# Solid State Detectors

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# Semi-Conductor based Detectors

- Materials and their properties
- Energy bands and electronic structure
- Charge transport and conductivity
- Boundaries: the p-n junction
- Charge collection
- Energy and time resolution
- Radiation damage

# Signal Generation → Needs transfer of Energy

Any form of elementary excitation can be used to detect the radiation signal

An electrical signal is generated by ionization: Incident radiation quanta transfer sufficient energy to form electron-hole pairs

Other detection mechanisms are:

- Excitation of optical states (scintillators)
- Excitation of lattice vibrations (phonons)
- Breakup of Cooper pairs in superconductors

Typical excitation energies:

| | |
|---|---|
| Ionization in semiconductors: | 1 – 5 eV |
| Scintillation: | appr. 20 eV |
| Phonons: | meV |
| Breakup of Cooper pairs: | meV |

Ionization chambers can be made with any medium that allows charge collection to a pair of electrodes

The medium can be: *Gas*, Liquid, Solid

| | **gas** | **liquid** | **solid** |
|---|---|---|---|
| **density** | low | moderate | high |
| **atomic number Z** | low | moderate | moderate |
| **ionization energy $\varepsilon_i$** | moderate | moderate | low |
| **signal speed** | moderate | moderate | fast |

Desirable properties:

Low ionization energy $\longrightarrow$ Increased charge yield *dq/dE*

Superior resolution

$$\frac{\Delta E}{E} \sim \frac{1}{\sqrt{N}} \sim \frac{1}{\sqrt{E/\epsilon_i}} \sim \sqrt{\epsilon_i}$$

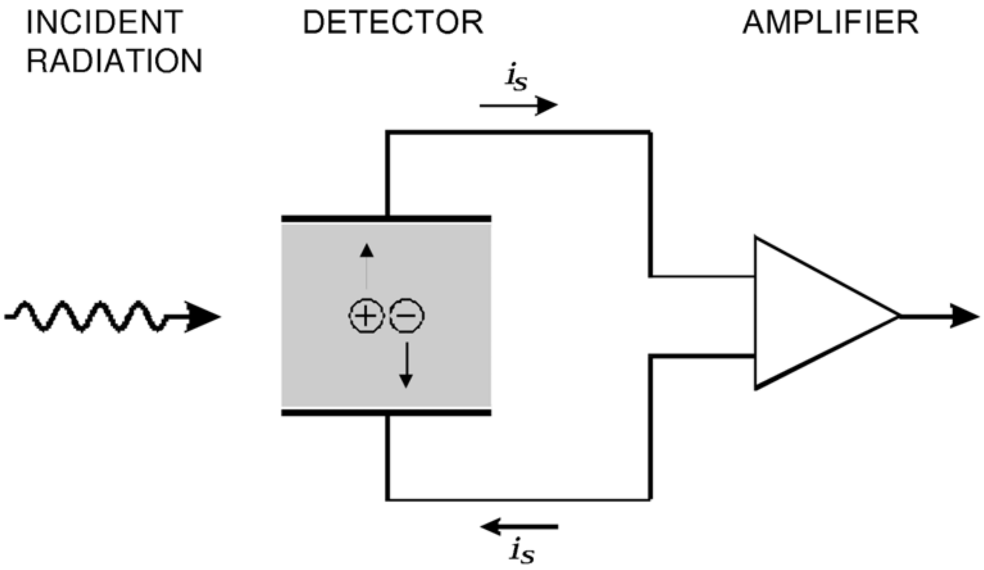
High field in detection volume $\longrightarrow$ Fast response

Improved charge collection efficiency

Q: what is the simplest solid-state detector ?

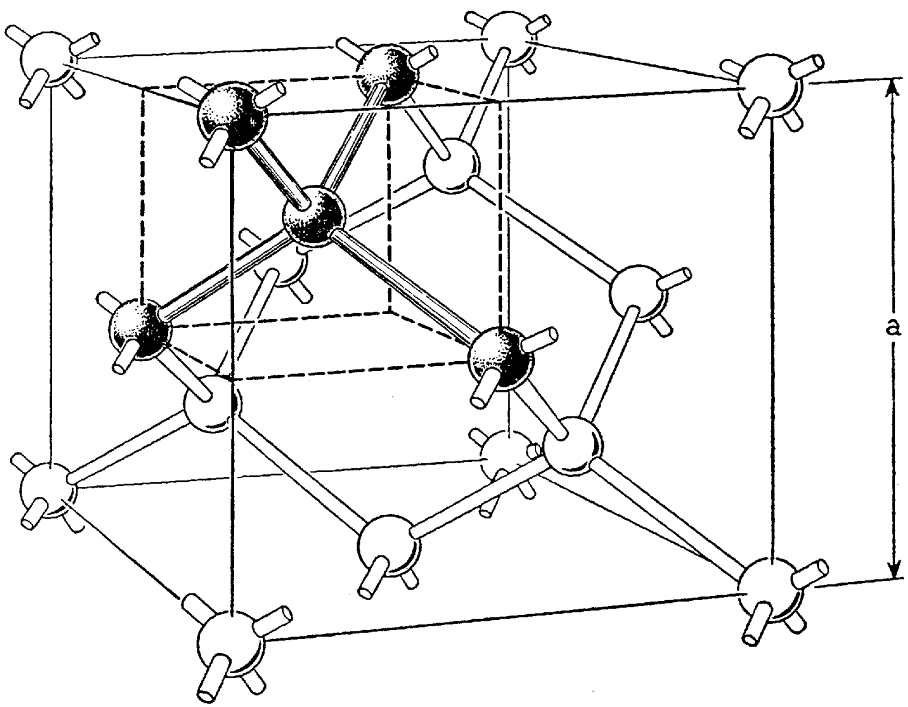
A: Photoconductor: Change of resistivity upon irradiation

Semiconductor detectors are ionization chambers:



# Semiconductor crystals

Lattice structure of diamond, Si, Ge (Diamond structure)




The crystalline structure leads to formation of electronic bandgaps

a = Lattice constant

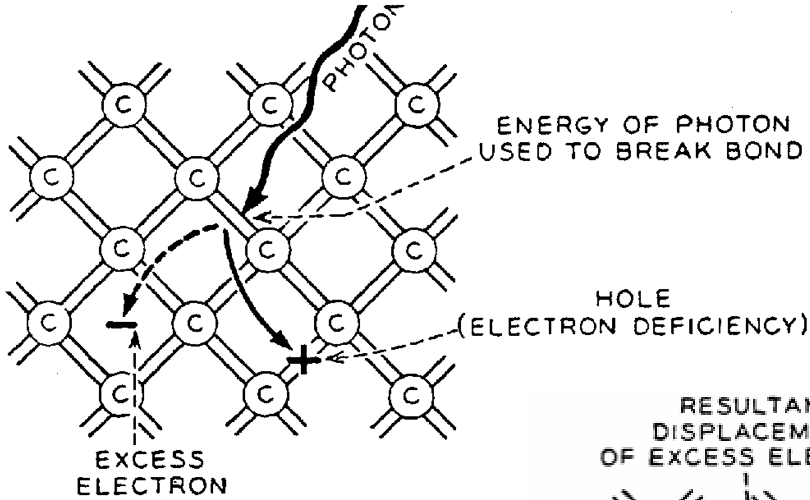
| | |
|---|---|
| Diamond: | a = 0.356 nm |
| Ge: | a = 0.565 nm |
| Si: | a = 0.543 nm |

