

Particle Detectors

Lecture 18

18/05/18

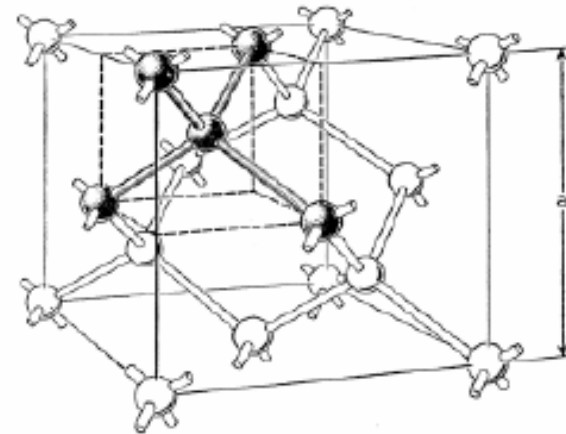
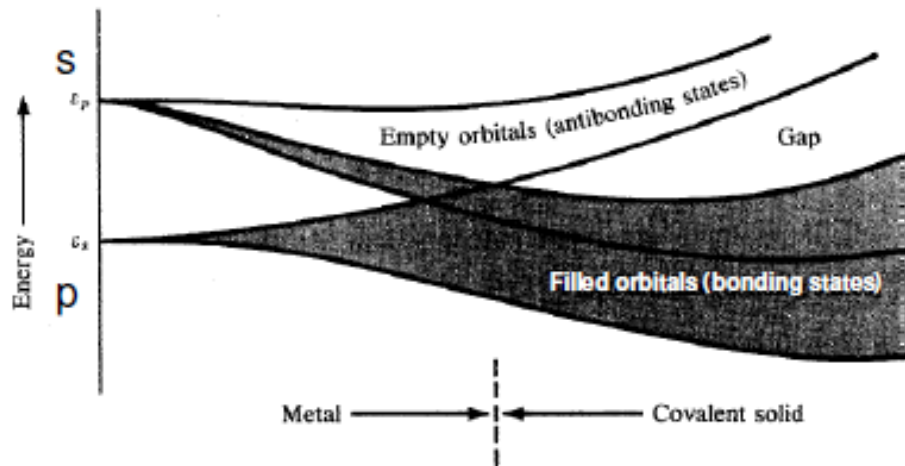
a.a. 2017-2018

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Rivelatori a stato solido

When atoms are joined to form a crystal lattice, the discrete energy levels are distorted and form continuous energy bands.

All atoms contribute.



Crystal structure of Si, Ge, diamond: Each atom shares four electrons with its four neighbors.

Bound states generate filled energy bands.

Anti-bound states generate empty bands.

Rivelatori a stato solido

In un metallo banda di conduzione e di valenza sono sovrapposte. →

molti elettroni liberi e alta conducibilità.
($n \sim 10^{28}$ elettroni/m³)

In un semiconduttore la banda di valenza e quella di conduzione non sono sovrapposte. La banda di valenza è **quasi** piena e quella di conduzione **quasi** vuota. La **GAP** fra le due bande è ~ 1.1 eV nel silicio →

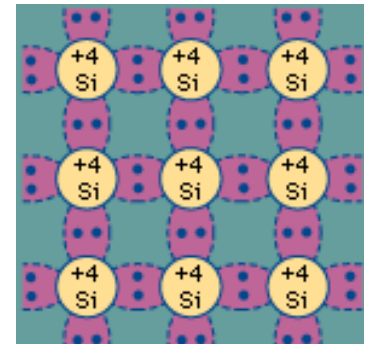
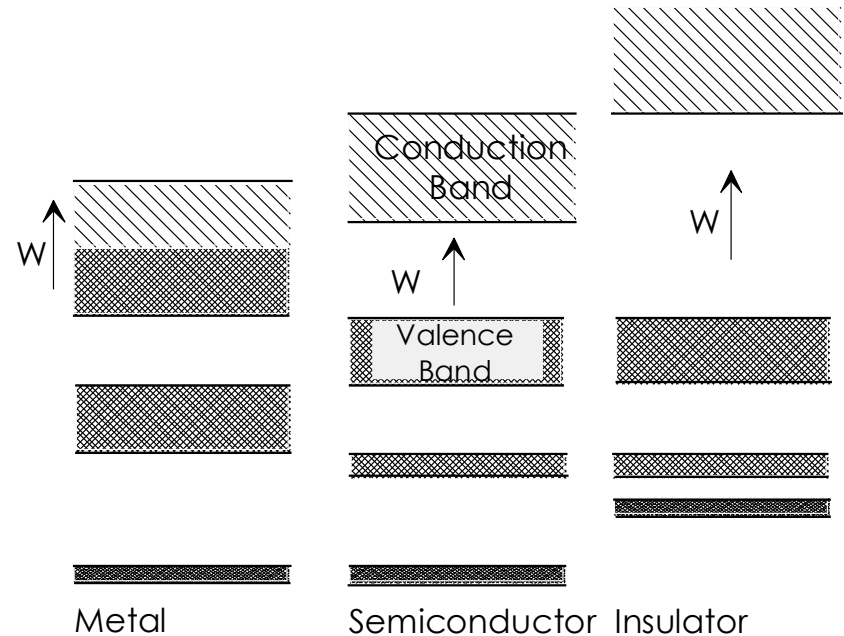
La conducibilità dipende dalla temperatura, cresce al crescere della temperatura.

In un isolante banda di conduzione e di valenza sono separate da una gap grossa (~ 8 eV in SiO₂ e ~ 5 eV nel diamante) →

Bassa conducibilità ($n \sim 10^7$ elettroni/m³).

Il silicio ha in totale 14 elettroni di cui 4 di valenza → il nucleo ionico ha carica +4.

Siccome gli elettroni di valenza servono ad unire gli atomi adiacenti, sono strettamente legati al nucleo a 0 K → bassa conducibilità.

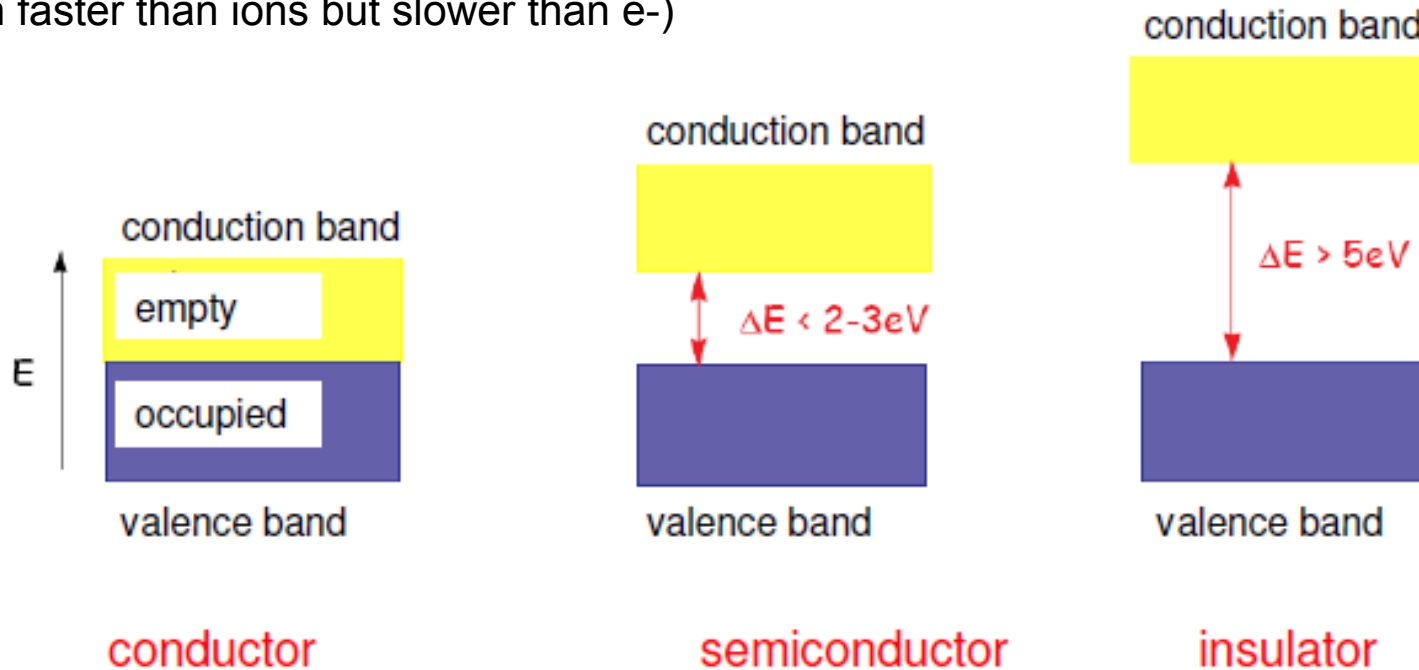


Conductivity

In semiconductors there are 2 charge carrier types: electrons and holes.

Holes are e- vacancies which behave as positive charges.

