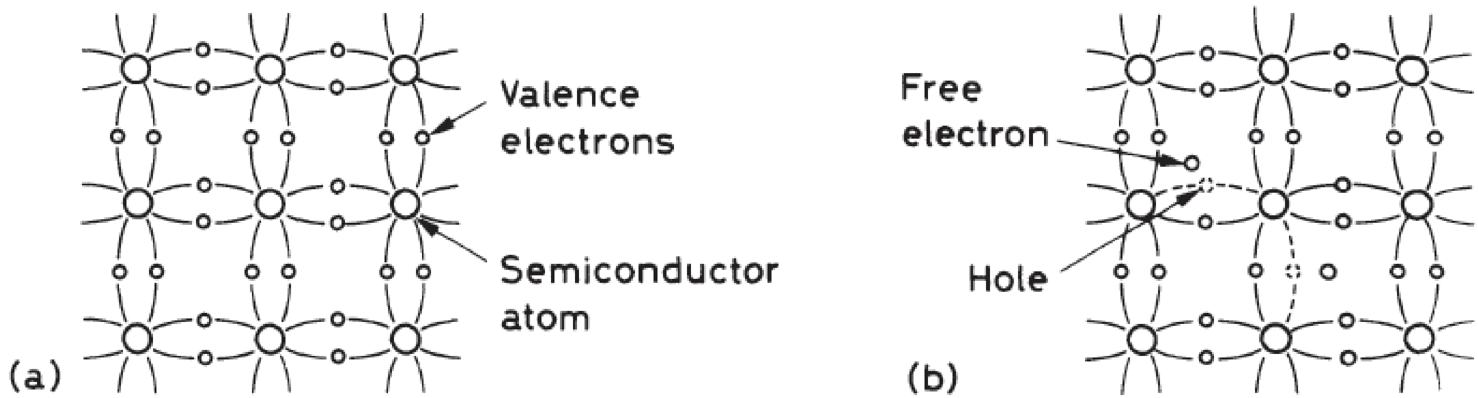
Source: W.R. Leo, Techniques for Nuclear and Particle Physics Experiments

Energy Band Structure (II)

- The band structure arises from the periodic arrangement of the atoms in the crystal.
- Taking the Pauli principle into account: As 2 electrons of opposite spin may occupy the same energy level, there are as many levels as there are pairs of electrons in the crystal.
- The width of the band gap is determined by the lattice spacing between the atoms in the crystal.
- These parameters are obviously dependent on temperature and pressure.
- Dependent on the width of the band gap, small „leakage“ currents can be observed at elevated temperatures.
- Hence when a semiconductor is cooled almost all electrons will fall into the valence band.

Charge Carriers in Semiconductors

- At 0 K (see figure (a)) all electrons are bound in covalent bonding between the lattice atoms.
- At higher temperatures (see figure (b)) some electrons are excited into the conduction band (i.e. free electrons), leaving a hole at their original positions.
- Subsequently it is very easy for a neighboring valence electron to jump to this hole.
- If this sequence is repeated very often, it looks like the hole is moving through the crystal, resulting in a positive charge carrier.



Source: W.R. Leo, Techniques for Nuclear and Particle Physics Experiments

Intrinsic Charge Carriers Density

- In a semiconductor electron and holes are generated permanently through thermal excitation.

- The number of electrons is equal to the number of holes.

- Some of them recombine instantaneously.

- So a stable equilibrium concentration of electrons *n* and holes *p* is being formed at the temperature T:

$$n = p = A \cdot T^{3/2} \, e^{-E_g/(2\,k\,T)}$$

- Typical values at 300 K are:
  Silicon: $1.5 \cdot 10^{10}\ cm^{-3}$
  Germanium : $2.4 \cdot 10^{13}\ cm^{-3}$