# Creation of electron-hole pairs

Upon absorption of a photon, a bond can be broken which

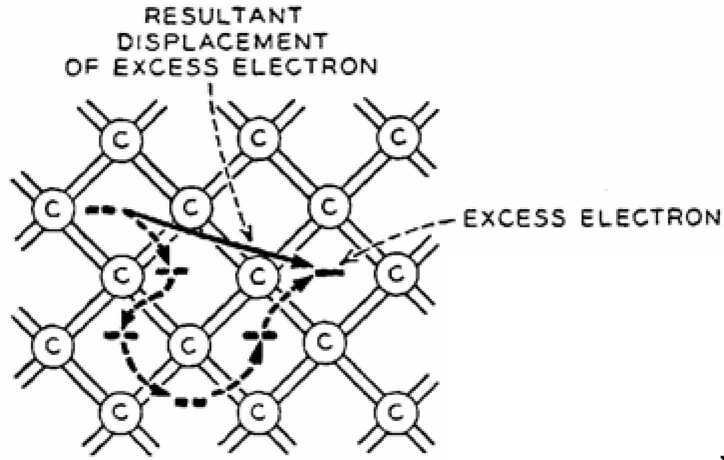
→ excites an electron into the conduction band and

→ leaves a vacant state in the valence band



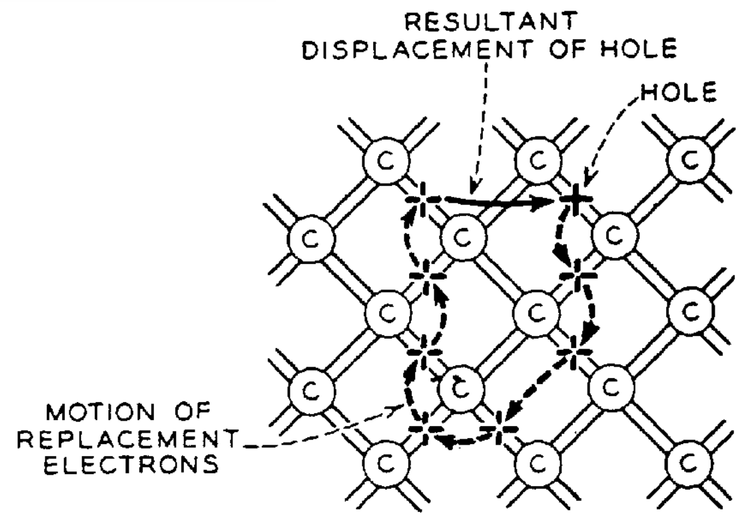

(a) PRODUCTION OF A HOLE-ELECTRON PAIR BY A PHOTON

The electron can move freely




(C) RANDOM MOTION OF AN EXCESS ELECTRON

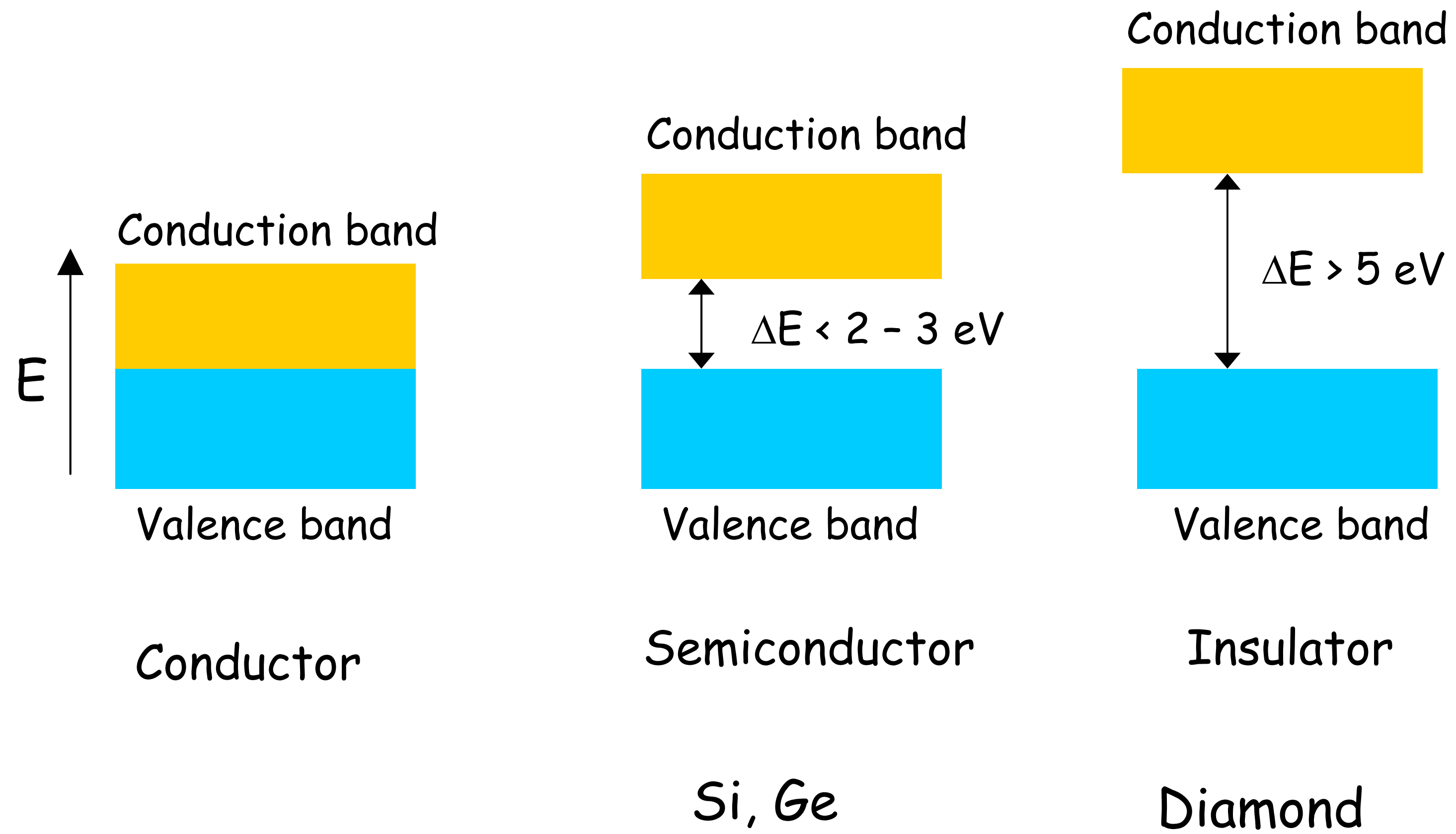
The hole is filled by a nearby electron, thus moving to another position