Holes "play" the same role of ions in gas but they are much faster → contribute to signal
(nb: much faster than ions but slower than e-)



The probability that an electron occupies a certain energy level is given by the Fermi-Dirac-Distribution:

$$f_e(E) = \frac{1}{e^{(E-E_F)/kT} + 1} \quad \text{and for holes} \quad f_h(E) = 1 - f_e(E) = \frac{1}{e^{(E_F-E)/kT} + 1}$$

For intrinsic semiconductors (e and h concentration equal): $E_F = E_{\text{gap}}/2$

For particles with $(E-E_F) \gg kT$, Maxwell Boltzmann statistics apply

Rivelatori a stato solido

Energy required for creation of an electron-hole pair

Ionization Energy > Band Gap

Formation of e-h pair requires both ...

1. Conservation of energy
 2. Conservation of momentum
- ⇒ additional energy excites phonons

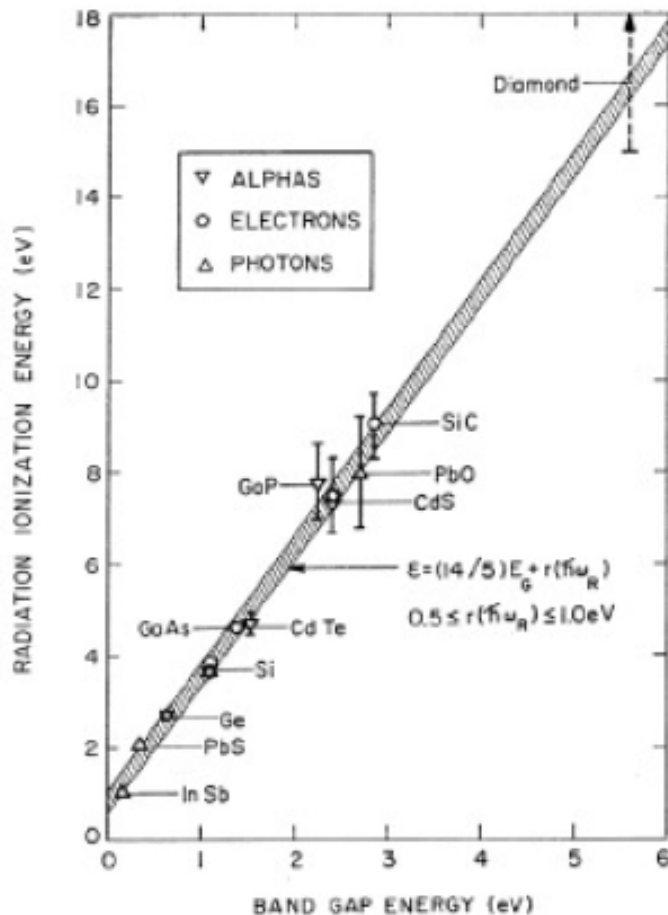
Ratio $E_{\text{ion}}/E_{\text{Gap}}$ independent of

- material
- type of radiation

Reason: Fraction of energy going into phonons (momentum transfer) is approximately the same for all semiconductors.

Compare with gas: $w_{\text{gas}} \sim 30 \text{ eV}$

Small w_i means large number of pairs:
no amplification required for the signal



Semiconductors General

Material	Z	Bandgap [eV]	Mobility [cm ² /Vs]		Density g/cm ³
			electrons	holes	
Si	14	1.1	1350	480	2.3
Ge	32	0.7	3800	1800	5.3
Diamond	6	5.5	1800	1200	3.5
GaAs	31-33	1.5	8600	400	5.4
AlSb	13-51	1.6	200	700	4.3
GaSe	31-34	2.0	60	250	4.6
CdSe	48-34	1.7	50	50	
CdS	48-16	2.4	300	15	4.8
InP	49-15	1.4	4800	150	
ZnTe	30-52	2.3	350	110	
WSe ₂	74-34	1.4	100	80	
BiI ₃	83-53	1.7	680	20	
Bi ₂ S ₃	83-16	1.3	1100	200	6.7
Cs ₃ Sb	55-51	1.6	500	10	
PbI ₂	82-53	2.6	8	2	6.2
HgI ₂	89-53	2.1	100	4	6.3
CdTe	48-52	1.5	1100	100	6.1
CdZnTe	48-30-52	1.5-2.4			

Semiconductor Detectors

Property		Si	Ge	GaAs	Diamond
Z		14	32	31/33	6
A		28.1	72.6	144.6	12.0
Band gap	[eV]	1.12	0.66	1.42	5.5
radiation length X_0	[cm]	9.4	2.3	2.3	18.8
mean energy to generate eh pair	[eV]	3.6	2.9	4.1	~ 13
mean E-loss dE/dx	[MeV/cm]	3.9	7.5	7.7	3.8
mean signal produced	[$e^-/\mu\text{m}$]	110	260	173	~ 50
intrinsic charge carrier concentration n_i	[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 compromise for strip detectors

Ge

- small band gap \rightarrow high amount of charge produced \rightarrow good for energy measurements
- high intrinsic charge carrier concentration \rightarrow has to be cooled (liquid N_2)

GaAs

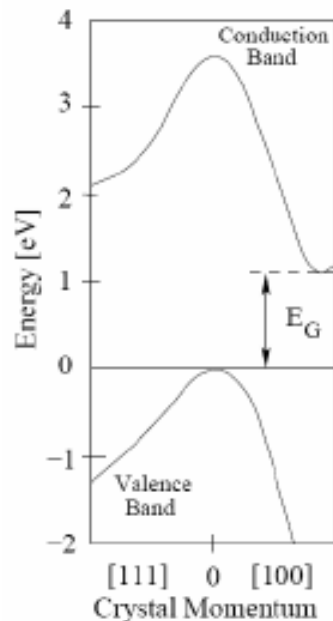
- good ratio generated charge/ noise
- but: charge collection efficiency strongly dependent on purity and composition

- radiation hard

Diamond

- radiation hard, but still quite expensive
- charge collection length $\sim 80\mu\text{m}$

Semiconductors: Silicon



- indirect band gap $\delta E = 1.12 \text{ eV}$

compare to $kT = 0.026 \text{ eV}$ at room temp. \rightarrow dark current under control

(indirect: maximum of valence band and minimum of conduction band at different crystal momenta $\rightarrow E$ and p can only be conserved if additional phonons are excited)

- energy per electron-hole pair: 3.6 eV

(rest in phonons, compared to $\sim 30 \text{ eV}$ for noble gases)

- high density compared to gases: $\rho = 2.33 \text{ g/cm}^3$

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

$$N = 1.664 \text{ MeV/g cm}^2 \times 2.33 \text{ g/cm}^3 / 3.6 \text{ eV}$$

$\rightarrow \sim 32000 \text{ electron-hole pairs in } 300 \mu\text{m (MIP)}$

- good mechanical stability \rightarrow possible to produce mechanically stable layers of this thickness

- large charge carrier mobility

\rightarrow fast charge collection $\delta t \sim 10 \text{ ns}$

Rivelatori a stato solido

Riassumendo:

- In un semiconduttore intrinseco (e.g. il Silicio, IV gruppo) ci sono 4 elettroni nella banda di valenza.
- A temperatura ambiente, la distribuzione dell'energia termica (Maxwell-Boltzman) fa sì che una frazione degli elettroni sia in banda di conduzione, cioè liberi di muoversi nel volume del solido.
- Il legame vacante (cioè l'assenza di un elettrone) si comporta come una carica positiva, detta lacuna, che si “sposta” quando viene riempita da un elettrone
- Quindi in un semiconduttore esistono due portatori di carica, analoghi alle coppie e- ione dei gas.
- La concentrazione intrinseca all'equilibrio è $n_i = p = n$ ed anche $np = n_i^2 = N_c N_v e^{-E_g/kT}$ con N_c ed N_v densità degli stati nella banda di conduzione e di valenza, rispettivamente. L'ultima relazione è valida per qualsiasi materiale semiconduttore anche drogato.
- Nel silicio puro $E_g = E_c - E_v = 1.12 \text{ eV}$ ed $n_i = 1.45 \times 10^{10} \text{ cm}^{-3}$ a temperatura ambiente.

Choice of material

$$Q_{\text{dep}} = e(dE/dx)(X/w)$$

$$\rightarrow y = x/X_0$$

$$= ey [(dE/dy)/w]$$

For Ionization chambers, in principle any material could be used that allows for charge collection at a pair of electrodes.

