Semiconductor Detectors
Summary of Last Lecture

Band structure in Solids:

- **Insulator**
  - \( E_g > 5 \text{ eV} \)
  - Valence band
  - Conduction band
  - Charge carrier in conductor: e⁻
  - Charge carrier in semiconductor: e⁻, holes

- **Semiconductor**
  - \( E_g \approx 2 \text{ eV} \)
  - Valence band
  - Conduction band

**Thermal conductivity:**
\[ n_i = AT \frac{e^{-E_g/(2kT)}}{3/2} \]

- **T** absolute temperature
- **K** Boltzmann constant
- **A** material constant
- **E\_g** band gap

**Room temperature:**
- Pure Si: \( \rightarrow 1.5 \times 10^{10}/\text{cm}^3 \)
- Pure Ge: \( \rightarrow 2.5 \times 10^{13}/\text{cm}^3 \)
Summary of Last Lecture

**Donor** (e.g. P in Si):
- \( \rightarrow \text{n-type Si} \)
- (extra electrons = majority charge carriers)

**Acceptor** (e.g. B in Si):
- \( \rightarrow \text{p-type Si} \)
- (extra holes = majority charge carriers)
Semiconductor Junction: np

- Rectifying diode
- Initial diffusion of holes towards the n-region and e- towards the p-region [a), b])
- Charge build-up on either side of the junction [c])
- p-region $\rightarrow$ negative
  n-region $\rightarrow$ positive [c])
- Electric field gradient across the junction $\rightarrow$ process halted $\rightarrow$ region of immobile space charge [d])
- Due to electric field: potential difference across the junction $\rightarrow$ contact potential $V_0$ ($\sim$1V)

Region of changing potential: depletion zone or space charge region
Summary of Last Lecture

Reversed bias junction

- pn junction:
  1) intrinsic electrical field not intense enough to provide efficient charge collection
  2) thickness of depletion zone only sufficient for stopping lowest energy particles
- apply reverse bias voltage to junction, i.e. a negative voltage on the p-side:
  - attracts holes in the p-region (e- in n-region)
  - enlarge depletion zone
  - “sensitive volume

1. \[ d \sim \sqrt{V_b} \]
2. the higher \( V_b \), the higher the charge collection efficiency
Summary of last lecture

Physics – device characteristics

- In general: depletion zone extends further into the light doped side
- Depletion zone
- Contact/depletion voltage
- Resistivity

\[
d = \sqrt{\frac{2\varepsilon V_{bias}}{qN_{eff}}}
\]

\[
V_{fd} = \frac{N_{eff} q D^2}{2\varepsilon}
\]

\[
\rho = \frac{1}{q(\mu_n N_n + \mu_p N_p)}
\]

\[
\mu_{e,h} = \text{electron, hole mobility}
\]

\[
N_{eff} = \text{Effective carrier concentration}
\]

\[
x = \text{distance from junction} \quad D = \text{silicon thickness}
\]
Detector characteristics of Semiconductors

Basic configuration for operating a junction diode as a radiation detector:

Electrodes must be fitted on the Two sides of the semiconductor

But: remember surface barrier diodes: Depositing metal directly onto the Semiconductor material results in the Creation of a rectifying junction with a Depletion zone ext. into the semiconductor

What’s needed: Ohmic contact (a metal-semiconductor contact with a linear or near linear current voltage characteristic)

Using heavily doped layer of n+ and p+ between metal and semiconductor solves the problem (see equation \( \text{\#} \rightarrow d \sim 0 \))
Average Energy per Electron-Hole Pair

- The average energy for creating an electron-hole pair at a given temperature is independent of the type and energy of the radiation and only dependent on the material.
- Number of charge carriers is almost an order of magnitude higher than in gases.
- Compared to the number of photoelectrons in a scintillation counter, the number of charge carriers are almost two orders of magnitude higher.
  → greatly improved energy resolution

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 K</td>
<td>3.62 eV</td>
<td></td>
</tr>
<tr>
<td>77 K</td>
<td>3.81 eV</td>
<td>2.96 eV</td>
</tr>
</tbody>
</table>

Energy gaps are only ~ 1 eV

Where do the other two thirds of the energy go?