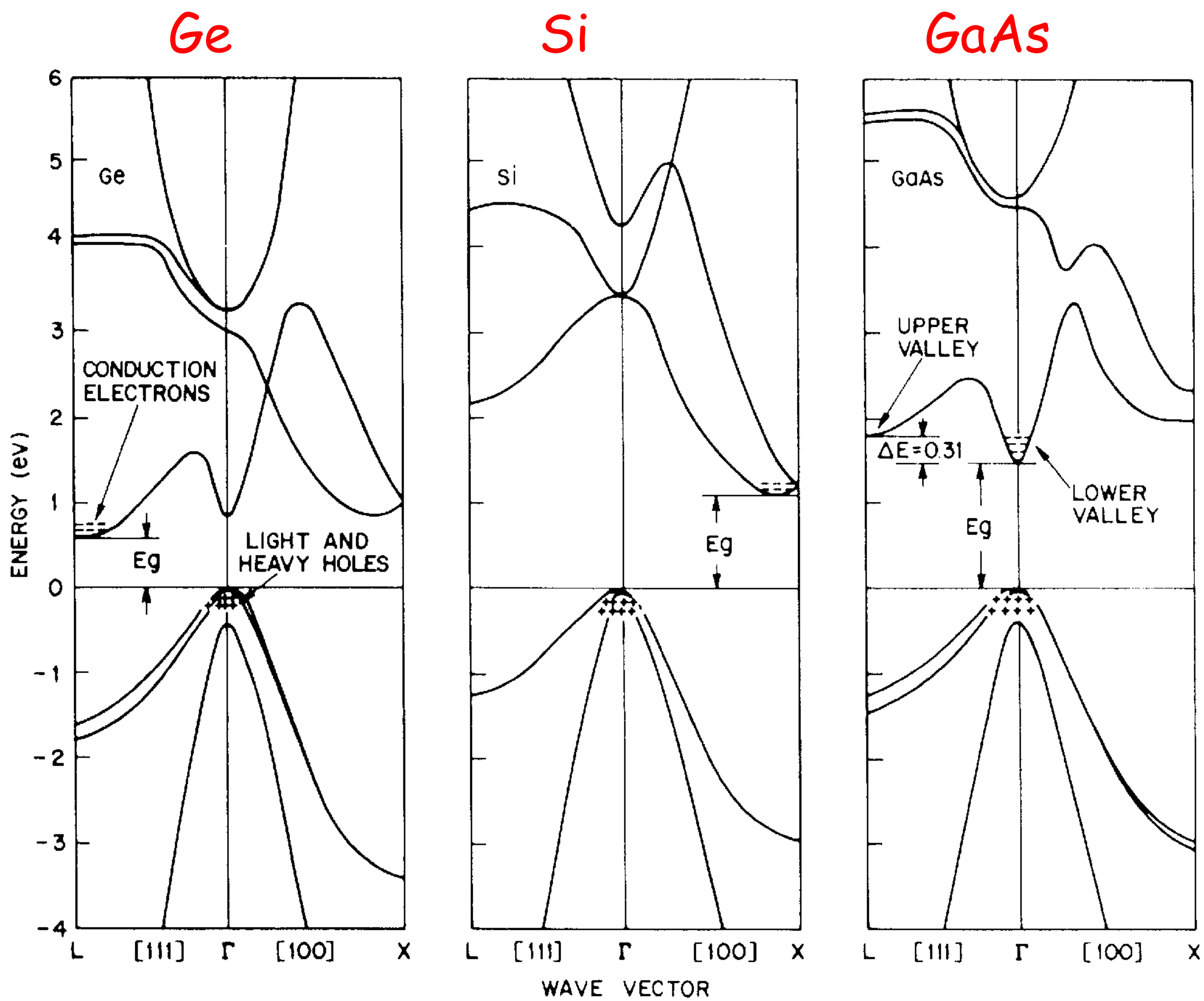

(d) RANDOM MOTION OF A HOLE

Holes behave like positive charge carriers. They move more slowly because hole transport involves many particles

Classification of Conductivity



# Band structure (3)




$E_g$ = 0.7 eV

$E_g$ = 1.1 eV

$E_g$ = 1.4 eV

Indirect band gap

Direct band gap

# Properties of semiconductors

| Property | | Si | Ge | GaAs | Diamond |
|---|---|---|---|---|---|
| Atomic Number | | 14 | 32 | 31/33 | 6 |
| Atomic Mass | [amu] | 28.1 | 72.6 | 144.6 | 12.6 |
| Band Gap | [eV] | 1.12 | 0.66 | 1.42 | 5.5 |
| Radiation Length $X_0$ | [cm] | 9.4 | 2.3 | 2.3 | 18.8 |
| Average Energy for Creation of an Electron-Hole Pair | [eV] | 3.6 | 2.9 | 4.1 | $\sim 13$ |
| Average Energy Loss $dE/dx$ | [MeV/cm] | 3.9 | 7.5 | 7.7 | 3.8 |
| Average Signal | [$e^-/\mu$m] | 110 | 260 | 173 | $\sim 50$ |
| Intrinsic Charge Carrier Concentration | [$cm^{-3}$] | $1.5 \cdot 10^{10}$ | $2.4 \cdot 10^{13}$ | $1.8 \cdot 10^{6}$ | $< 10^3$ |
| Electron Mobility | [$cm^2$/Vs] | 1500 | 3900 | 8500 | 1800 |
| Hole Mobility | [$cm^2$/Vs] | 450 | 1900 | 400 | 1200 |

Si  Currently best quality material

Ge  Small band gap, i.e., high generated charge. Well suited for energy measurements

GaAs  good ratio of generated charge/noise, charge collection efficiency dependent on purity and composition, radiation hard

Diamond  radiation hard, expensive

# Energy required for creation of an electron-hole pair

Ionization Energy > Band Gap

Formation of e-h pairs requires both

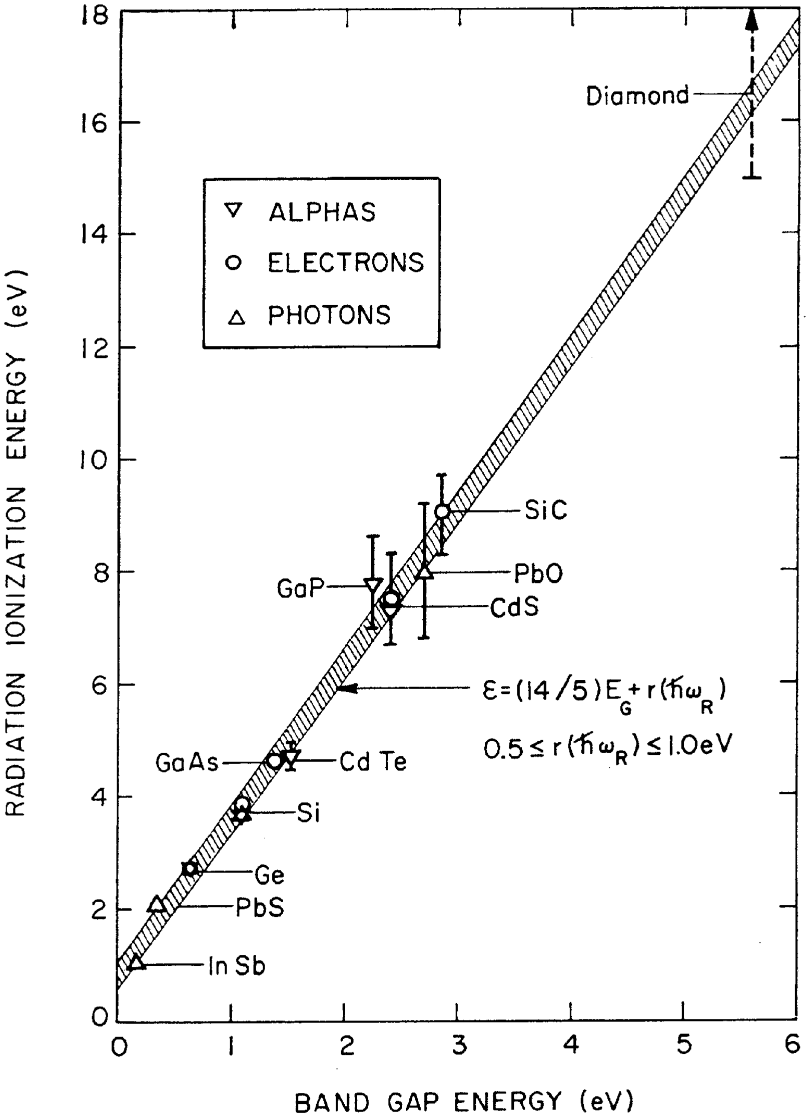
1) Conservation of energy

2) Conservation of momentum

→ additional energy excites phonons

$$\boxed{\varepsilon_i = C_1 + C_2 * E_g}$$

Independent of material and type of radiation




C. A. Klein, J. Appl. Phys. 39,2029 (1968)

# Silicon as detector material

Energy gap : $E_g$ = 1.12 eV

Ionization energy : $\varepsilon_i$ = 3.6 eV

Density : $\rho$ = 2.33 g/cm$^3$

## Example: Estimation of generated charge

Thickness : d = 300 $\mu$m

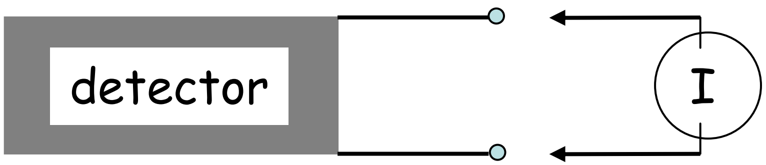
$dE/dx|_{min}$ = 1.664 MeV/g cm$^{-2}$

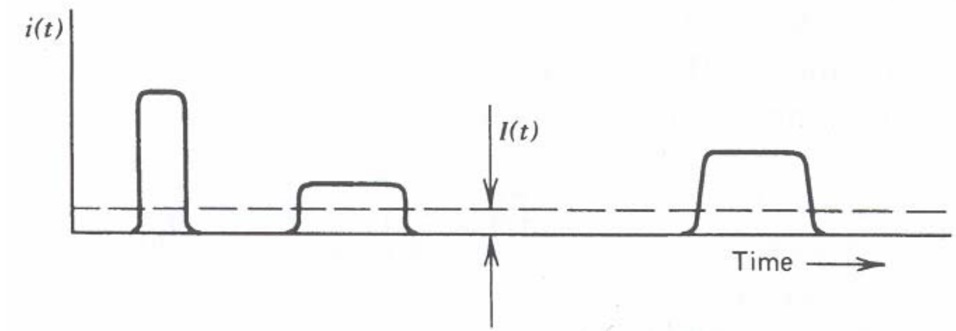
$$\longrightarrow \quad N = \rho\, d\, \frac{dE}{dx} \frac{1}{\epsilon_i} \quad = 32000$$