	Gas	liquid	solid
Density	low	moderate	high
Z	low	moderate	moderate
Ionization energy ϵ_i	moderate	moderate	small
Signal velocity	moderate	moderate	fast

Ideal material for "high" Q_{dep} and low σ_Q

- high specific E loss dE/dy
- low effective ionisation energy w
- Thickness y compromise for high Q collected and low multiple scattering (typically $< 1\% X_0$)

High electric field
in detection volume

→ fast response

better charge collection efficiency

→ Solid state detectors
offer the best compromise

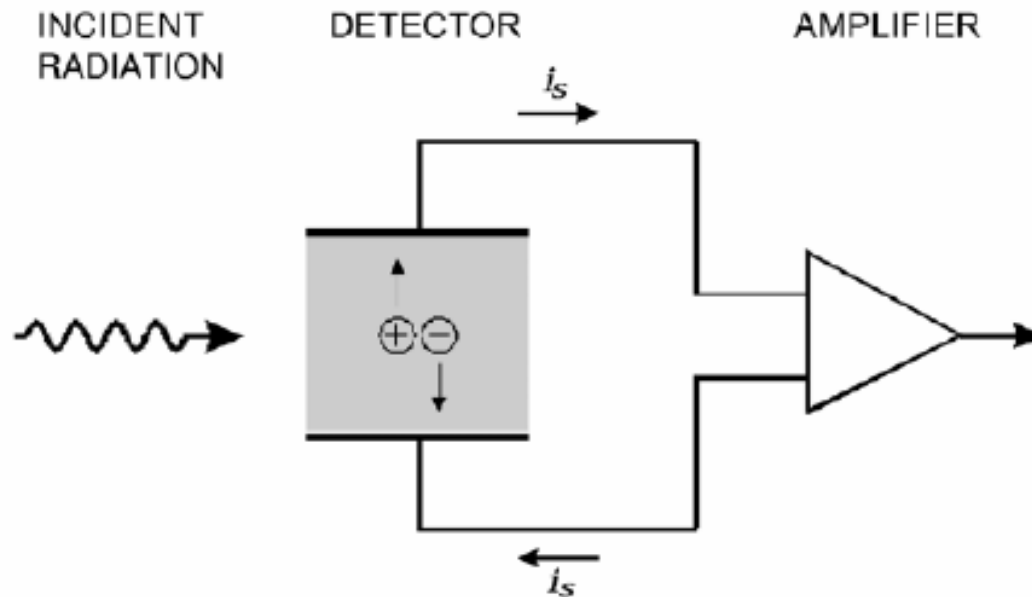
Semiconductor Detectors

Generally, Two kinds of solid state detectors can be distinguished:

- Photo resistors: Resistance changes with irradiation
- Photo diode: Depleted semiconductor layer with typically large electric field used as active zone

→ionization chamber

There is not charge multiplication, only charges due to ionization are collected



Semiconductor Detectors

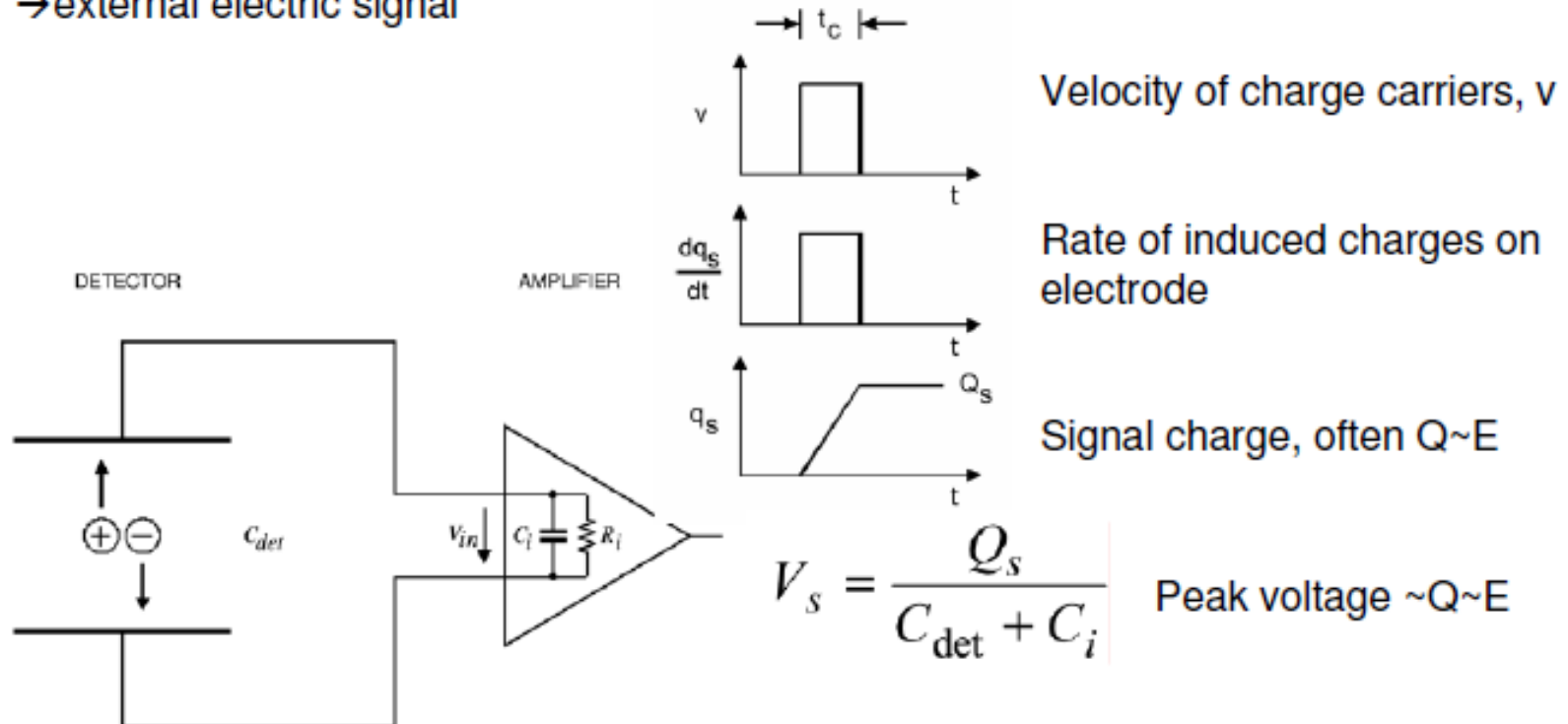
The same considerations made for gas ionization chambers apply for charge collection in semiconductor detectors

Detection volume with electric field

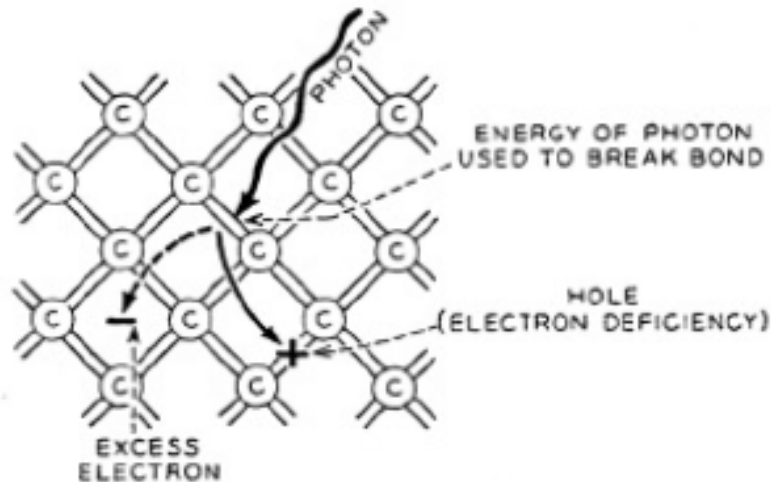
Charge carrier pairs generated via ionization

Charges drift in the electric field

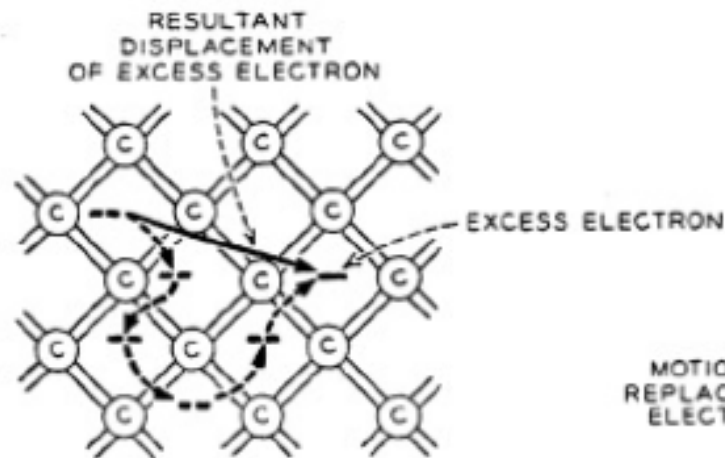
→ external electric signal



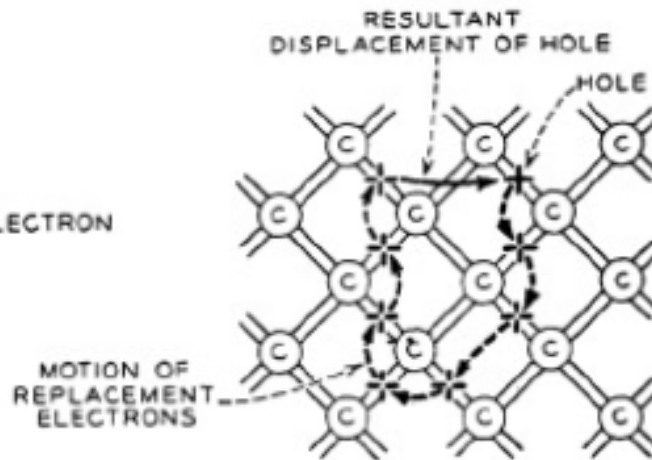
Charge transport



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



(c) RANDOM MOTION OF AN EXCESS ELECTRON



(d) RANDOM MOTION OF A HOLE

Charge transport is different for electrons and holes: electrons scatter and drift in the crystal lattice as single particles. Holes move via successive replacements by electrons → their transport properties are determined by the collective motion of electrons. Motion of holes is slower than for electrons. Electrons and holes have different mobilities and diffusion coefficients

Drift velocity in Silicon

$$v_N = -\frac{q\tau_c}{m_N} E = -\mu_N E$$

$$v_p = \frac{q\tau_c}{m_p} E = \mu_p E$$

with $\tau_c = 10^{-12}$ s being the average time between collisions with irregularities in the crystal lattice due to thermal vibrations, impurities and defects.