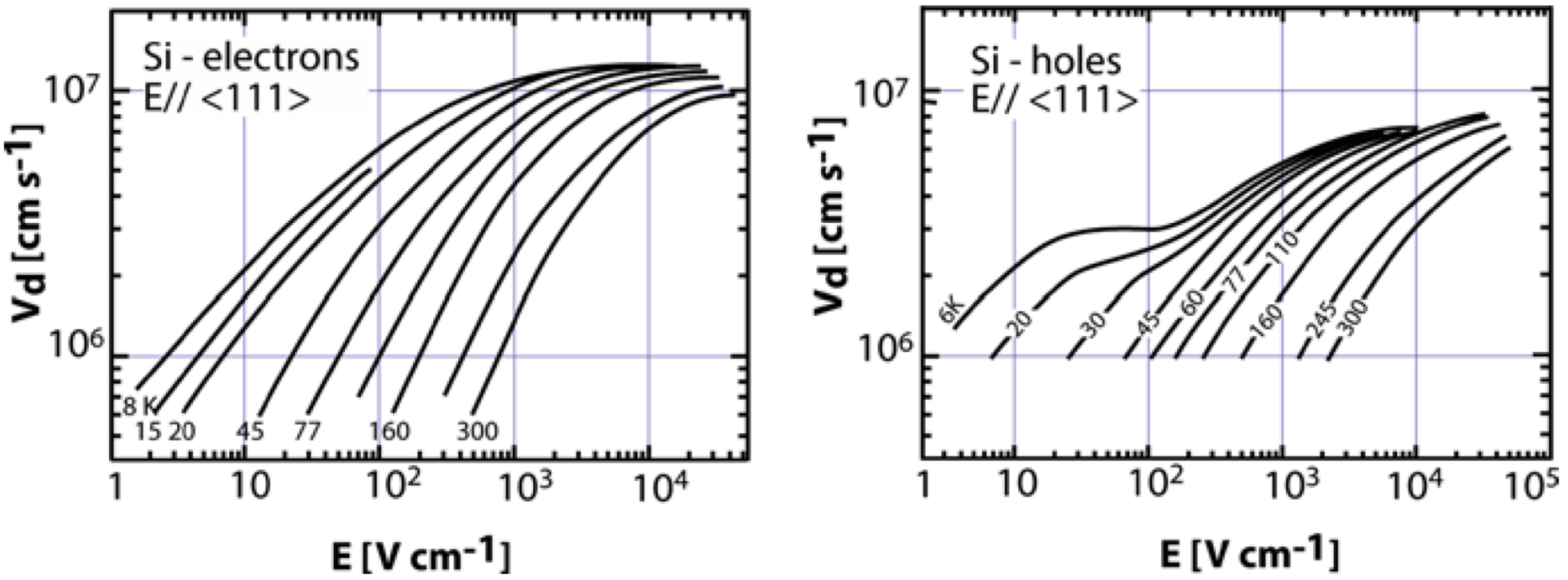
- However in a cubic centimeter of these materials are in the order of $10^{22}\ to\ 10^{23}\ atoms$, so the concentration of charge carriers is very low.

Mobility of Charge Carriers

- Under the influence of an external electrical field E, the drift velocity $v_{e,h}$ through a semiconductor is:

$$v_{e,h} = \mu_{e,h} E$$

where $\mu_{e,h}$ are the mobilities of the electrons and the holes, respectively.

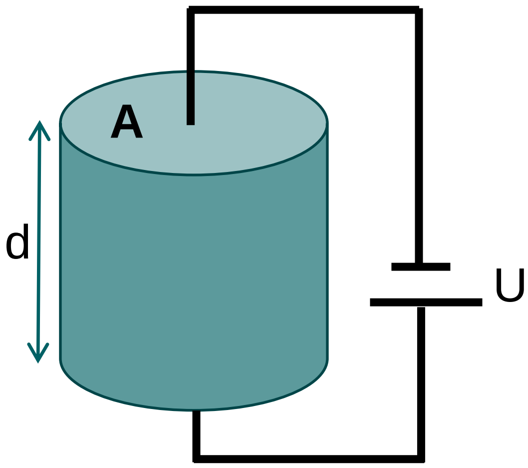


Source: S. Tavernier, Experimental Techniques in Nuclear and Particle Physics

Specific Resistivity of Semiconductors

- Apply a voltage U on the surface A of a cylinder (or block) with a thickness d and a specific resistivity ρ. Then the electrical resistance R is:

  $$R = \frac{d}{A}\,\rho \qquad I = \frac{U}{R} = \frac{A \cdot U}{d \cdot \rho}$$



- On the other hand, the current in this cylinder is related to the velocities of electrons and holes:

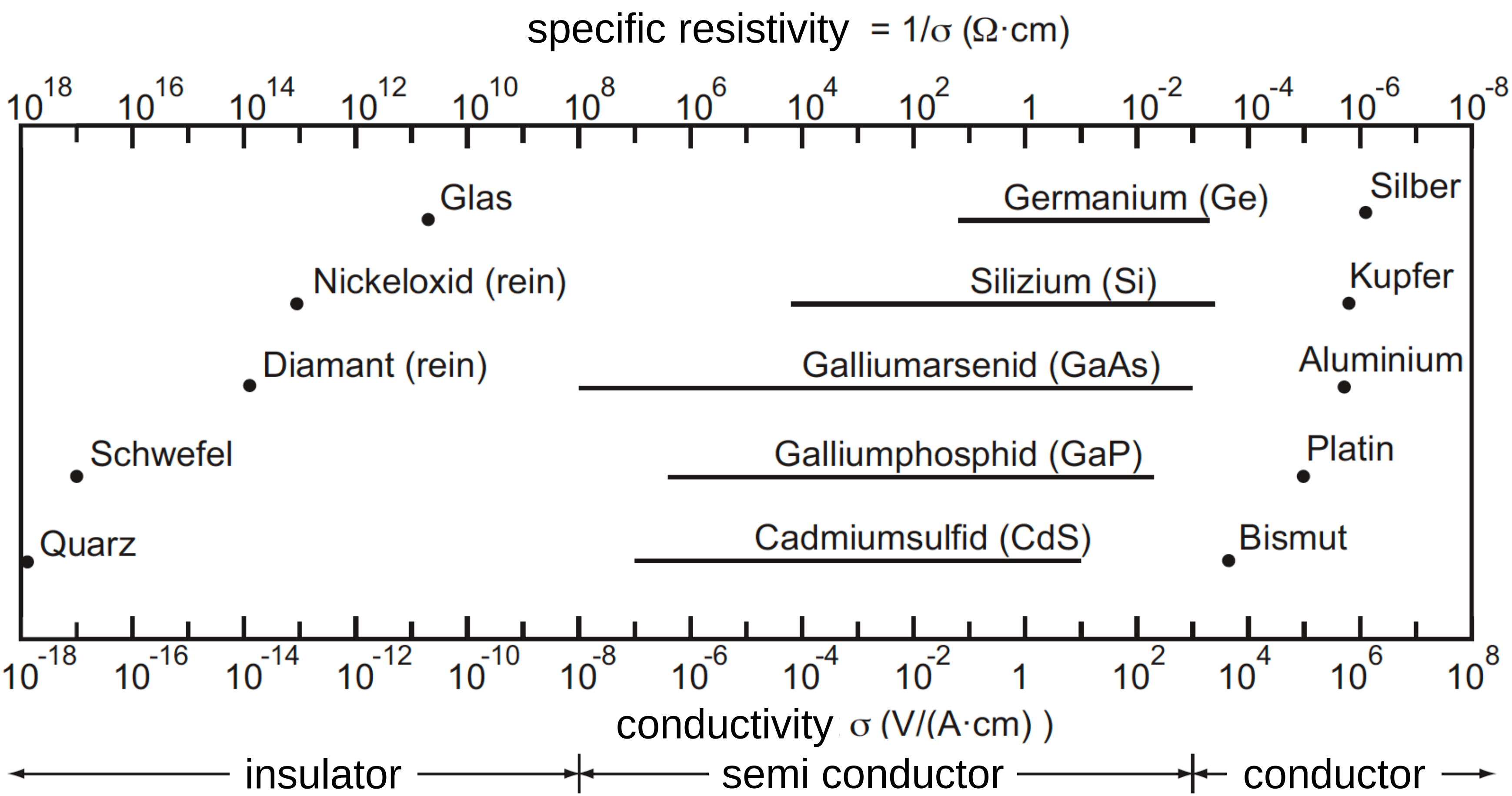
  $$I = e\,A\,(n \cdot v_e + p \cdot v_h)$$

- Using $v_{e,h} = \mu_{e,h}\,E = \mu_{e,h}\,\frac{U}{d}$ gives for the specific resistivity: $\boldsymbol{\rho} = \frac{\mathbf{1}}{\boldsymbol{e\,(n\,\mu_e + p\,\mu_h)}}$

- If the number one type of charge carriers is much larger than the other type, then this carrier density dominates the resistivity.

- The conductivity σ is the invers of the specific resistivity.

Specific Resistivity of Different Materials



Some Physical Properties of Si and Ge

Characteristic property	Si	Ge
Atomic number	14	32
Atomic weight	28.09	72.60
Density in g/cm^3	2.33	5.32
Dielectric constant	12	16
Energy gap at 300 K in eV	1.12	0.67
Energy gap at 0 K in eV	1.17	0.75
Charge carrier density at 300 K in cm^{-3}	$1.5 \cdot 10^{10}$	$2.4 \cdot 10^{13}$
Resistivity at 300 K in $\Omega\,cm$	$2.3 \cdot 10^5$	47
Electron mobility at 300 K in $cm^2/V\,s$	1350	3900
Electron mobility at 77 K in $cm^2/V\,s$	$2.1 \cdot 10^4$	$3.6 \cdot 10^4$
Hole mobility at 300 K in $cm^2/V\,s$	480	1900
Hole mobility at 77 K in $cm^2/V\,s$	$1.1 \cdot 10^4$	$4.2 \cdot 10^4$
Energy per e–h pair at 300 K in eV	3.62	≈ 3 for HPGe[a]
Energy per e–h pair at 77 K in eV	3.76	2.96
Fano factor[b] at 77 K	≈ 0.15	≈ 0.12

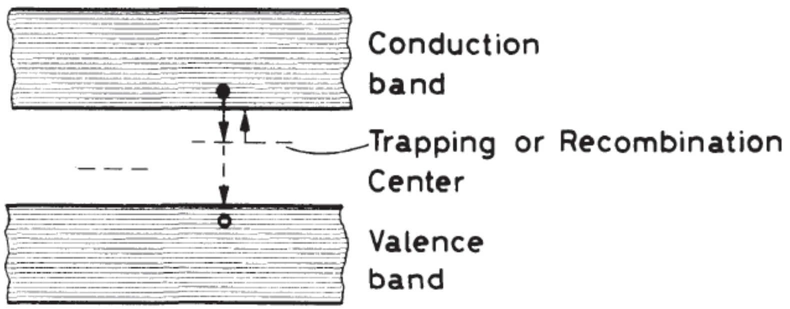
Source: C. Grupen and B. Shwartz, Particle Detectors

Recombination of Charge Carriers in Semiconductors

- An electron may recombine with a hole by falling from the conducting band into an open level in the valence band, emitting a photon.
- This process is called *direct recombination*. It is the opposite of e-h-pair generation.
- However, energy and momentum must be conserved. So e and h must have exactly the right values, which is very unlikely.
- This gives theoretical lifetimes of seconds.
- Measurements shows values in the order of nano- to microseconds. This implies that other mechanisms are involved.
- The most prominent one comes from recombination centers from impurities in the crystal.