- This is a very strong signal and easy to measure
- High charge mobility, fast collection, $\Delta$t appr. 10 ns
- Good mechanical stability

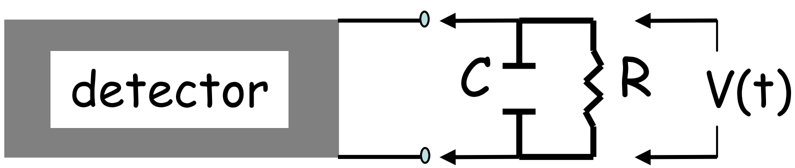
# How can we measure this ?

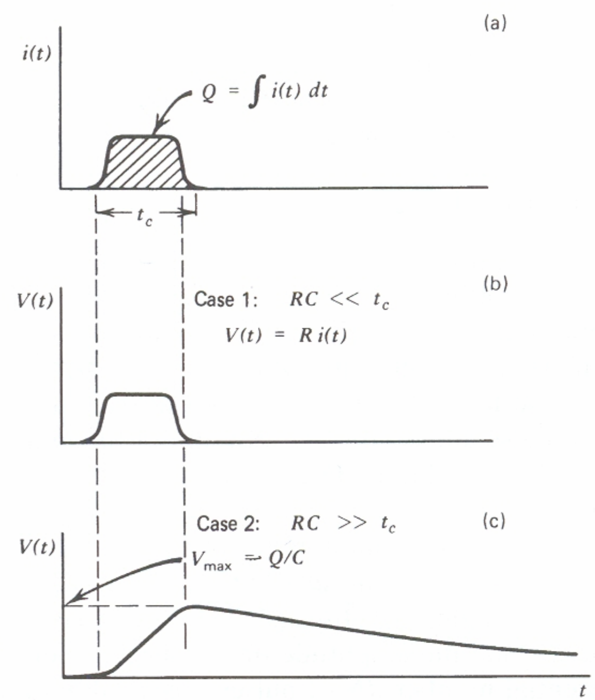
## 1) Current mode measurement:




## 2) Pulse mode measurement:



# Intermezzo:
# what is the “Fano-Factor” ?

# Fluctuations in the Signal Charge: The Fano Factor

Observation : Many radiation detectors show an inherent fluctuation in the signal charge that is less than predicted by Poisson statistics

Fano factor : $F = \dfrac{\text{Observed variance in N}}{\text{Poisson predicted variance}}$

The mean ionization energy exceeds the bandgap because conservation of momentum requires excitation of phonons

Upon deposition of energy $E_0$, two types of excitations are possible:

a) Lattice excitation with no formation of mobile charge
$\longrightarrow$ $N_x$ excitations produce $N_p$ phonons of energy $E_x$

b) Ionization with formation of a mobile charge pair
$\longrightarrow$ $N_i$ ionizations form $N_Q$ charge pairs of energy $E_i$

In other words: $E_0 = E_i N_i + E_x N_x$

The total differential : $$dE_0 = \frac{\partial E_0}{\partial N_x} dN_x + \frac{\partial E_0}{\partial N_i} dN_i = 0$$

Thus : $E_x \Delta N_x + E_i \Delta N_i = 0$

This means : If for a given event more energy goes into charge formation, less energy will be available for excitation

From averaging over many events one obtains for the variances : $$E_i \sigma_i = E_x \sigma_x$$

With $\sigma_x = \sqrt{N_x}$ (assuming Gaussian statistics)

It follows: $$\sigma_i = \frac{E_x}{E_i}\sqrt{N_x}$$

From the total energy

$$E_i N_i + E_x N_x = E_0$$

It follows:

$$N_x = \frac{E_0 - E_i N_i}{E_x}$$

$$\boxed{\sigma_i = \frac{E_x}{E_i}\sqrt{\frac{E_0}{E_x} - \frac{E_i}{E_x} N_i}}$$

Each ionization leads to a charge pair that contributes to the signal. Therefore:

$$N_i = N_Q = \frac{E_0}{\varepsilon_i}$$

and:

$$\sigma_i = \frac{E_x}{E_i}\sqrt{\frac{E_0}{E_x} - \frac{E_i}{E_x}\frac{E_0}{\varepsilon_i}} = \sqrt{\frac{E_0}{\varepsilon_i}} \cdot \underbrace{\sqrt{\frac{E_x}{E_i}\left(\frac{\varepsilon_i}{E_i} - 1\right)}}_{\text{Fano factor } F}$$

Thus, the variance in signal charge Q is given by :

$$\boxed{\sigma_Q = \sqrt{F N_Q}}$$

For silicon :

$$E_x = 0.037 \text{ eV}$$
$$E_i = E_g = 1.1 \text{ eV}$$
$$\varepsilon_i = 3.6 \text{ eV}$$

$\longrightarrow$ F = 0.08 (exp. Value: F = 0.1)

$$\downarrow$$

$$\sigma_Q \approx 0.3\sqrt{N_Q}$$

This means, the variance of the signal charge is smaller than naively expected.

Ref.: U. Fano, Phys. Rev. 72, 26 (1947)

Bottom line:

Only if all generated electron-hole pairs were independent:

$$\sigma_Q = \sqrt{N_Q}$$

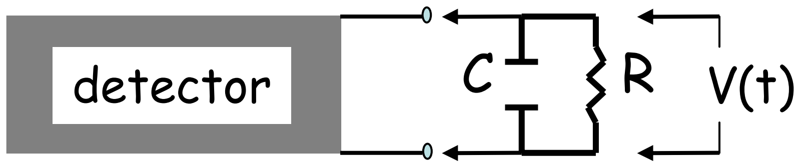
But they all originate from the same event
➔cannot be independent ➔ variance smaller
this is material dependent!

$$\sigma_Q = \sqrt{F \times N_Q}$$

With F smaller than 1.

# End Intermezzo:
# what is the “Fano-Factor” ?

Q: If a detector is this simple:




why do we need so many expensive people ?

A: Because this photoconductor detector does not do the job!

Q: Why not?

A: Thermally generated dark current >> signal current !

# Charge Carrier Density

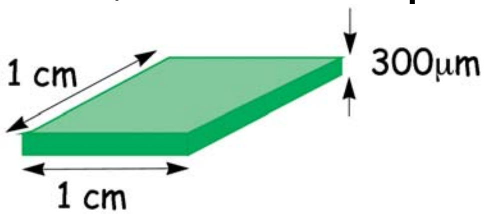
Thermally activated charge carriers in the conduction band

Their density is given by

$$n_i = \sqrt{n_V\, n_C}\, \exp\left(-\frac{E_G}{2k_B T}\right) = 1.5{\times}10^{10}\,\mathrm{cm}^{-3}$$

at room temperature

In a typical Si detector volume one obtains 4.5 x $10^8$ free carriers compared to 3.2 x $10^4$ e-h pairs for MIP




For a detection of such an event, the number of free carriers has to be substantially reduced.