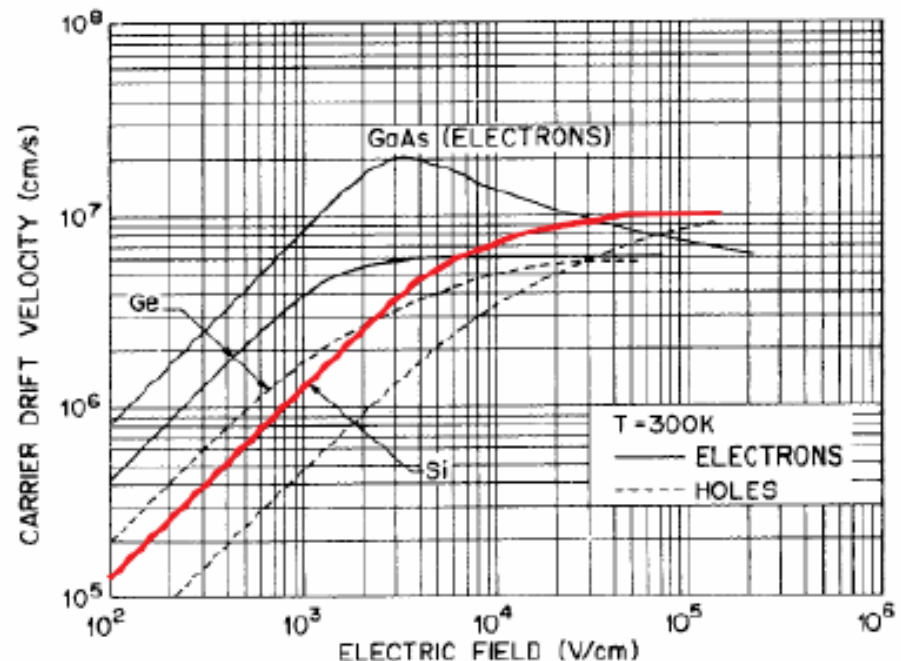
m_N, m_p effective mass of the electrons, holes: Inverse of the 2. derivative of the energy with respect to the momentum at the minimum of the conduction band (e), and the maximum of the valence band (p), respectively.

Only valid for sufficiently small field strength.

- \rightarrow mobility $\mu = 1450 \text{ cm}^2/\text{Vs}$ for electrons and $450 \text{ cm}^2/\text{Vs}$ for holes.
- For larger field strengths: Saturation of drift velocities.
- Typical fields in Si with $V_{\text{bias}} = 100 \text{ V}$, $d = 300 \text{ }\mu\text{m}$:

$$E = 100 \text{ V} / 300 \mu\text{m} = 3.3 \times 10^3 \text{ V/cm}$$

$$\text{charge collection time } t = \frac{d}{v_{\text{Drift}}} \approx 3 - 15 \text{ ns}$$



Rivelatori a stato solido

Resistività.

La resistività ρ (inverso della conducibilità) del materiale è connessa alla densità dei portatori di carica ed alla mobilità:

$$\rho = \frac{1}{q(\mu_n n + \mu_p p)}$$

Deriva immediatamente dalla legge di Ohm:

$$\mathbf{j} = \mathbf{E}/\rho$$

e dalla definizione di densità di corrente

$$\mathbf{j} = en\mathbf{v}_D = en\mu\mathbf{E}$$

dove $q=1.6 \times 10^{-19} \text{ C}$ è la carica dell'elettrone.

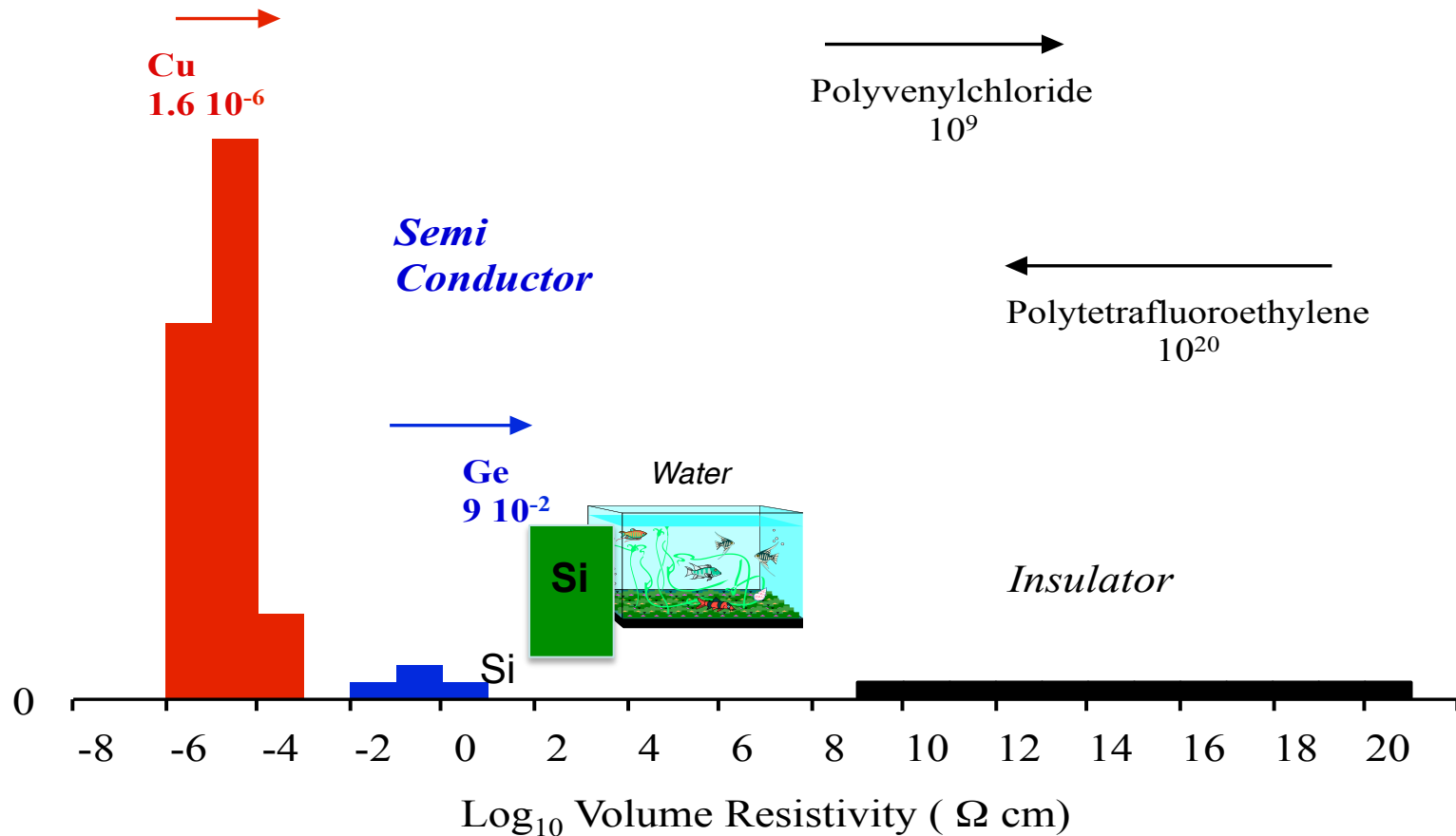
Per il silicio intrinseco $\rho=235 \text{ K}\Omega/\text{cm}$.

Per il silicio drogato è minore in quanto ci sono più portatori di carica.

Parametro operativo importante di un rivelatore perché determina correnti, tensione di lavoro,...

