Semiconductor Detectors

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Section 1

Introduction

Semiconductor Detectors

- Detectors based on on the detection of electron-hole pairs created in semiconductor materials:
  - Silicium
  - Germanium
  - CdTe, AsGa, CdZn, diamant (CVD)
- Main characteristics are
  - $w \sim$3 eV $\rightarrow$ Lots of electron-hole pairs created
  - $\rho \sim$3 gr/cm^3 $\rightarrow$ Dense material ($\frac{dE}{dx} \propto \rho$)
- If we compare with gasses ($w \sim$30 eV and $\rho \sim$3 mgr/cm^3)
  - $\sim 10^4$ more charge carriers
  - expected a better $\frac{\sigma_E}{E}$
- On the other hand, semiconductors provide no or little internal amplification
- Small signals are then expected and low noise readout circuits are required

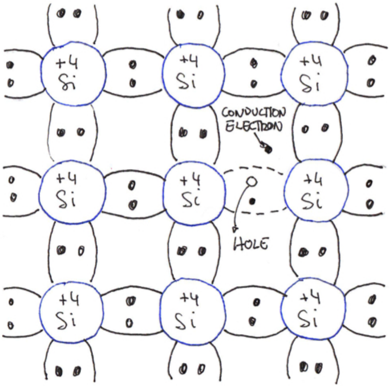
Section 2

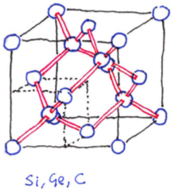
Semiconductor Materials

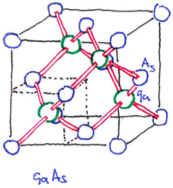
Crystalline structure

- Semiconductors are materials that have a crystalline structure
  - Atoms are arranged with a periodic structure
  - Physical properties of the material depends strongly on this arrangement
  - Main parameter is the lattice distance
- There are four types of crystalline structure
  - Ionic crystals: coulombian attraction
  - Covalent crystals: electron sharing
  - Metals: each atom share an electron with the whole material
  - Molecular crystals: Van der Waals attraction
- Main effect of the aggregation of atoms is the splitting of atomic energy levels
  - 2 atoms $\rightarrow$ 2 times more levels than a single atom
  - 3 atoms $\rightarrow$ 3 times more levels
  - N atoms $\rightarrow$ N times more levels

Crystalline structure

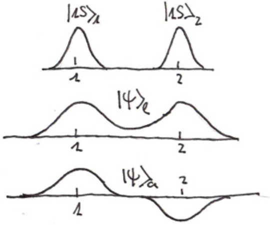


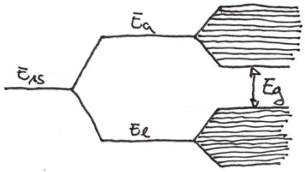




Band structure

- Main effect of the aggregation of atoms is the splitting of atomic energy levels
  - 2 atoms → 2 times more levels than a single atom
  - 3 atoms → 3 times more levels
  - N atoms → N times more levels

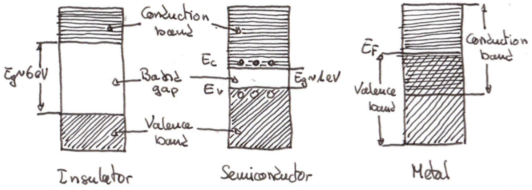




- In case of a crystal $N \sim 10^{23}$
  - Energy degeneracy
  - Band formation

Conductors, Insulators, Semiconductors

- Conductors: Energy gap is non-existent
  - Conduction band and valence band overlaps
  - Electrons can move freely through all crystal
- Insulators: Energy lap is large (∼6 eV)
  - Electrons are always tightly bounded in valence band
  - No electrons in conduction band
- Semiconductors: Small energy gap (∼1 eV)
  - Electrons bounded in valence band
  - Non negligible probability to reach conduction band
  - Reduced conductivity