Trapping at Recombination Centers in Semiconductors

- These recombination centers introduce additional energy levels in the forbidden energy gap.
- These states may capture an electron from the conduction band and
  - Either release the electron back into the conduction band after some time,
  - Or may capture a hole which then annihilates with the trapped electron.

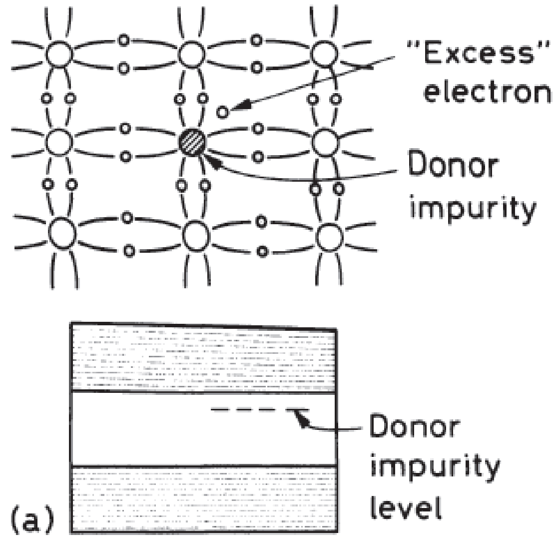


Source: W.R. Leo, Techniques for Nuclear and Particle Physics Experiments

- Recombination centers reduce the mean free lifetime of charge carriers, which limits the charge collection time in radiation detection and hence the usable volume of the detector.
- However, some traps can only capture one type of carriers. Such centers hold either e or h and then release them after some time. This charge is obviously lost and so the collected charge is incomplete.

N-Doped Semiconductors

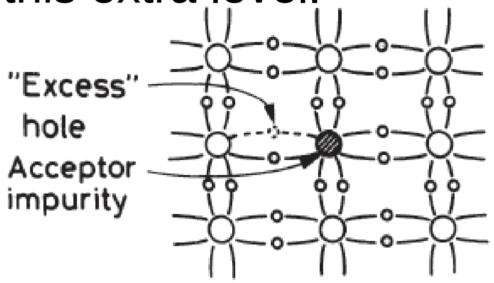
- In a pure semiconductor, the number of electrons equals the number of holes.
- This equilibrium can be changed by introducing small numbers of impurity atoms having one more or one less valence electron.
- If the dopant is pentavalent 4 of the 5 electrons fill up the valence band.
- The extra or excess electron does not fit into this band, creating a discrete energy level in the energy band gap.
- In contrast to recombination and trapping centers the level is very close to the conduction band (difference typically in the order of tens of meV).
- Therefor the extra electron is easily excited into the conduction band, increasing the conductivity.
- In addition those electrons will fill up holes, decreasing the hole concentration.
- In such doped semiconductors the current comes mainly from electrons.
- These types are called n-type semiconductor.

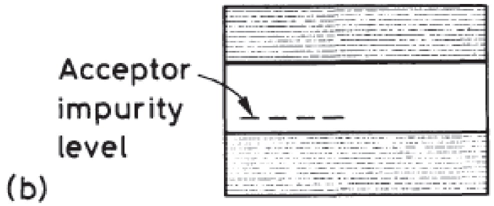


Source: W.R. Leo, Techniques for Nuclear and Particle Physics Experiments

P-Doped Semiconductors

- If the dopant is trivalent with one electron less, there will be not enough electrons to fill the valence band.
- So there are excess holes, creating another discrete energy level in the energy band gap.
- But in this case close to the valence band.
- Electrons in the valence band can easily be excited into this extra level.
- Hence extra holes are left behind.
- This excess of holes decreases the concentration of free electrons.
- In such doped semiconductors the holes are the majority charge carriers and the electrons the minority.
- These types are called p-type semiconductor.