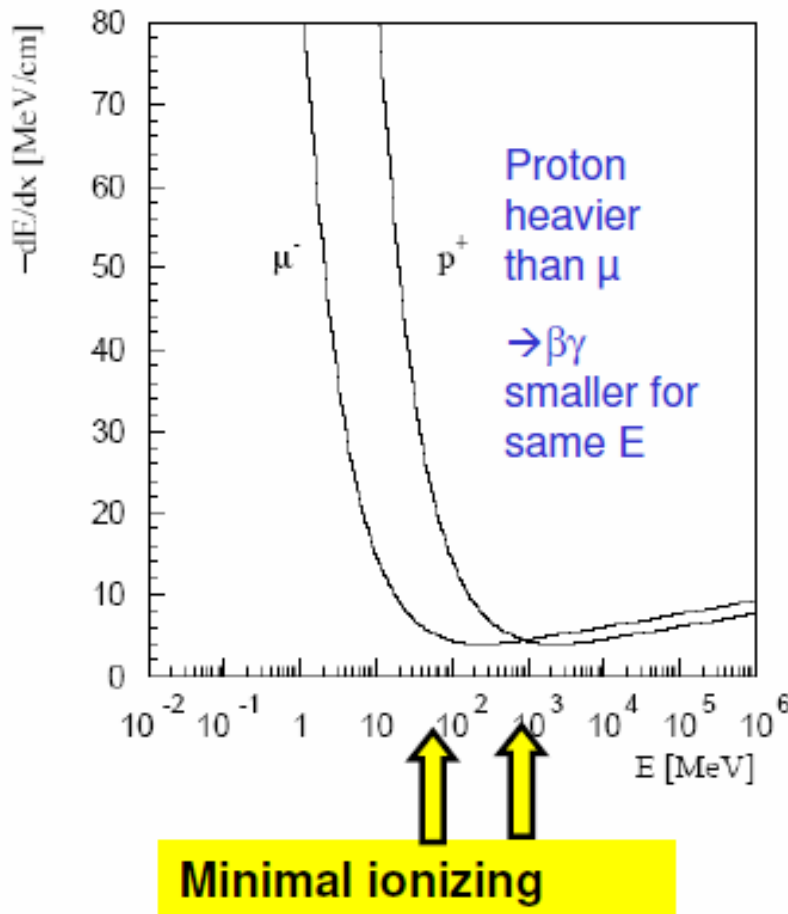
Rivelatori a stato solido

Conductor



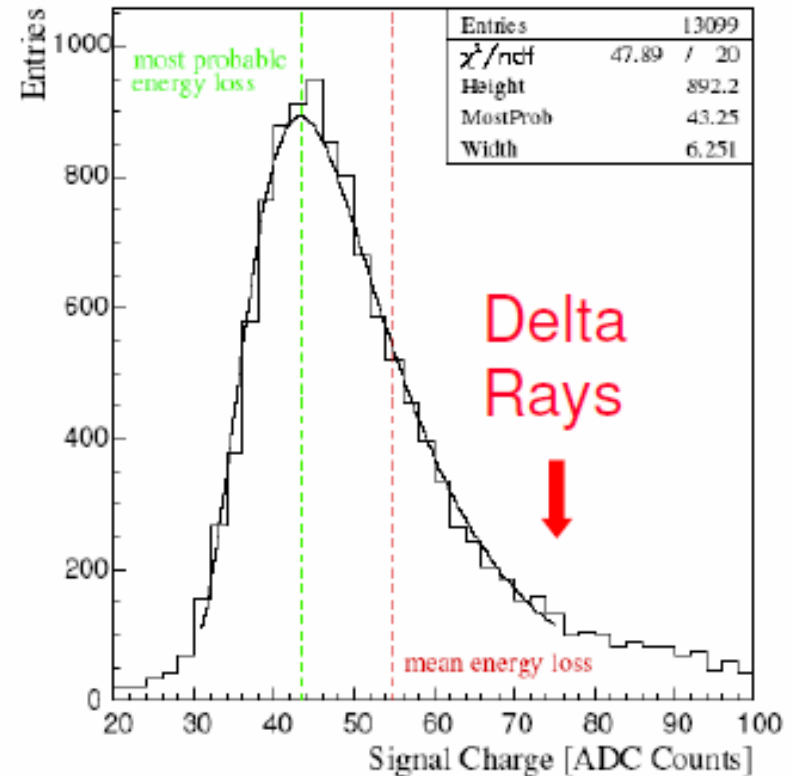
Rivelatori di Particelle

Number of pairs in Silicon



Bethe-Bloch Formula

24000 most probable



1 Mip = on average 32500 e-hole pairs in 300 μ m silicon

Landau distribution

Signal in Silicon

- Conduction band really empty only at $T=0$
- Distribution according Fermi-Dirac Statistics
- Number of electrons in conduction band at room temp.:

$$n_1 = \sqrt{n_V n_C} \cdot \exp\left(-\frac{E_{Gap}}{2kT}\right) = 1.5 \times 10^{10} \text{ cm}^{-3}$$

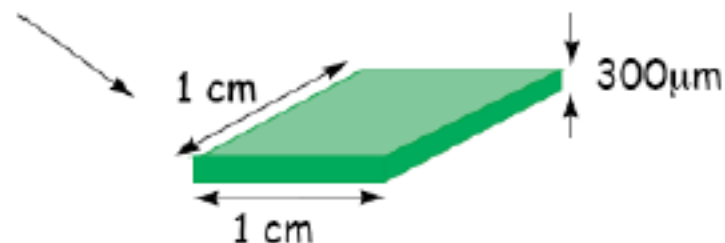
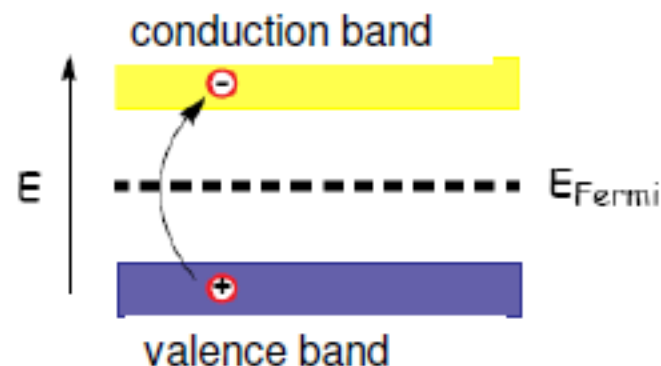
→ Ratio of electrons in conduction band 10^{-12}
(Silicon $\sim 5 \times 10^{22}$ Atoms/cm³)

- A volume of **intrinsic Si** of 1 cm x 1 cm x 300 μm contains $\sim 4.5 \times 10^8$ free charge carriers at RT compared to only 2.3×10^4 electron-hole pairs for a MIP.

→ To detect this signal, the number of free charge carriers has to be reduced drastically.

Possibilities are:

- cooling
- pn-junction in reverse bias



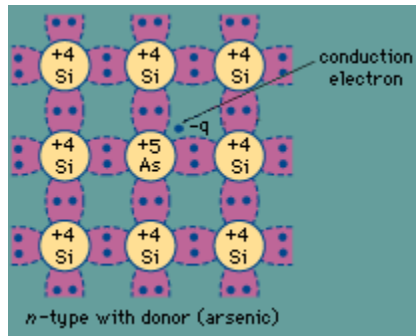
Rivelatori a stato solido

Drogaggio dei semiconduttori



Inserendo nel reticolo cristallino atomi opportuni e' possibile "modulare" le proprieta' elettriche dei semiconduttori

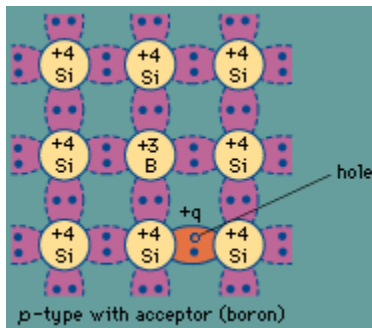
TIPO n



Aggiungendo al silicio impurità del V gruppo (**Pentavalenti: antimonio, fosforo, arsenico**) con 5 elettroni di valenza (**donori**) facciamo diventare il silicio di tipo **n**.

Gli elettroni sono portatori di maggioranza

TIPO p

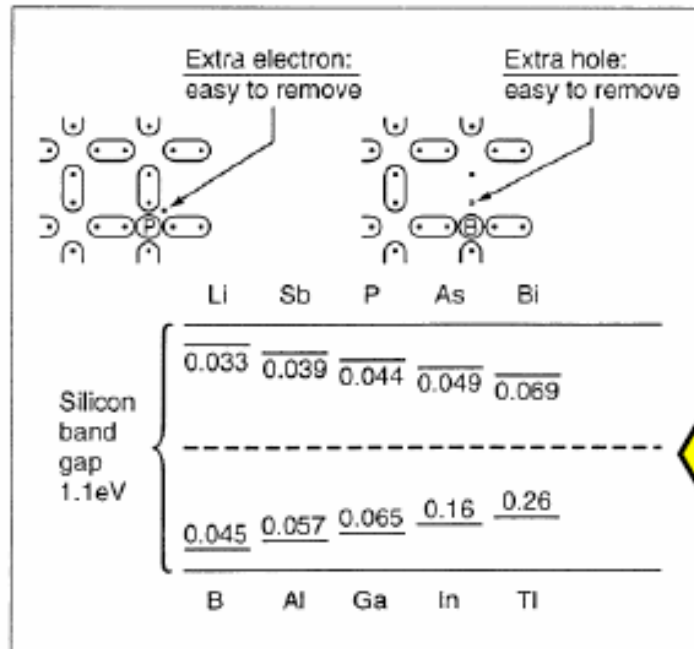


Aggiungendo impurità del III gruppo (**Trivalenti: boro, gallio, indio**) con tre elettroni di valenza (**accettori**), il silicio diventa di tipo **p**.