Band Structure

- Bands are created because of crystalline structure
- They are composed by degenerate levels very close in energy
- Different energy level are distinguished by the wave number k

$$p^* = k\hbar \quad \rightarrow \quad \text{quasi momentum}$$

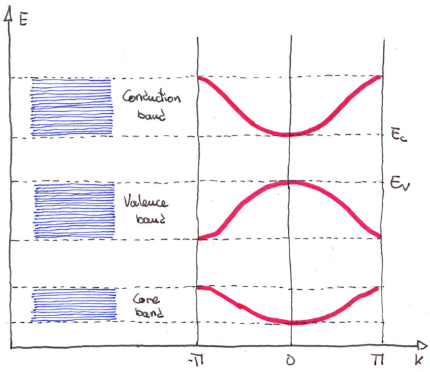
- Electrons (holes) tend to loose its energy in non-radiative way to occupy the lowest (highest) level inside the band
- We can distinguish three bands:
  - core band: inner electrons, no importance in this discussion
  - valence band: band where bonding electrons lies
  - conduction band: band where electrons can move freely
    for holes valence band act as conduction band

Band Structure

- Close to the minimum (maximum) of the conduction(valence) band:

$$\text{electrons:} \quad E(\vec{k}) = E_c(\vec{k}_{0c}) + \frac{1}{2}\frac{\partial^2 E}{\partial \vec{k}^2}(\vec{k} - \vec{k}_{0c})$$

$$\text{holes:} \quad E(\vec{k}) = E_v(\vec{k}_{0v}) - \frac{1}{2}\frac{\partial^2 E}{\partial \vec{k}^2}(\vec{k} - \vec{k}_{0v})$$



- In a classical approach
  - Electrons in the conduction band:

$$E = E_c + \frac{(p^* - p_0^*)^2}{2m_0^*}$$

  - Holes in the valence band

$$E = E_v - \frac{(p^* - p_0^*)^2}{2m_h^*}$$

- m_0^*, m_h^*=effective masses

Effective Masses

- Electrons in the conduction band can be considered as a quasi-free electrons
  - There is still some influence of the crystalline structure
  - In classical terms:

$$m_0 \frac{d\vec{v}}{dt} = \vec{F}_{ext} + \vec{F}_{int}$$

$\vec{F}_{int}$: Internal force due to crystalline structure

$\vec{F}_{ext}$: External force applied

  - We can redefine this equation as the one of a free particle with mass and charge in vaccum reacting to an external field:

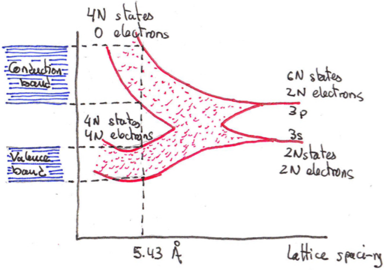
$$m^* \frac{\vec{v}}{dt} = \vec{F}_{ext}$$

  - m^* is called effective mass and it takes into account the extra inertia given to the electron by the periodic potential

$$\frac{1}{m^*} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k^2} \quad \rightarrow \quad \frac{1}{m^*_{ij}} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k_i \partial k_j}$$

Band structure for Si

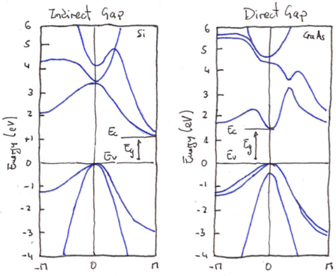
- Silicon (Z=14)
  - Atomic config.: $1s^2\,2s^2p^6\,3s^23p^2$
- In case of N atoms
  - $4N$ bonding states
  - $4N$ anti-bondig states
- If $N \sim 10^{23}$
  - Band formation (degeneracy)
  - E_g depends on lattice spacing.