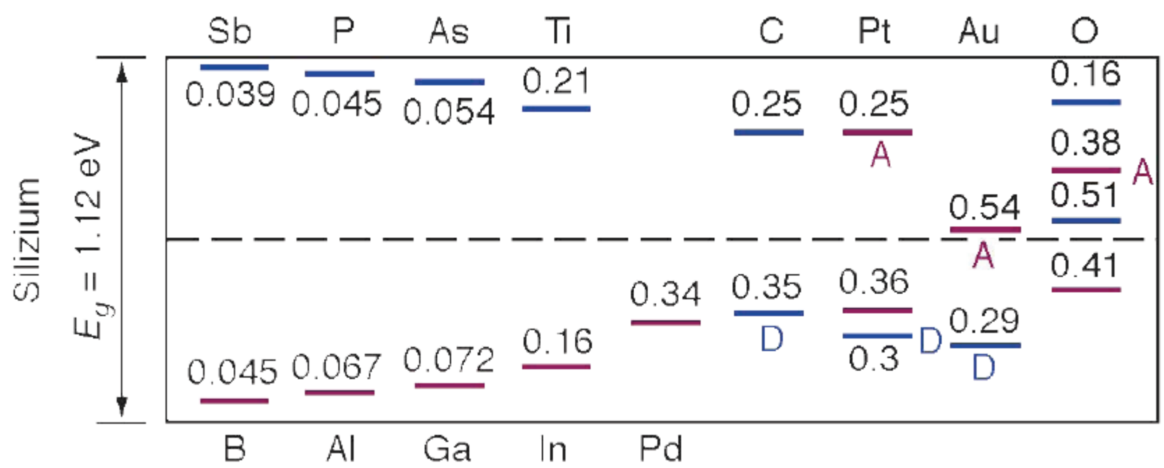




Source: W.R. Leo, Techniques for Nuclear and Particle Physics Experiments

Ionization Energies for Commonly Used Dopants in Silicon

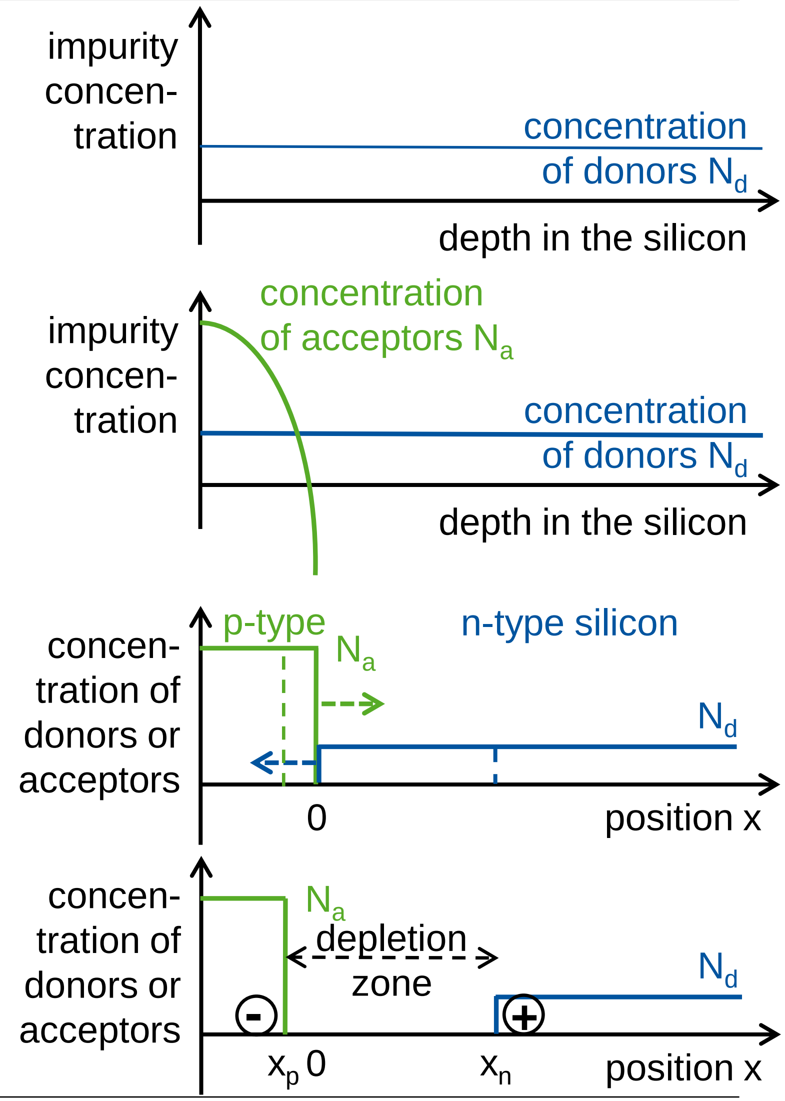
- Typically antimony, phosphorous and arsenic are used as donors.
- While boron, aluminum, gallium and indium are the most used acceptors.
- The concentration of dopants is usually very small, e.g. in the order of $10^{10}\ to\ 10^{13}\ {}^{atoms}/_{cm^3}$
- However, heavily up to $10^{20}\ {}^{atoms}/_{cm^3}$ doped n- and p-type materials are used for electrical contacts in semiconductor devices.
- “+”-sign after the material is used to distinguish this from normally doping.



Source: S.M. Sze, Physics of Semiconductor Devices

The p-n Semiconductor Junction (I)

- E.g. implant n-type material homogenously into a semiconductor.
- Next step: diffuse sufficient amount of p-type material into one end so that this region changes from n- to p-type semiconductor.
- This forms a p-n junction.
- Because of the different electron and hole concentrations there will be an initial diffusion of electrons towards the p-region and vice versa.
- So electrons in the n-type are filled by the diffusing holes and correspondingly the holes in the p-type by the electrons.
- Initially n- and p-type regions were electrically neutral.
- But after contact the p-region becomes negative and the n-region positive.