Le lacune sono portatori di maggioranza

Silicon doping

- Pure silicon has a very high resistance at room temp. (235 kOhm cm)
- Doping: A few silicon atoms can be replaced by atoms of an element of the 3rd main group (i.e. Boron) → p type, or of the 5th main group (i.e. Phosphorus) → n type.



Typical doping concentration 10^{11} !

n type: Fermi level in upper half
p type: Fermi level in lower half

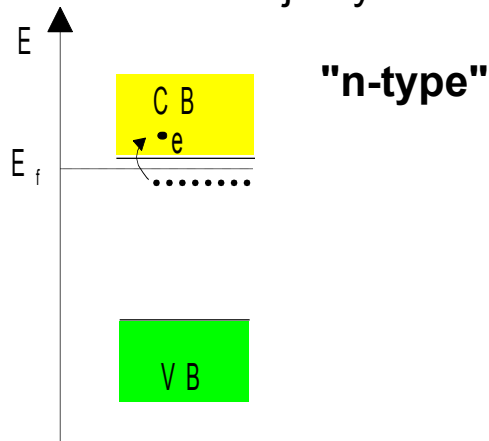
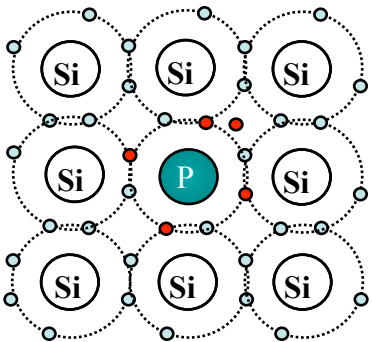
Important: Charge carriers only weakly bound.

Doping and resistivity

■ Doping: n-type Silicon

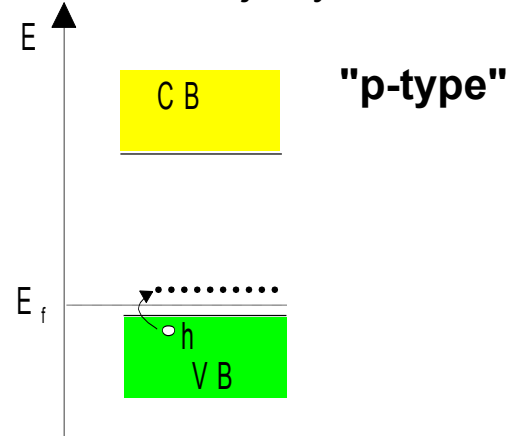
- add elements from Vth group
⇒ **donors** (P, As,...)
- electrons are majority carriers

e.g. Phosphorus



■ Doping: p-type Silicon

- add elements from IIIrd group
⇒ **acceptors** (B,...)
- holes are the majority carriers



■ Resistivity

- carrier concentrations n , p
- carrier mobility μ_n , μ_p

$$\rho = \frac{1}{q_0 (\mu_n n + \mu_p p)}$$

- Energy levels very close conduction bands.
- Energy difference $< \sim$ thermal energy $(3/2)kT = 40$ meV
- At room T, donors and acceptor levels ionized → charge carriers in conduction band
- Electrical properties determined mainly by doping

Rivelatori a stato solido

In un semiconduttore in cui le impurità sono uniformemente distribuite, la densità di carica netta δq in un elemento di volume δV è =0. Indicando con N_d la concentrazione di donori e con N_a quella di accettori si ha:

$$\frac{\delta q}{\delta V} = q(p - n + N_d - N_a) = 0$$

Mettendo a sistema con $pn = n_i^2$ si ha

$$n = \frac{1}{2} \left(N_d - N_a + \sqrt{(N_d - N_a)^2 + 4n_i^2} \right)$$

$$p = \frac{1}{2} \left(N_a - N_d + \sqrt{(N_a - N_d)^2 + 4n_i^2} \right)$$

Tipicamente $N_a - N_d \gg n_i^2$

Doping:

Tipo n: $N_d \gg N_a$

$$n = N_d - N_a \approx N_d \quad \Rightarrow \quad \rho = \frac{1}{q\mu_n N_d}$$

Tipo p: $N_a \gg N_d$

$$p = N_a - N_d \approx N_a \quad \Rightarrow \quad \rho = \frac{1}{q\mu_p N_a}$$

	detector grade	electronics grade
doping	$\approx 10^{12} \text{ cm}^{-3}$	$\approx 10^{17} \text{ cm}^{-3}$
resistivity ρ	$\approx 5 \text{ k}\Omega \cdot \text{cm}$	$\approx 1 \text{ }\Omega \cdot \text{cm}$

La resistività è un parametro importante del silicio. Da essa dipendono parametri operativi come la tensione di lavoro, efficienza di raccolta di carica, rumore dell'apparato

Rivelatori a stato solido

La giunzione p-n.

Abbiamo visto che occorre ridurre la carica libera nel volume attivo per ottenere un rapporto fra segnale e rumore favorevole (24000 coppie di segnale vs 1.5×10^{10} di coppie termiche) occorre svuotare di carica libera il volume attivo → **diodo in polarizzazione inversa**

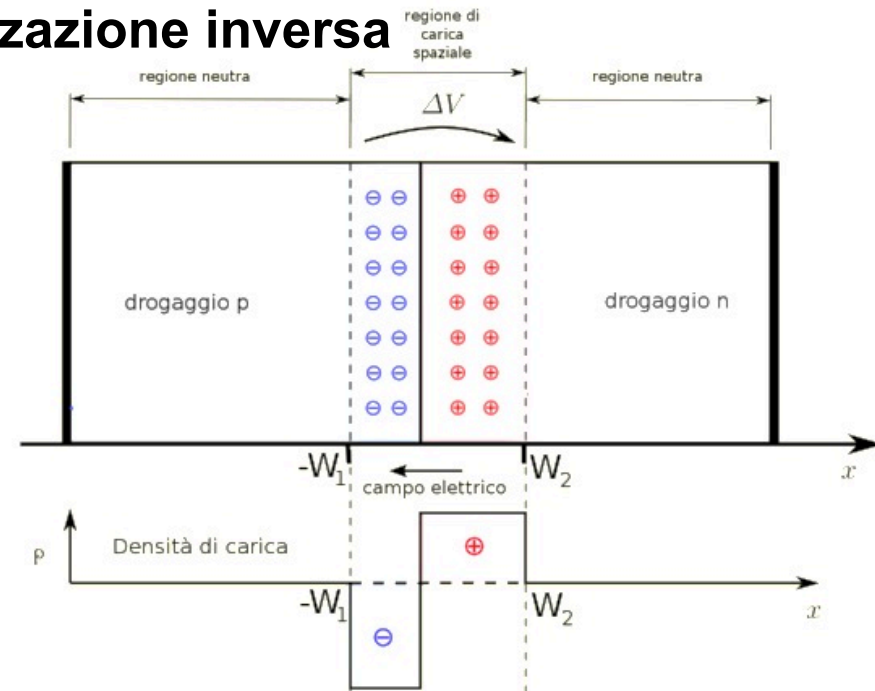
Date 2 regioni contigue di silicio
una di tipo **p** e l'altra di tipo **n**.

La giunzione e' costituita dall'interfaccia
tra la regione p ed n, in cui la densita'
di carica cambia bruscamente

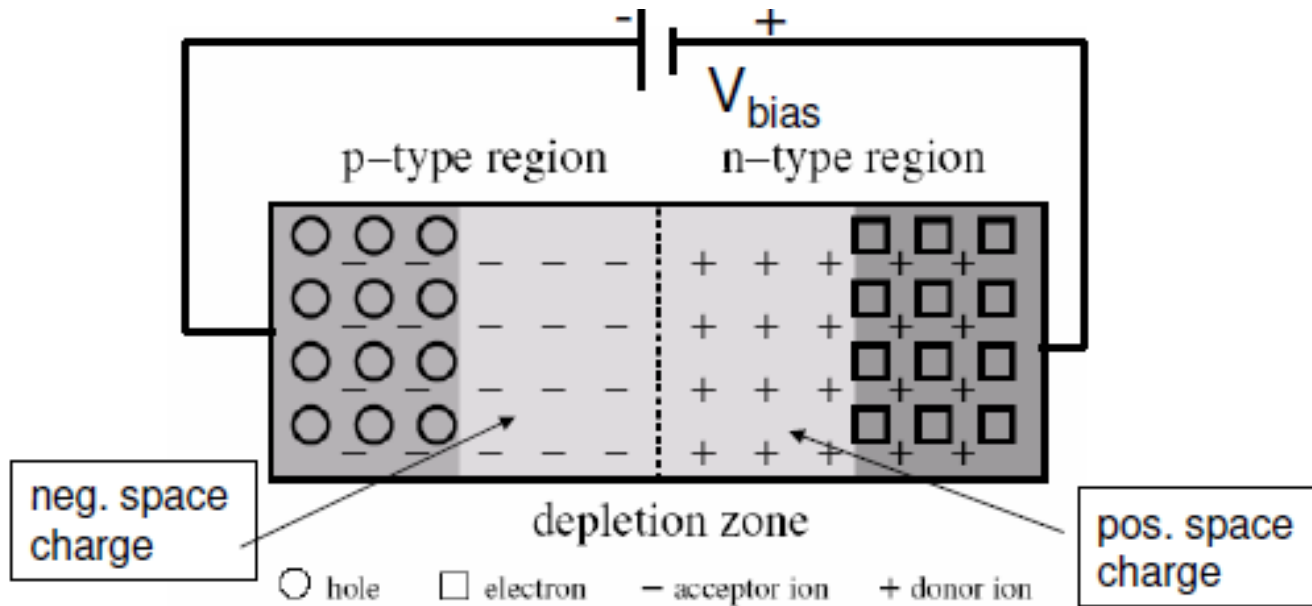
Valori tipici di drogaggio sono:

$10^{12}/\text{cm}^3$ (**n**) e $10^{15}/\text{cm}^3$ (**p**)

(molto minori che nei circuiti integrati e diodi o transistor,
nei quali la concentrazione è $\sim 10^{17(18)}/\text{cm}^3$)



P-N junction



**electrons drift towards p-side, holes
towards n-side → buildup of a potential.**

Without an external potential applied, there will be a thermal flux of charge carriers at the junction: a flux of e^- from n to p region and h from p to n region. A space charge region forms due to fixed positive ions in the n region and fixed e^- in the p region. Net flux is = 0 when the built-up electric field, or the contact potential V_c due the space charge stops further diffusion

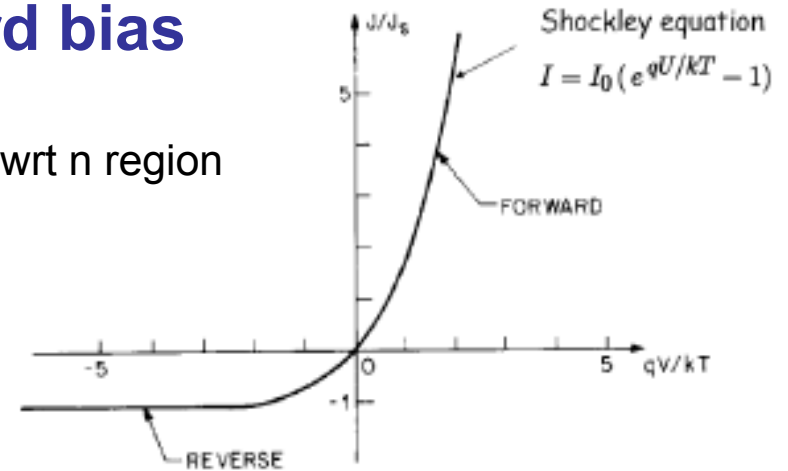
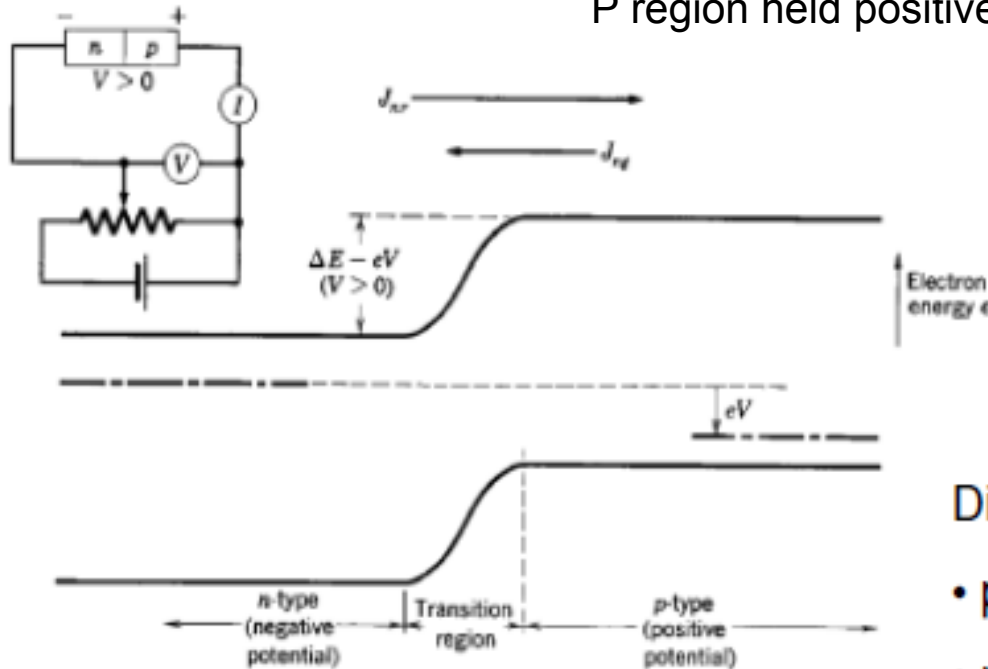
$$V_d = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2} \approx 600 \text{ mV}$$

Correnti alla giunzione

- Per es. prendiamo gli elettroni. All'equilibrio, non c'è corrente netta.
- All'equilibrio, nella zona n ci sono cariche con energia termica sufficiente a superare la barriera di potenziale V_d ($n \sim \exp(-eV_d/2kT)$) e diffondere nella zona p, dove si ricombinano → flusso di ricomb. o di saturazione da n a p, J_{nr}
- Deve esserci flusso di cariche dalla zona p a quella n, generate termicamente nella zona p che diffondono attraverso la giunzione, J_{ng} .
- All'equilibrio $J_{ng} + J_{nr} = 0$
- Lo stesso argomento si applica alle lacune: $J_{pg} + J_{pr} = 0$
- Quando un pot. V esterno è applicato, l'altezza della barriera di pot alla giunzione diventa $V_d + V$

P-N junction in forward bias

P region held positive wrt n region



from Sze, Physics of Semiconductor Devices

Diode in Forward Bias

- positive potential at p-region
- negative potential an n-region

• **The external voltage reduces the potential barrier.**

→ electrons from the n-region can cross the barrier.

In tal caso il # di e⁻ che supera la barriera e'
 $\propto \exp[-e(V_d - V)/kT] = (\text{cost.}) \exp[eV/kT]$, quindi
 la corrente di saturazione J_{nr} e $J_{pr} \propto \exp[eV/kT]$.

Per $V = 0$, $J_{pr} = J_{pg}$ e $J_{nr} = J_{ng}$

→ $J_{pr} = J_{pg} \exp[eV/kT]$ e $J_{nr} = J_{ng} \exp[eV/kT]$

La corrente di generazione e' indipendente dal
 pot $V \rightarrow$ la corrente totale e'

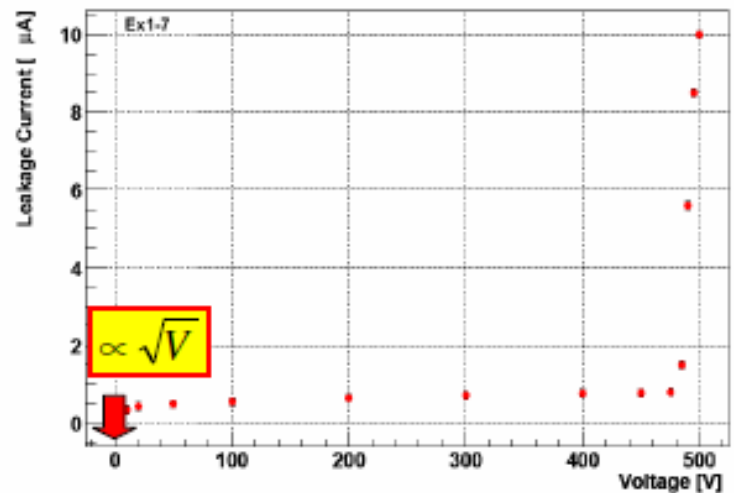
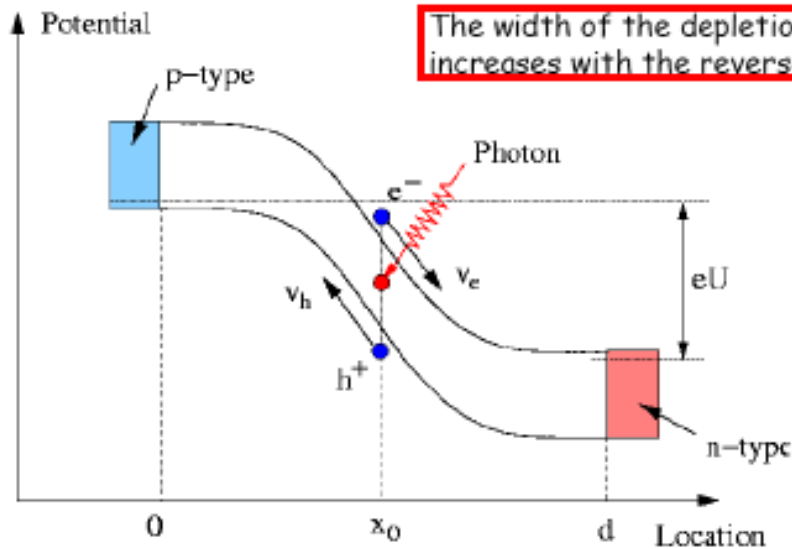
$$J_{\text{tot}} = (J_{pg} + J_{ng})(\exp[eV/kT] - 1)$$

P-N junction in reverse bias

N positive wrt p

- The external voltage increases the potential barrier
- The depletion zone can be used as detector, since it contains an electric field (and is depleted of free charges).