This can be achieved via

a) cooling

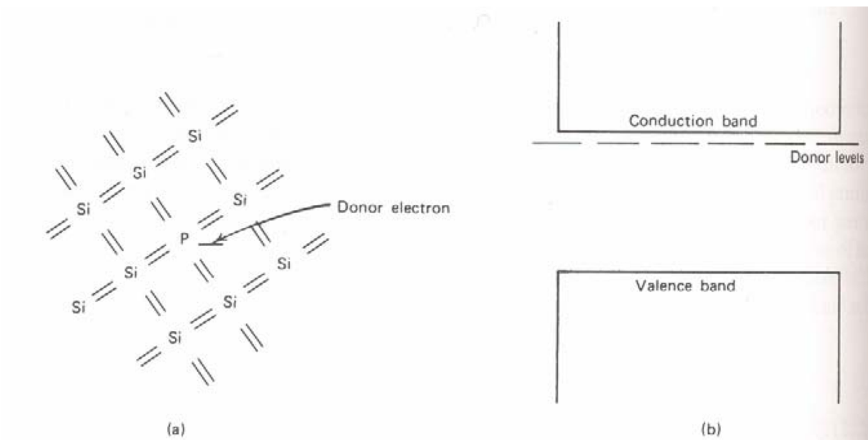
b) **pn-junction in reverse bias**

# Doping of semiconductors

By addition of impurities (doping) the conductivity of semiconductors can be tailored:

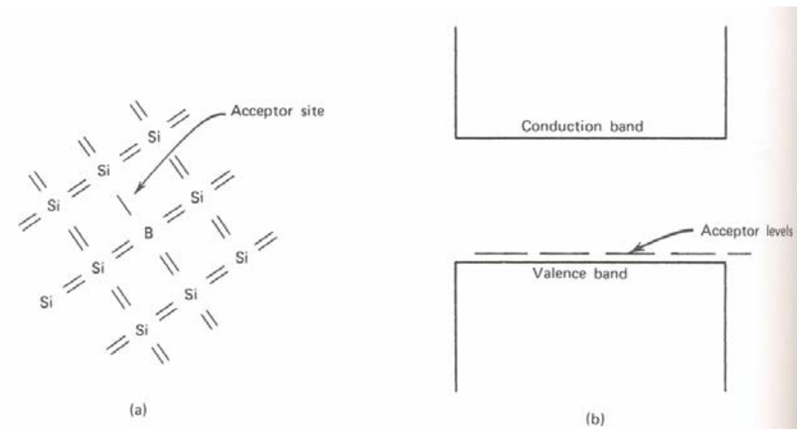
By doping with elements from group V (Donor, e.g., As, P) one obtains n-type semiconductors

One valence electron without partner, i.e. impurity contributes excess electron




By doping with elements from group III (Acceptor, e.g., B) one obtains p-type semiconductors

One Si valence electron without a partner, impurity borrows an electron from the lattice




| Use for: | Detectors | Electronics |
|---|---|---|
| Doping concentration | $10^{12}$ - $10^{15}$ $cm^{-3}$ | $10^{17}$ - $10^{18}$ $cm^{-3}$ |
| Resistivity | ~ 5 k$\Omega$ cm | ~ 1 $\Omega$ cm |

In a n-type semiconductor (Si):

- Due to doping: $N_d = 10^{15}$ electrons and 0 holes
- Due to thermal generation: $n_i = 10^{10}$ electrons and $p_i = 10^{10}$ holes

➔ $N_d$ so large that it will compensate many holes so that: $np = n_i p_i$

$$np = N_d p = 10^{15} p = n_i p_i = 10^{20} \Rightarrow p = 10^5.$$

Means mainly one type of carrier = electrons = Majority carriers
Holes are minority carriers. Opposite situation for p-type silicon

Note: $n+p = 10^{15}$ in stead of $2\times 10^{10}$ ➔ much more conducting!

Resistivity $\rho$ can be calculated by:

$$\rho = \frac{1}{eN_D \mu_e}$$

Similar expression for p-type silicon

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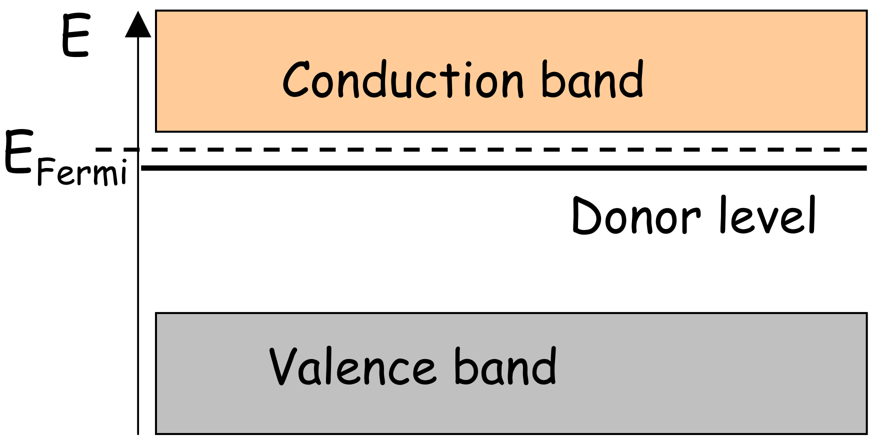


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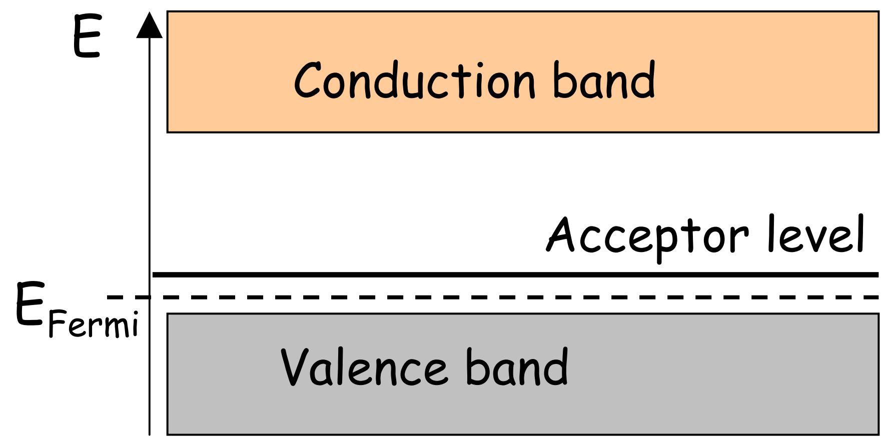


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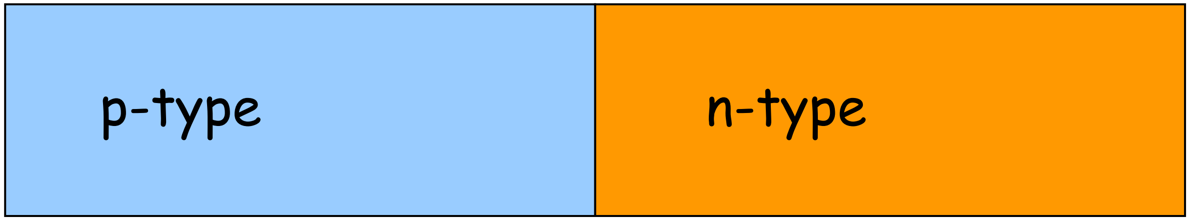
# The p-n junction (1)

Donor region and acceptor region adjoin each other :