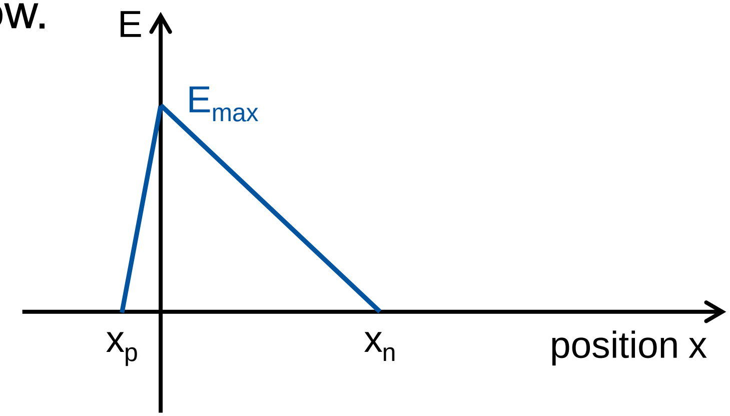


The p-n Semiconductor Junction (II)

- The different electron and hole concentrations create an electrical field across the p-n-junction.
- This is commonly called "*contact potential*".
- The region where the potential changes is the "depletion zone" or "space charge region".
- Any electron or hole created in or entering this zone will be swept out by the electric field. This makes it ideal for detection of ionizing radiation.
- The current measured at the contacts is proportional to the introduced ionization.

Model of a One-Sided Abrupt Junction

- The shape of the electric field across a simple p-n junction (model of a "*one-sided abrupt junction*") should be like in the figure below.



- Assumptions:
  - The depletion zone is completely free of carriers.
  - $N_a \gg N_d$

    $\Rightarrow N_d \cdot x_n = N_a \cdot x_p$

    $\Rightarrow x_n \gg x_p$

- The electric potential inside the p-n junction can be found by solving the Poisson equation.

Solving the Poisson Equation of a One-Sided Abrupt Junction (I)

- The Poisson equation for this simple one-dimensional model is:

$$\frac{d^2V}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

  - Where ρ is the charge density and ε is the dielectric constant.

- The diode can be divided into 4 regions:
  - Region 1: $V_1(x)\ \ in\ \ -\infty < x < -x_p\ \ with\ \ \rho = 0$
  - Region 2: $V_2(x)\ \ in\ \ -x_p < x < 0\ \ with\ \ \rho = -e\,N_a$
  - Region 3: $V_3(x)\ \ in\ \ 0 < x < x_n\ \ with\ \ \rho = e\,N_d$
  - Region 4: $V_4(x)\ \ in\ \ x_n < x < \infty\ \ with\ \ \rho = 0$

- In region 1 and 4 there are free carriers and so the electric field must be zero:

$$\frac{dV_1}{dx} = 0 \Rightarrow V_1(x) = const.$$

$$\frac{dV_4}{dx} = 0 \Rightarrow V_4(x) = const.$$

Solving the Poisson Equation of a One-Sided Abrupt Junction (II)

- The potential for region 2 is found by solving the Poisson equation in region 2:

$$\frac{d^2V_2}{dx^2} = \frac{e\,N_a}{\varepsilon} \quad for \quad -x_p < x < 0$$

$$\int \frac{d^2V_2}{dx^2}\,dx = \frac{d\,V_2}{dx} = \frac{e\,N_a}{\varepsilon} \cdot x + C_p$$

- Since the electric field at $-x_p$ disappears:

$$\frac{dV_2}{dx}(-x_p) = 0 = \frac{e\,N_a}{\varepsilon} \cdot (-x_p) + C_p$$

$$C_p = \frac{e\,N_a}{\varepsilon} \cdot x_p$$

- The electric potential in region 2 is then:

$$V_2(x) = \int \frac{d\,V_2}{dx}\,dx = \frac{e\,N_a}{\varepsilon}\left(\frac{x^2}{2} + x_p \cdot x\right) + C_2$$

Solving the Poisson Equation of a One-Sided Abrupt Junction (III)

- Similar calculations for region 3 gives the potential V_3 for $0 < x < x_n$:

$$V_3(x) = \frac{e\,N_d}{\varepsilon}\left(-\frac{x^2}{2} + x_n \cdot x\right) + C_3$$

- The continuity condition at $x = 0$ require $V_2(0) = V_3(0)$ and so $C_2 = C_3$.

- The potential difference over the p-n junction is therefore:

$$V_0 = V_4 - V_1 = V_3(x_n) - V_2(-x_p) = \frac{e\,N_d}{\varepsilon}\frac{x_n^2}{2} + \frac{e\,N_a}{\varepsilon}\frac{x_p^2}{2} \approx \frac{e\,N_d}{\varepsilon}\frac{x_n^2}{2}$$

  - Keeping in mind that $N_a \gg N_d\ and\ x_n \gg x_p$

Thickness of a One-Sided Abrupt Junction

- Using $N_a\, x_p = N_d\, x_n$ one gets for x_p and for x_n:

$$x_p = \sqrt{\frac{2\,\varepsilon\, V_0}{eN_a(1+\frac{N_a}{N_p})}} \qquad x_n = \sqrt{\frac{2\,\varepsilon\, V_0}{e\, N_d\,(1+\frac{N_d}{N_a})}}$$

- One can see that, if one side is heavily doped compared to the other $(N_a \gg N_d)$ the depletion zone will extend far into the lightly doped region (in the end entirely in the n-doped region).