- Electrons ($4N$) will populate the lower $4N$ states (valence band)
  - Electrons contribute to covalent bonds
- If electrons acquires enough energy they can reach conduction band
  - Quasi-free electron(hole)
  - In presence of electric field, electron(hole) will contribute to current

Band Structure

- Valence band centered at $k = 0$
- Symmetry considerations alone cannot determine the location of the bottom of the conduction band
  - Direct Gap: (GaAs)
    Bottom of conduction band centered at $k = 0$
  - Indirect Gap: (Si,Ge)
    Bottom of conduction band off-centered at different k-values
- Consequences when carrier transfer between minimum gap
  - Momentum conservation
  - Different electron constant energy surfaces



Important Semiconductor Properties

		Si	Ge	GaAs	SiC
atomic number		14	32	31 / 33	14 /12
atomic weight		28.09	72.59	144.63	40
density	g/cm^3	2.33	5.33	5.32	3.21
band gap (RT)	eV	1.12	0.66	1.42	3.0
av. energy for e-h pair	eV	3.65	2.85	4.2	~8.5
electron mobility μ_e	cm^2/Vs	1500	3900	8500	~1000
hole mobility μ_h	cm^2/Vs	450	1900	400	~100
minority carrier lifetime τ	s	$2.5 \cdot 10^{-3}$	10^{-3}	$\sim 10^{-8}$	$\sim 10^{-6}$
$\mu\tau$ – product (e)	cm^2/V	2 – 5	5	$\sim 10^{-4}$	$\sim 10^{-3}$
$\mu\tau$ – product (h)	cm^2/V	1 – 2	2	$\sim 10^{-5}$	$\sim 10^{-4}$
intrinsic resistivity	Ω cm	$2.3 \cdot 10^5$	47	10^8	$> 10^{12}$
intrinsic carrier conc.	cm^{-3}	$1.45 \cdot 10^{10}$	$2.5 \cdot 10^{13}$	$1.8 \cdot 10^6$	10^{-6}

Properties of Important Semiconductors

Appendix F
Properties of Important Semiconductors

	Semiconductor		Crystal Struct.	Lattice Const. at 300 K (Å)	Bandgap (eV) 300 K	Bandgap (eV) 0 K	Band	Mobility at 300 K (cm^2/V-s) μ_n	Mobility at 300 K (cm^2/V-s) μ_p	Effective Mass m_n^*/m_0	Effective Mass m_p^*/m_0	$\varepsilon_s/\varepsilon_0$
	C	Carbon (diamond)	D	3.56683	5.47	5.48	I	1,800	1,200	0.2	0.25	5.7
	Ge	Germanium	D	5.64613	0.66	0.74	I	3,900	1,900	$1.64^l,0.082^t$	$0.04^{lh},0.28^{hh}$	16.0
	Si	Silicon	D	5.43102	1.12	1.17	I	1,450	500	$0.98^l,0.19^t$	$0.16^{lh},0.49^{hh}$	11.9
IV-IV	SiC	Silicon carbide	W	a=3.086,c=15.117	2.996	3.03	I	400	50	0.60	1.00	9.66
III-V	AlAs	Aluminum arsenide	Z	5.6605	2.36	2.23	I	180		0.11	0.22	10.1
	AlP	Aluminum phosphide	Z	5.4635	2.42	2.51	I	60	450	0.212	0.145	9.8
	AlSb	Aluminum antimonide	Z	6.1355	1.58	1.68	I	200	420	0.12	0.98	14.4
	BN	Boron nitride	Z	3.6157	6.4		I	200	500	0.26	0.36	7.1
	”	”	W	a=2.55,c=4.17	5.8		D			0.24	0.88	6.85
	BP	Boron phosphide	Z	4.5383	2.0		I	40	500	0.67	0.042	11
	GaAs	Gallium arsenide	Z	5.6533	1.42	1.52	D	8,000	400	0.063	$0.076^{lh},0.5^{hh}$	12.9
	GaN	Gallium nitride	W	a=3.189,c=5.182	3.44	3.50	D	400	10	0.27	0.8	10.4
	GaP	Gallium phosphide	Z	5.4512	2.26	2.34	I	110	75	0.82	0.60	11.1
	GaSb	Gallium antimonide	Z	6.0959	0.72	0.81	D	5,000	850	0.042	0.40	15.7
	InAs	Indium arsenide	Z	6.0584	0.36	0.42	D	33,000	460	0.023	0.40	15.1
	InP	Indium phosphide	Z	5.8686	1.35	1.42	D	4,600	150	0.077	0.64	12.6
	InSb	Indium antimonide	Z	6.4794	0.17	0.23	D	80,000	1,250	0.0145	0.40	16.8
II-VI	CdS	Cadmium sulfide	Z	5.825	2.5		D			0.14	0.51	5.4
	”	”	W	a=4.136,c=6.714	2.49		D	350	40	0.20	0.7	9.1
	CdSe	Cadmium selenide	Z	6.050	1.70	1.85	D	800		0.13	0.45	10.0
	CdTe	Cadmium telluride	Z	6.482	1.56		D	1,050	100			10.2
	ZnO	Zinc oxide	R	4.580	3.35	3.42	D	200	180	0.27		9.0
	ZnS	Zinc sulfide	Z	5.410	3.66	3.84	D	600		0.39	0.23	8.4
	”	”	W	a=3.822,c=6.26	3.78		D	280	800	0.287	0.49	9.6
IV-VI	PbS	Lead sulfide	R	5.9362	0.41	0.286	I	600	700	0.25	0.25	17.0
	PbTe	Lead telluride	R	6.4620	0.31	0.19	I	6,000	4,000	0.17	0.20	30.0