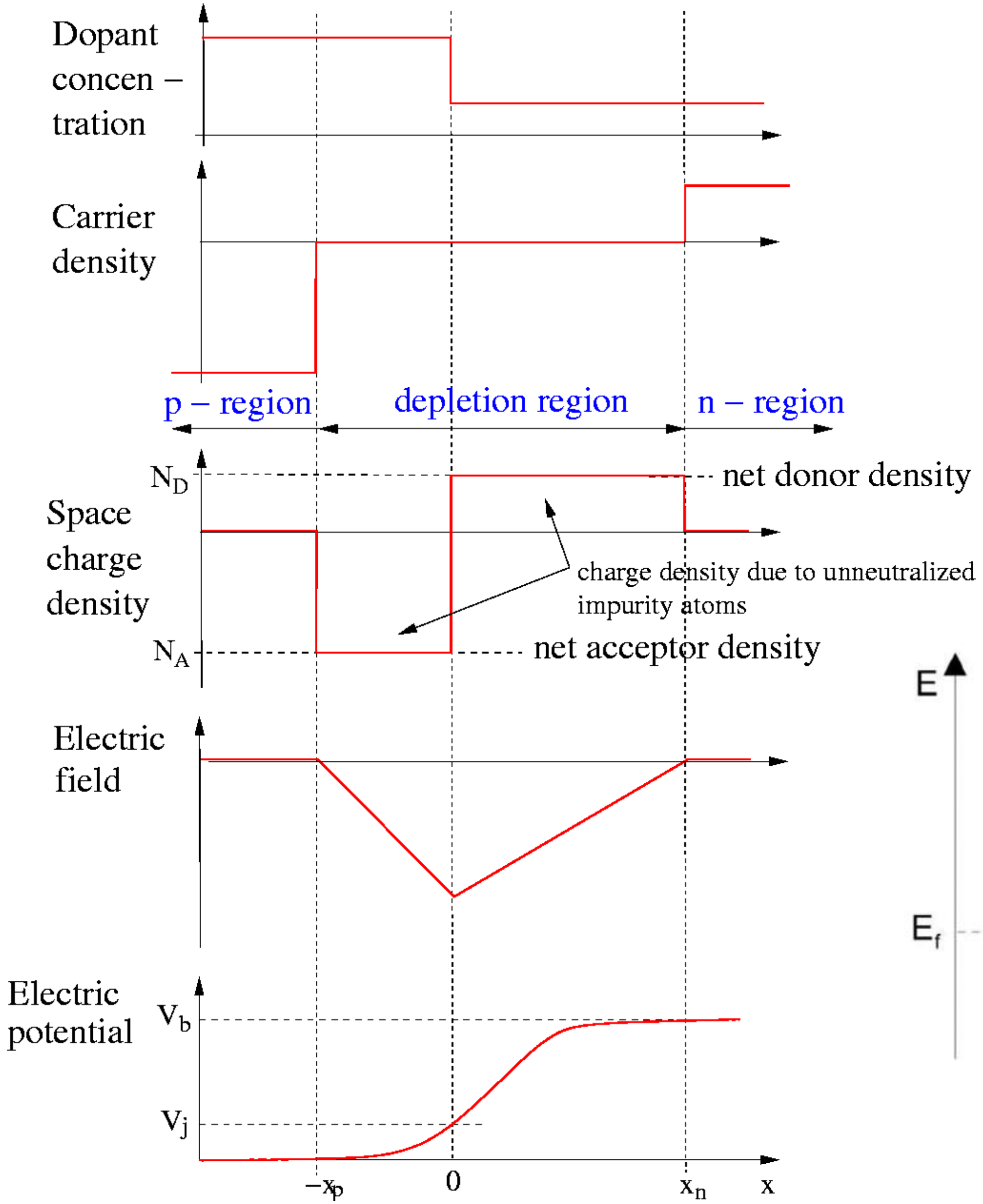

Thermal diffusion drives holes and electrons across the junction

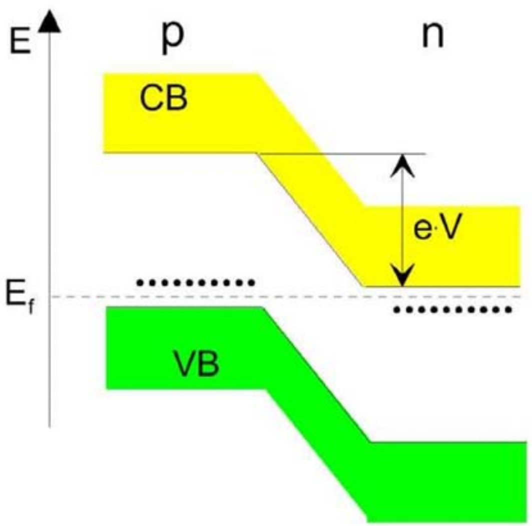
Electrons diffuse from the n- to the p-region, leaving a net positive space charge in the n-region and building up a potential (similar process for the holes)

The diffusion depth is limited when the space charge potential energy exceeds the energy for thermal diffusion

Due to preparation conditions (implantation), the p-n junction is often highly asymmetric

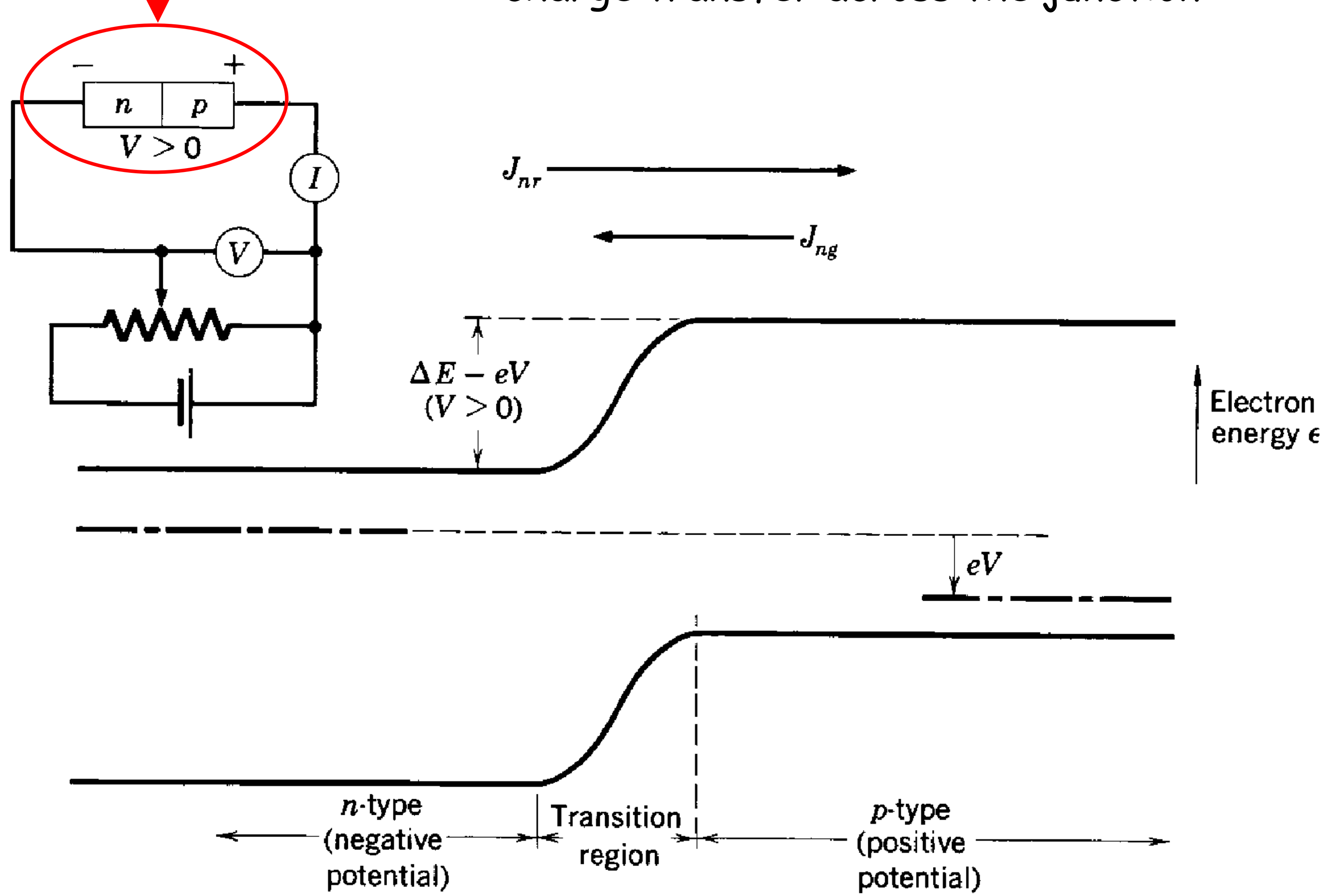
# The p-n junction (2)