- The thickness of the depletion zone is then

$$d = x_p + x_n = \sqrt{\frac{2\,\varepsilon\, V_0}{e}\,\frac{(N_a + N_d)}{N_a\, N_d}} \approx \sqrt{\frac{2\,\varepsilon\, V_0}{e\, N_d}}$$

- If no external voltage is applied the potential difference across the depletion zone is 0.7 V, and for typical donor concentration of a few times $10^{11}/\mathrm{cm}^3$ one gets several tens of µm thickness.

Maximum Electric Field of a p-n Junction

- For a one-side abrupt junction the electric field has this triangular shape (see above).
- It reaches it maximum at x = 0:

$$E_{max} = E(x=0) = \frac{e\, N_d x_n}{\varepsilon} \approx \frac{d\; e\; N_d}{\varepsilon}$$

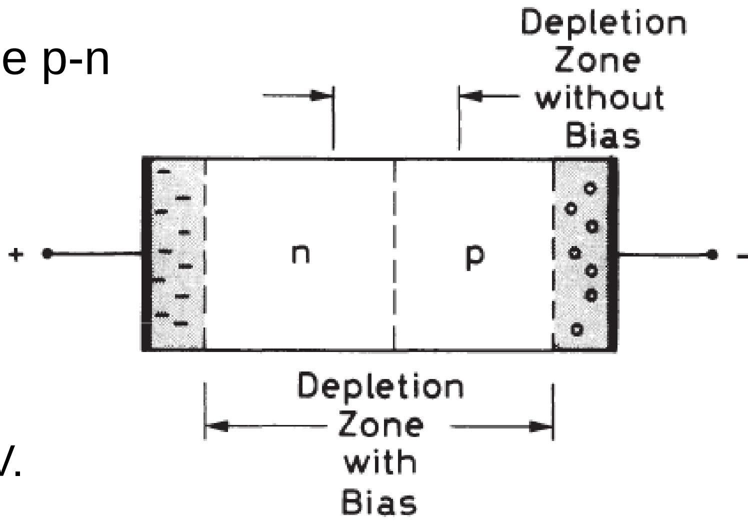
- For the breakdown voltage (i.e. maximum electric field) across the p-n junction of about 16 V/µm in silicon one gets a maximum reachable depletion zone thickness of several mm in high resistivity material (corresponding to low doping concentration)

Biased p-n Junction

- The detector described before will work but it is not optimal!
- Actually the intrinsic field from the diffusion of the electrons and holes will not be strong enough to collect all the induced charges and to prevent recombination.
- And the depth of the depletion zone is only sufficient to stop short range particles or low energy radiation.
- So it is better to apply a reverse bias voltage to the p-n junction.
- The width of the junction increases to

$$d = \sqrt{\frac{2\,\varepsilon\,(V_0+V_{ext})}{e}\,\frac{(N_a+N_d)}{N_a\,N_d}}$$

  - A few mm can be achieved while using several 100’s V.
- In addition the capacitance of the diode is reduced.



Source: W.R. Leo, Techniques for Nuclear and Particle Physics Experiments

Characteristics of a Semiconductor Detector

- Average Energy per Electron-Hole Pair:
  - Si: at 300 K => w = 3.62 eV
  - Ge: at 77 K => w = 2.96 eV
- This value is ca. 3x of the band gap energy because 2/3 of the energy go into lattice vibrations.
- But the number of electrons will be ca. one order of magnitude higher than in gases.
- If N electron-hole pairs are created than the measured energy is: $E = w \cdot N$
- The energy resolution of the measured energy as FWHM is given:

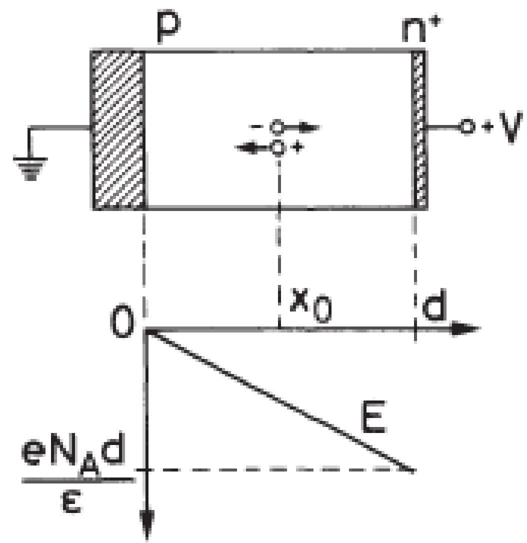
  $\mathrm{FWH}M = 2.35 \cdot \sqrt{\frac{w \cdot F}{E}}$ where F is the Fano-factor (ca. 0.15 for Si)
- Although the intrinsic resolution is about 4 keV, the actually measured $\geq 10\ keV$.
  - So it is clear that other sources contribute and limit the resolution (e.g. electronics).
- A MIP with $\frac{dE}{dx} \cong 0.4\ {}^{MeV}/_{mm}$ creates in 300 µm silicon ca. 33000 e-h pairs ($\cong 5 fC$).