Lattice vibrations
Linearity

- If depletion region is sufficiently thick to completely stop all particles → semiconductor response ~ E
- If E energy of radiation E/w electron-hole pairs should be produced, w average energy from table before
- Voltage observed at the electrodes:
  \[ V = \frac{Q}{C} = n \frac{E}{w C} \]
  C capacitance of semiconductor, w average energy, n charge collection efficiency → V ~ E
- w independent of type of radiation → E independent of type of radiation
  (only true for lightly ionizing particles such as electrons and positrons, plasma effects occur for heavier ions)

If depletion zone is smaller → nonlinear response (not the full Energy is deposited);
Instead the energy loss \( \Delta E \) is measured, which is a non-linear Function of energy
Leakage current

- Reversed bias diode is ideally nonconduction, but a small fluctuating current flows through the semiconductor when a voltage is applied → noise
- Sources of leakage current:
  - Movement of minority charges (e.g. holes from the n-region attracted across the junction to p-region), ~ nA/cm²
  - Thermally generated electron-hole pairs originating from the recombination and trapping centers in the depletion region (depends on the absolute number of traps), ~μA/cm²
  - Leakage current through the surface channels (depends on very many factors, e.g. the surface chemistry, contaminants, surrounding atmosphere, etc.)
    minimize by clean encapsulation
Sensitivity and Intrinsic Efficiency

• Intrinsic detection efficiency close to a 100% for charged particles (as very few particles will fail to create some ionization in the sensitive volume)

limiting factors: leakage current in the detector and noise from the associated electronics → sets lower limit on the pulses which can be detected

• Ensure adequate signal: depletion depth sufficiently thick → $S_{\text{ioniz}} > S_{\text{noise}}$

• Energy measurements: $d > \text{particle range}$
Sensitivity

Leo, page 230
Gamma Ray Detection

- Germanium is preferred over silicon because of higher Z
- However because of the smaller band gap, leakage current in Ge to high at room temperatures $\rightarrow$ Ge must be cooled (liquid nitrogen)
- For low energies below $\sim 30$ keV silicon detectors are preferred because the K-edge in Ge is located at $\sim 11$ keV
Comparison of NaI detector and Ge detector for Co-60

Fig. 10.19. Comparison of a $^{60}$Co source taken with a NaI detector and a germanium detector.
Energy Measurement:

<table>
<thead>
<tr>
<th>Energy resolution: # of information carriers:</th>
</tr>
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<tbody>
<tr>
<td>Scintillator: &gt; 100 eV / photon</td>
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<tr>
<td>Gas: 20 – 40 eV / charge</td>
</tr>
<tr>
<td>Silicon: 3.6 eV / charge</td>
</tr>
<tr>
<td>Germanium: 2.8 eV / charge</td>
</tr>
</tbody>
</table>

**Silicon** advantages:
- low ionization energy (good signal)
- long mean free path (good charge collection efficiency)
- high mobility (fast charge collection)
- low Z (low multiple scattering)
- production technologies very well developed

**Germanium**: higher Z → detect $\gamma$ radiation (needs cooling…)
Diffused Junction Diodes

- Among the first fabricated
- Produced by diffusing n-type impurities such as phosphorus into one end of a homogeneous p-type semiconductor at high temperatures (~1000 deg C)
- By adjusting concentrations and diffusion time → junctions lying at a depths of few tenths of a microns to two microns can be produced
Ion-Implanted Diodes

- Formed by bombarding the semiconductor crystal with a beam of impurity ions from an accelerator
- By adjusting the beam energy, the impurity concentration and depth profile can be controlled
- Since radiation damage is incurred, the semiconductor must be annealed at temperatures of 500 deg C
Surface Barrier Diode

See previous lecture
Position Sensitive Detector
Micro-Strip Detectors

Fig. 10.16. Layout of micro-strips (from Hyp...
Applications

- CCD detectors
- APS detectors
- Micro vertex detectors
- More about those later