D = Diamond, W = Wurtzite, Z = Zincblende, R = Rock salt. I, D = Indirect, direct bandgap. l,t,lh,hh = Longitudinal,transverse,light-hole,heavy-hole effective mass.

Charge carriers: thermal generation

- At 0K
  - All electrons are in valence band
  - All electrons remain static and contribute to covalent bond
- At normal temperature
  - Thermal energy can excite a valence atom into the conduction band
    - The electron can move "freely" along the semiconductor
    - In presence of an electric field they contribute to electrical current
  - The excited electron leaves a hole in the valence band
    - It's easy for a neighboring electron to jump from it's bond to fill the original hole
    - This mechanism repeated looks like a positive charge moving into a see of negative valence electrons
    - In presence of an electric field they move opposite to electrons and they also contribute to electrical current
- This process is called thermal generation
  - It depends strongly with temperature
  - It results in creation of free electrons and holes in equal number/concentration

Thermal Energy

- The average thermal energy:

$$\overline{E} = \frac{3}{2} kT$$

where $k = 8.61710 \times 10^{-5}\,\mathrm{eV/K})$

- If $T = 300K$ then $\overline{E} = \frac{3}{2} 0.025\,\mathrm{eV}$

- The probability to pass from valence band to conduction band is:

Metals	$P_{e-h} = \frac{3}{2} \frac{kT}{E_F}$
Semiconductors	$P_{e-h} = \left(\frac{kT}{E_F}\right)^{3/2} e^{-E_g/2kT}$

Charge carriers: Recombination

- Free electrons and holes move randomly through the semiconductor
- Eventually some free electron may fill a hole. This process is called recombination
- Recombination rate is proportional to the number of free electrons and holes
- In thermal equilibrium recombination rate is equal to thermal generation

- Recombination reduces then current in the semiconductors
- Other processes that can modify current are related with the presence of impurities in the semiconductors
  - Impurities creates energy levels in the band gap
  - These impurities can trap electron/holes and also emit them

Charge carrier concentration

- In presence of an external field there are two contributions to the current:
  - Those of electrons in conduction band
  - Those of holes in valence band

- The most important properties that characterize the electrical behavior of a semiconductor are the charge carrier concentrations:
  - Number of electrons per unit volume in the conduction band (n_c)
  - Number of holes per unit volume in the valence band (p_v)

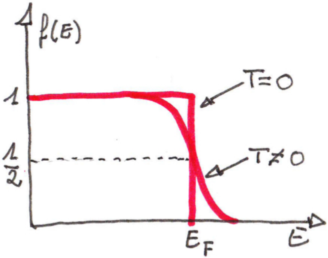
$$\frac{dn(E)}{dE} = N(E)f(E) \quad \rightarrow \quad \begin{array}{l} n_c(T)=\int_{E_c}^{\infty} N_c(E)f_n(E)dE \\ p_v(T)=\int_{-\infty}^{E_v} N_v(E)f_v(E)dE \end{array}$$