Pulse Shape and Rise Time of a Semiconductor Detector (I)

- The collection time for electrons and holes depend on the distance of the charges from the electrodes.
- The pulse comes from induction due the movement of the charges.
- Assuming a semiconductor detector with 2 parallel plates at a distance d, the change in potential energy dQ of a charge that travels a distance dx from x_0 is:

$$dQ = \frac{q\,dx}{d}$$

- Consider a heavily n-doped semiconductor where the depletion zone almost entirely stretches into the p-doped region with an external voltage V applied.
  - $E(x) = -\frac{e\,N_a}{\varepsilon}\,x$
  - For p-doped material the conductivity is $\sigma = {}^{1}/_{\rho} \cong e\,N_a\,\mu_h$
  - $E(x) = -\frac{\sigma}{\varepsilon\,\mu_h}\,x = -\frac{x}{\mu_h\,\tau}$ with $\tau = {}^{\varepsilon}/_{\sigma}$



Source: W.R. Leo, Techniques for Nuclear and Particle Physics Experiments

Pulse Shape and Rise Time of a Semiconductor Detector (II)

- The electrons will drift to the n+ layer and the holes to the p layer.
- The velocity of the electrons is:

$$v = \frac{dx}{dt} = -\mu_e E = \frac{\mu_e}{\mu_h}\frac{x}{\tau}$$

- If the motilities are independent of the electric field:

$$x(t) = x_0\, e^{\frac{\mu_e t}{\mu_h \tau}}$$

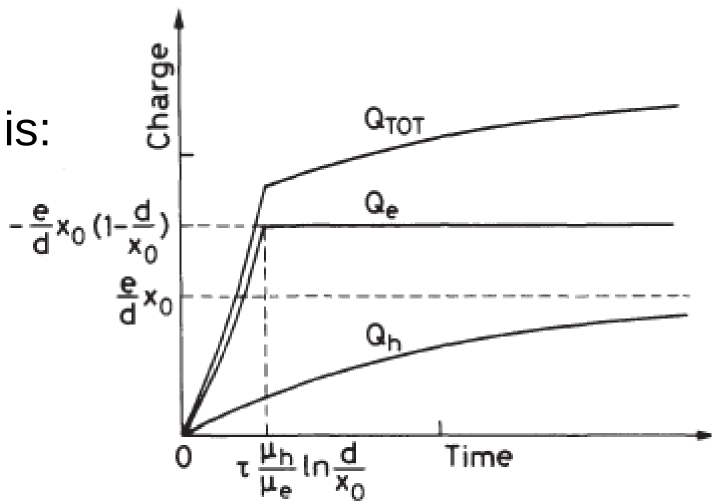
- So the time for the electrons to reach the electrode is:

$$t = \tau \frac{\mu_h}{\mu_e} \ln(\frac{d}{x_0})$$

- The charge induced by the electrons is then:

$$Q_e(t) = -\frac{e}{d}\int dx\, \frac{dt}{dt} = \frac{e}{d}\, x_0\, (1 - e^{\frac{\mu_e t}{\mu_h}})$$

- Similar results are found for the holes.



Source: W.R. Leo, Techniques for Nuclear and Particle Physics Experiments

Other Semiconductor Detector Materials

- Si and Ge are by far the most used materials for radiation detection. However,
  - Detector grade Ge is expensive and must be cooled.
  - And Z is only 32 (could be higher for higher photoelectric cross section).
  - Si could have a lower dark current at room temperature (due to band gap energy).
  - Si exhibits a pronounced radiation damage.
- An alternative for detecting gammas is e.g. CdTe (CT) or CdZnTe (CZT)

Material	Z	Density [g/cm^3]	Radiation length [mm]	Bandgap [eV]	Energy per e–h pair [eV]	Intrinsic resistivity [Ωcm]	Electron mobility [cm^2/(Vs)]	Hole mobility [cm^2/(Vs)]	Electron lifetime [s]	Hole lifetime [s]
Si	14	2.33	93.6	1.12	3.62	320′000	1450	450	10^{-4}	10^{-4}
Ge	32	5.32	23	0.66 at 77 K	2.9 at 77 K	50	36000 at 77 K	42000 at 77 K	10^{-4}	10^{-4}
InP	49/15	4.97		1.35	4.2	$\approx 10^7$	4600	150		
GaAs (bulk)	31/33	5.32	23.5	1.424	4.2	$3.3\ 10^8$	>8000	400	10^{-8}	10^{-9}
CdTe	48/52	6.2	14.7	1.4	4.4	$\approx 10^9$	1000	80	10^{-6}	10^{-6}
$Cd_{0.8}Zn_{0.2}Te$	48/30/52	6		1.6	4.7	$\approx 10^{11}$	1350	120	10^{-6}	$2\ 10^{-7}$
HgI	80/53	6.4	11.8	2.13	4.3	$\approx 10^{13}$	100	4	$7\ 10^{-6}$	$3\ 10^{-6}$
Diamond	6	3.5	122	5.5	13	$>10^{11}$	1800	1200		
a-selenium	34	4.27	29		6–8					

Source: S. Tavernier, Experimental Techniques in Nuclear and Particle Physics

- Thank you for your attention.