Leakage current: Thermal generation of e h pairs → temperature dependant



Break through:

Detector behaves like a conductor (charge avalanche)

Nella zona di carica spaziale non ci sono cariche libere di muoversi

Se n e' tenuto positivo rispetto a p, la barriera di potenziale cresce di $-eV$ → le correnti di saturazione sono sopresse dall'exp, mentre quelle di generazione rimangono costanti. Quindi in condizioni di "reverse" bias"

$$J_{\text{tot}} = J_{\text{pg}} + J_{\text{ng}}$$

La zona di carica spaziale alla giunzione si allarga

Depth of the depletion region

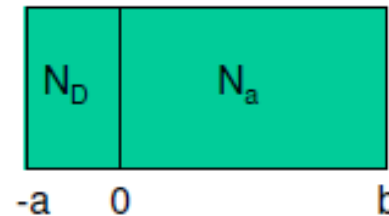
Poisson-Equation for the potential $U(x)$ (1-dimensional for simplicity):

$$\frac{d^2U(x)}{dx^2} = \frac{-\rho(x)}{\epsilon\epsilon_0}$$

with $E_x = -dU/dx \rightarrow \frac{dE_x(x)}{dx} = \frac{\rho(x)}{\epsilon\epsilon_0}$

$$\rho(x) = \begin{cases} eN_D & \text{für } -a < x \leq 0 \\ -eN_A & \text{für } 0 < x \leq b \end{cases}$$

Asymmetric double layer with N_D, N_A density of donor- and acceptor impurities.



Assumption: $N_D \gg N_A$ and $a < b$

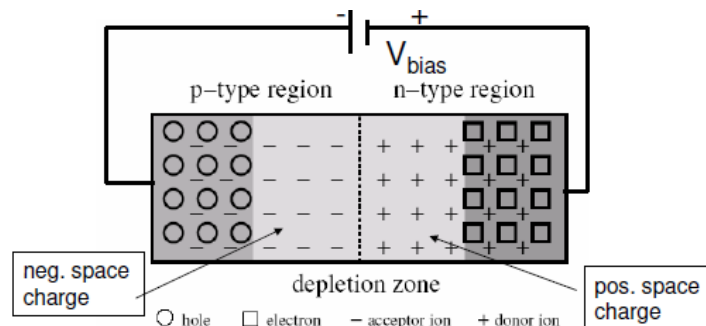
Boundary conditions for electric field:

$$E_x(-a) = 0 = E_x(b)$$

1. Integration of Poisson equation with above boundary conditions



$$dU/dx = \begin{cases} -\frac{eN_D}{\epsilon\epsilon_0}(x+a) & \text{für } -a < x \leq 0 \\ +\frac{eN_A}{\epsilon\epsilon_0}(x-b) & \text{für } 0 < x \leq b \end{cases}$$



Depth of the depletion region

Boundary condition for the potential:

$$U(-a) = 0 \quad \text{und} \quad U(b) = -U_0 \quad \leftarrow \text{applied voltage}$$

2. Integration:

$$U(x) = \begin{cases} -\frac{eN_D}{2\epsilon\epsilon_0}(x+a)^2 & \text{für } -a < x \leq 0 \\ +\frac{eN_A}{2\epsilon\epsilon_0}(x-b)^2 - U_0 & \text{für } 0 < x \leq b \end{cases}$$

Require continuity of potential and its derivative at the junction @ $x=0$

$$b(a+b) = \frac{2\epsilon\epsilon_0 U_0}{eN_A}$$

$$b \approx \left(\frac{2\epsilon V}{qN_d \left(1 + \frac{N_d}{N_a} \right)} \right)^{1/2}$$

$$a \approx \left(\frac{2\epsilon V}{qN_a \left(1 + \frac{N_a}{N_d} \right)} \right)^{1/2}$$

The highest field strength is then at $x=0$:

$$E_x(0) = \sqrt{\frac{2eN_A U_0}{\epsilon_0 \epsilon}} = \frac{2U_0}{d}$$

Rivelatori a stato solido

In assenza di potenziale esterno, l'altezza della barriera di potenziale di contatto V_d è :

$$V_d = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2} \approx 600 \text{ mV}$$

la zona di svuotamento è in genere piccola, circa 10 μm , con i valori tipici di doping

$$x_n = \left(\frac{2\varepsilon(V_d + V)}{qN_d \left(1 + \frac{N_d}{N_a}\right)} \right)^{1/2}$$

Se viene applicato un potenziale V , la zona di svuotamento diventa:

Se $N_a \gg N_d$ $x_n \gg x_p$ la zona di svuotamento è quasi tutta nella regione n (meno drogata):

$$x_p = \left(\frac{2\varepsilon(V_d + V)}{qN_a \left(1 + \frac{N_a}{N_d}\right)} \right)^{1/2}$$

$$d \approx x_n \approx \left(\frac{2\varepsilon(V_d + V)}{qN_d} \right)^{1/2}$$

$$= (2\varepsilon\rho\mu V)^{1/2}$$

La tensione a cui lo spessore svuotato $e' = a$ quello del rivelatore, d , e' il "depletion voltage"

$$V_{dep} \approx \frac{d^2}{2\varepsilon\rho\mu}$$

Il potenziale di contatto V_d e' di solito $\ll V$ e puo' essere trascurato

In tal caso tutto il volume del diodo diventa "attivo", cioe' capace di dare un segnale utile.

→ **Fissa il punto di lavoro $V > V_{dep}$**
NB: si noti che piu' alta e' ρ , minore e' la tensione necessaria per svuotare il rivelatore

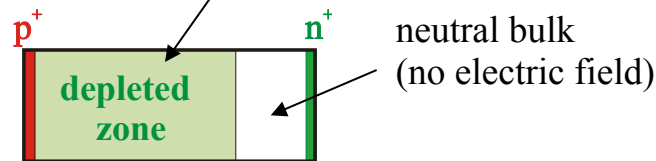
Valori tipici delle tensioni di svuotamento 50-100 V per 300 μm di spessore

Reverse biased abrupt p⁺ n junction

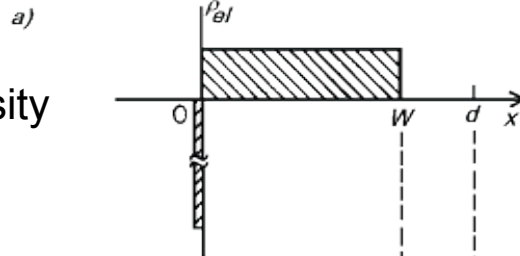
Poisson's equation

$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\epsilon\epsilon_0} \cdot N_{eff}$$

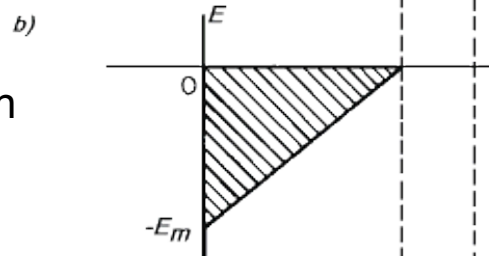
Positive space charge, $N_{eff}=[P]$
(ionized Phosphorus atoms)



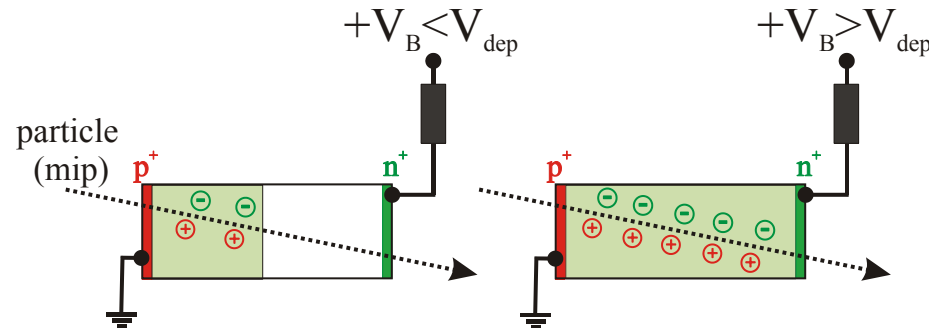
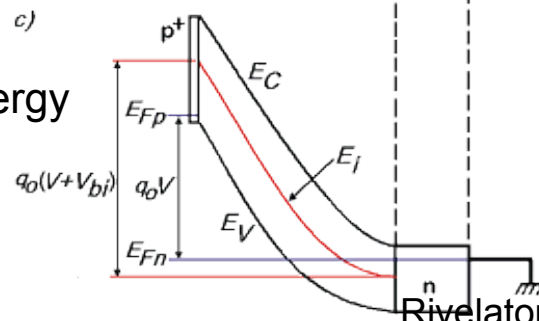
Electrical
charge density



Electrical
field strength



Electron
potential energy



The charge liberated in the undepleted region is not collected since there is no electric field applied in that region and the free charge is much greater.

Full charge collection only for $V_B > V_{dep}$!