  - $N(E)$= density of states.
    Similar of density of states of free particles in cubic potential well
  - $f(E)$=probability to occupy an state of energy E

Fermi-Dirac Statistics

- Electrons are fermions, so they follow the Fermi-Dirac statistics
- The probability to find an electron in an energy level E at temperature T is:

$$f(E) = \frac{1}{1 + e^{\frac{E-E_F}{kT}}}$$



- E_F = Fermi Energy. $f(E_F) = \frac{1}{2}\ \forall T$
- At $T = 0$ f(E)=1 $E < E_F$
  f(E)=0 $E > E_F$
- If $E - E_F > 2kT \rightarrow f(E) \sim e^{-(E-E_F)/kT}$

- The probability function for a hole is

$$f_h(E) = 1 - f(E) = \frac{1}{1 + e^{-\frac{E-E_F}{kT}}} \simeq e^{(E-E_F)/kT}$$

Charge carrier concentration: Electrons

$$N_c(E)dE = 4\pi \left(\frac{2m_e^*}{h^2}\right)^{3/2} (E - E_c)^{1/2} dE$$

$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}} \simeq e^{-(E-E_F)/kT}$$

$$n_c(T) = \int_{E_c}^{\infty} N_c(E) e^{-(E-E_F)/kT} dE$$

$$\Big\downarrow \times \frac{e^{E_c/kT}}{e^{E_c/kT}}$$

$$n_c(T) = N_c(T) e^{-(E_c-E_F)/kT}$$

Charge carrier concentration: Electrons

$N_c(T)$ = Effective density of states in the conduction band

- Weighted sum of all states in conduction band
- It represents the number of available states

$$N_c(T) = \int_{E_c}^{\infty} N_c(E) e^{-(E-E_c)/kT}$$
$$= \frac{1}{4}\left(\frac{2m_e^* kT}{\pi\hbar^2}\right)^{\frac{3}{2}}$$
$$= 2.5 \times 10^9 \left(\frac{m_e^*}{m_0}\right)^{\frac{3}{2}} \left(\frac{T}{300\ K}\right)^{\frac{3}{2}} \ [cm^{-3}]$$

Charge carrier concentration: Holes

$$N_v(E)dE = 4\pi \left(\frac{2m_h^*}{h^2}\right)^{3/2} (E_v - E)^{1/2} dE$$

$$f(E) = 1 - \frac{1}{1 + e^{(E-E_F)/kT}} \simeq e^{(E-E_F)/kT}$$

$$p_v(T) = \int_{-\infty}^{E_v} N_v(E) e^{(E-E_F)/kT} dE$$

$$\Big\downarrow \times \frac{e^{E_v/kT}}{e^{E_v/kT}}$$

$$p_v(T) = N_v(T) e^{(E_v-E_F)/kT}$$

Charge carrier concentration: Holes

$N_v(T)$ = Effective density of states in the valence band

- Weighted sum of all states in valence band
- It represents the number of available states

$$N_v(T) = \int_{-\infty}^{E_v} N_v(E) e^{(E-E_v)/kT}$$
$$= \frac{1}{4}\left(\frac{2m_h^* kT}{\pi\hbar^2}\right)^{\frac{3}{2}}$$
$$= 2.5 \times 10^9 \left(\frac{m_h^*}{m_0}\right)^{\frac{3}{2}} \left(\frac{T}{300\ K}\right)^{\frac{3}{2}} \ [cm^{-3}]$$

Charge carrier concentrations

$$n_c(T) = N_c(T) e^{-(E_c - E_F)/kT}$$
$$p_v(T) = N_v(T) e^{(E_v - E_F)/kT}$$

- Charge carrier concentration $(n_c(T), p_v(T))$ depends doubly on temperature
  - $T^{3/2}$ with effective density of states
  - explicitly in the exponential
- We can multiply both charge carrier concentrations

$$np = N_c N_v e^{E_g/kT}$$

- This expression is known as Action mass law
- The product of charge carrier concentration depends on
  - temperature
  - energy gap