# Forward bias

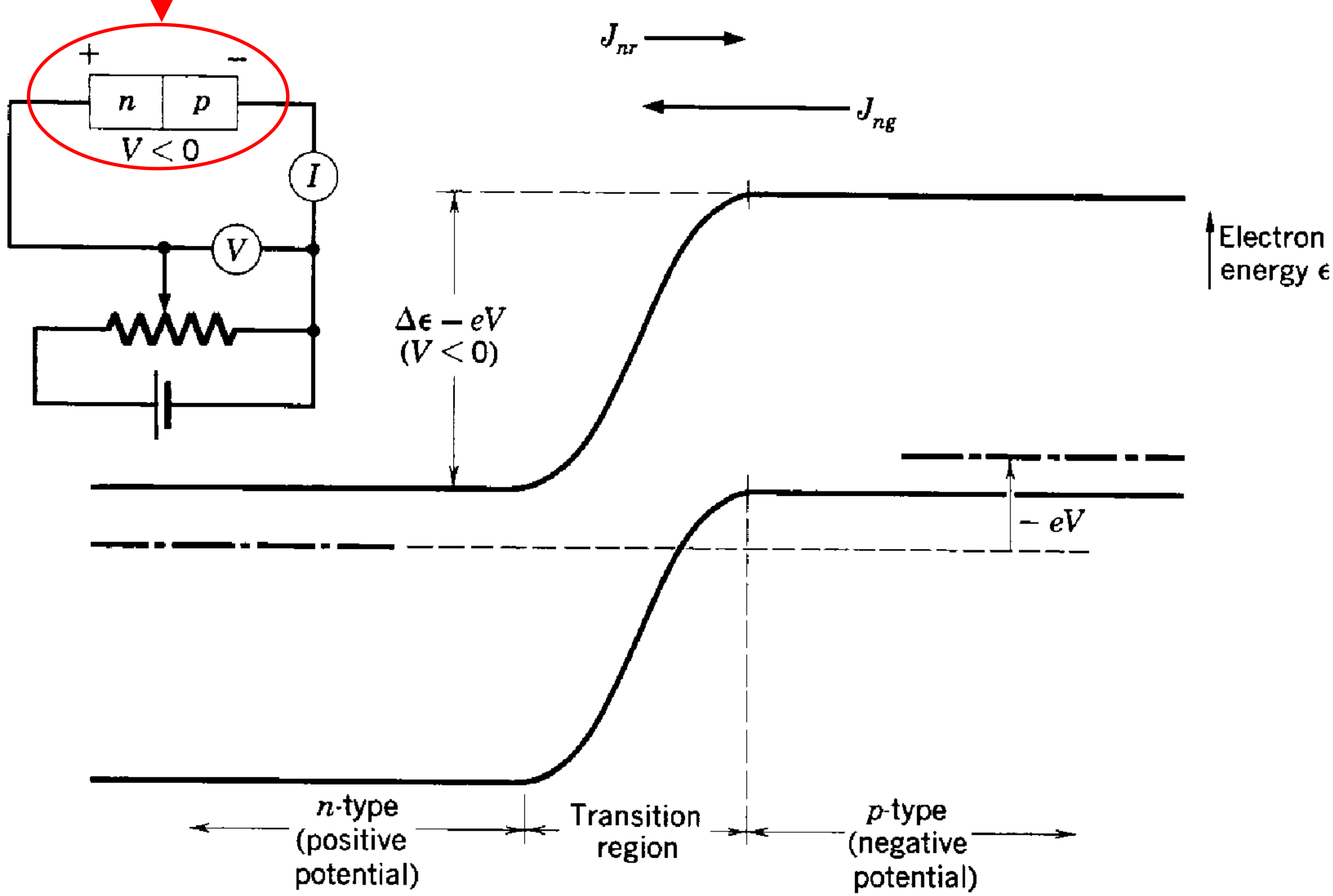
The externally applied voltage reduces the potential barrier, increasing the charge transfer across the junction




from *Kittel*, Introduction to Solid State Physics

# Reverse bias

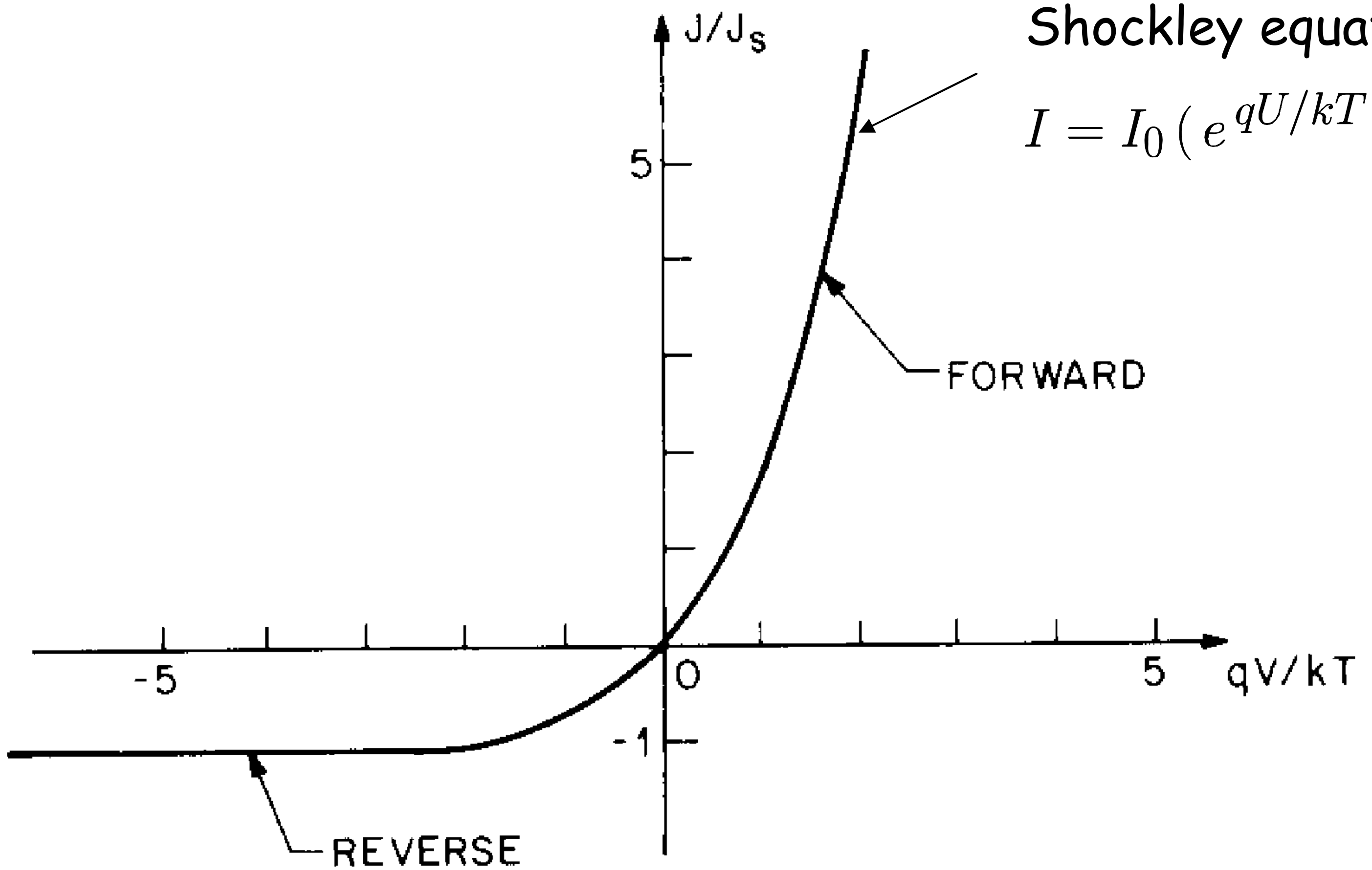
The externally applied voltage increases the potential barrier, hindering the charge transfer across the junction



# Diode current vs. voltage

Shockley equation

$$I = I_0\left(e^{qU/kT} - 1\right)$$

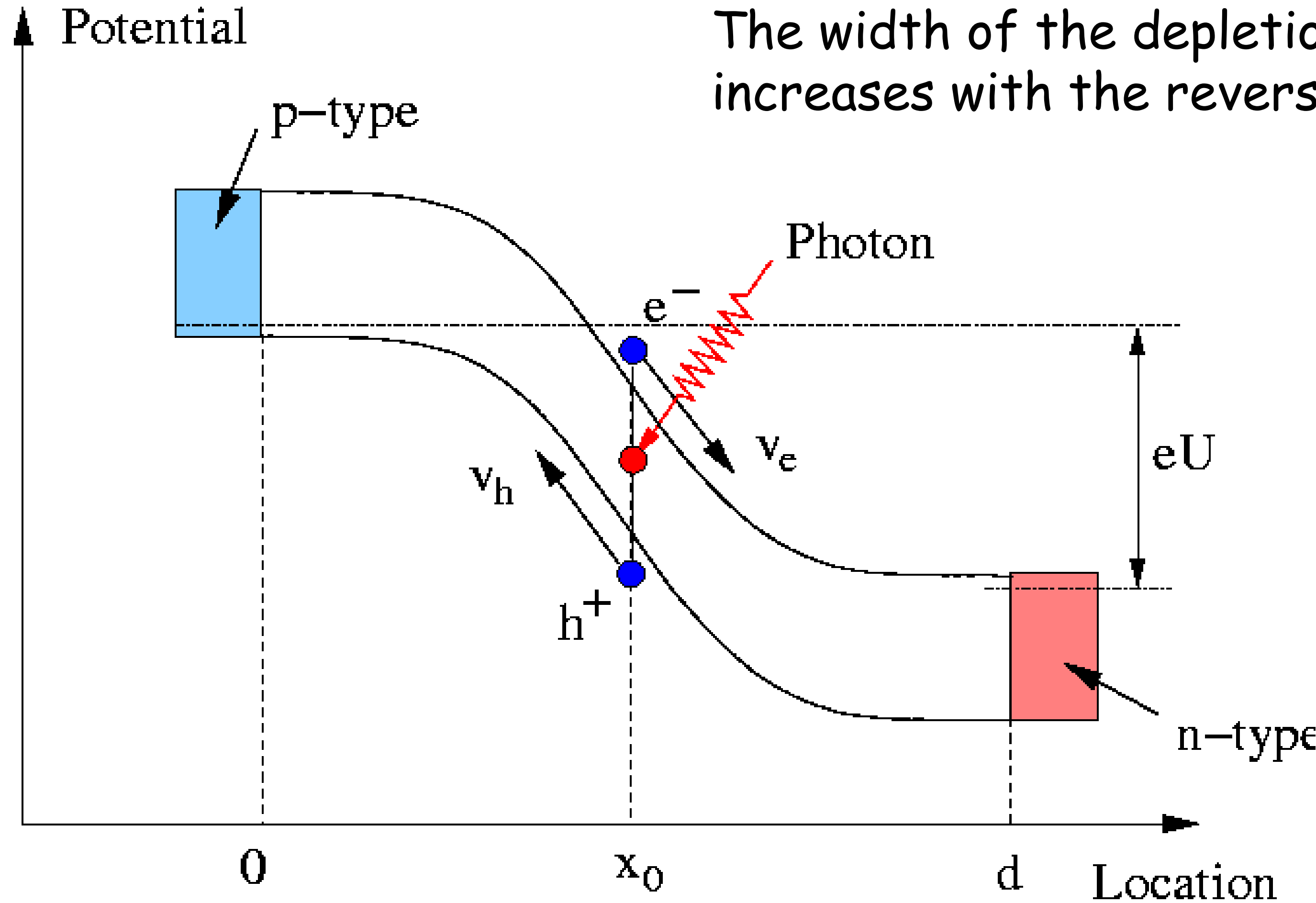



from Sze, Physics of Semiconductor Devices

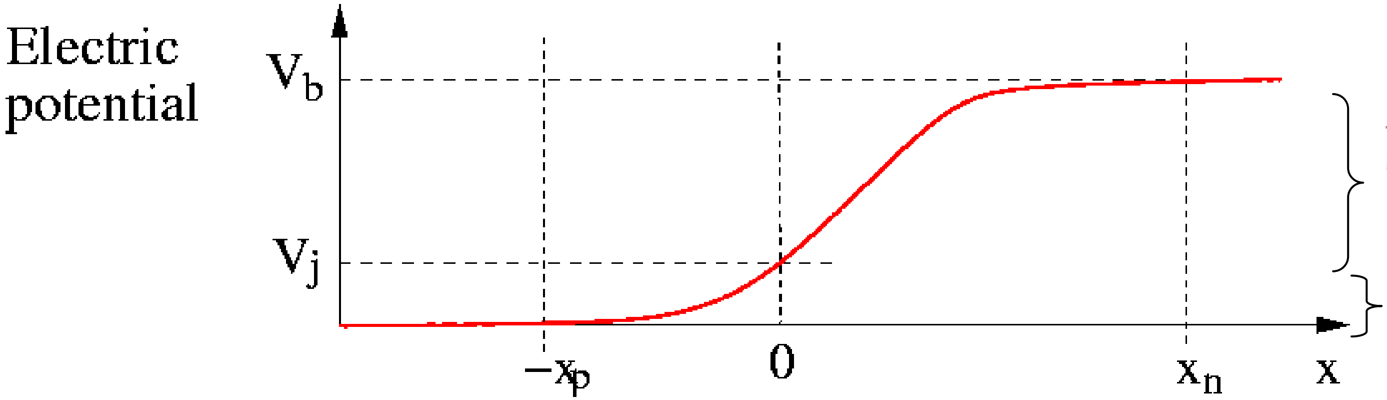
# p-n junction with reverse bias

Since the depletion region is a volume with an electric field, it can be used as a radiation detector:

The width of the depletion region increases with the reverse bias



# The pn - junction: Properties in reverse bias




$$V_b - V_j = \frac{q_e N_d x_n^2}{2\varepsilon}$$

$$V_j = \frac{q_e N_a x_p^2}{2\varepsilon}$$

What determines the shape of this curve, i.e., what is

1) The magnitude of the potential $V_b$ ?
2) The width of the depletion zone $W = x_p + x_n$ ?

$$\frac{d^2V}{dx^2} + \frac{N q_e}{\varepsilon} = 0$$

Poisson´s equation;

with $\varepsilon$ the relative permitivity

Two successive integrations: Electric field and potential

$$\frac{dV}{dx} = -\frac{q_e N_d}{\varepsilon}(x - x_n)$$

$$V = -\frac{q_e N_d}{\epsilon}\left(\frac{1}{2}x^2 - x\,x_n\right) + V_j$$

# Depletion width of the p-n junction in reverse bias

Bias voltage : $$V_b = \frac{q_e}{2\varepsilon}(N_d x_n^2 + N_a x_p^2)$$

Charge neutrality : $$N_d x_n = N_a x_p$$

Both equations can be solved for $x_p$ and $x_n$ resulting in the following expression for the depletion width :

$$W = x_n + x_p = \sqrt{\frac{2\varepsilon V_b}{q_e} \frac{N_a + N_d}{N_a N_d}}$$

If, for example, $N_a \gg N_d$, this expression simplifies to

$$W \approx x_n = \sqrt{\frac{2\varepsilon V_b}{q_e N_d}}$$