Intrinsic semiconductors

- Intrinsic semiconductors are materials that contains no impurities
- In practice there are always some impurities.
- In an intrinsic semiconductor the number of impurities is small compared with the number of thermally generated electron and holes

$$n_c(T) = p_v(T) = n_i(T) \qquad \rightarrow \qquad \text{Intrinsic carrier density}$$

- Fermi level

$$n_c(T) = p_v(T)$$
$$N_c(T)e^{-(E_c - E_F)/kT} = N_v(T)e^{(E_v - E_F)/kT}$$

$$E_i = E_F = \frac{E_v + E_c}{2} + \frac{kT}{2} \ln\left(\frac{N_v}{N_c}\right)$$
$$= \frac{E_v + E_c}{2} + \frac{3kT}{4} \ln\left(\frac{m_v}{m_c}\right)$$

Intrinsic semiconductors

- Carrier Density

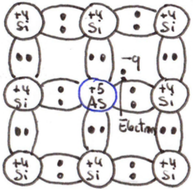
$$\begin{aligned} n_i^2(T) &= n_c(T)p_v(T) \\ &= N_c(T)N_v(T)e^{-E_g/kT} \\ &= 4\left(\frac{kT}{2\pi\hbar^2}\right)^3 (m_c m_v)^{3/2} e^{-E_g/kT} \end{aligned}$$

	$T(K)$	$n_i(cm^{-3})$
Si	300	1.45×10^{10}
	273	1.30×10^{9}
	77	2.30×10^{-20}
Ge	300	2.40×10^{13}
	273	4.68×10^{12}
	77	3.17×10^{-7}
GaAs	300	1.79×10^{6}
	273	8.83×10^{4}
	77	7.74×10^{-32}

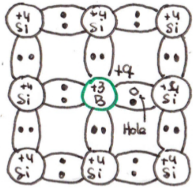
$$\begin{aligned} n_i(T) &= \sqrt{N_c N_v} e^{-E_g/2kT} \\ &= 2.5 \times 10^9 \left(\frac{m_c}{m_0}\right)^{\frac{3}{4}} \left(\frac{m_h}{m_0}\right)^{\frac{3}{4}} \left(\frac{T}{300\ K}\right)^{\frac{3}{2}} [cm^{-3}] \end{aligned}$$

Extrinsic semiconductors

- Electrical characteristics of semiconductors can be modified doping it
  - Adding impurities means the creation of localized energy levels in the band gap
  - Few meV wrt valence or conduction band
- Donor impurities
  - Pentavalent atoms (As,P,Bi,Sb)
  - Energy levels close to the conduction band
  - Four to form covalent bond
  - 5^{th} electron can be promoted to conduction band



- Acceptor impurities
  - Trivalent atoms (Al,B,Ga)
  - Energy levels close to the valence band
  - One bond is missing and one hole is created
  - This hole can be filled by an electron from valence band



Extrinsic semiconductors

	Donor	E_d (meV)	Acceptor	E_a (meV)
GaAs	Si	5.8	Si	35
	C	5.9	Ge	40
Si	As	54	B	45
	P	45	Ga	72
Ge	As	13	B	10
	P	12	Ga	11

- At room temperature all donors and acceptors are ionized
  - Donors positively: All extra electrons are in conduction band
  - Acceptors negatively: All extra holes have been filled and transferred to valence band

Extrinsic Semiconductors

- In an extrinsic semiconductor we will have:
  - intrinsic densities (n and p)
  - donor/acceptor densities (N_d, N_a). Typically $\sim 10^{12} - 10^{13}$
- Electrical neutrality equation should be accomplished

$$\begin{aligned} n + N_a &= p + N_d \\ np &= n_i^2 \end{aligned} \quad \rightarrow \quad \begin{aligned} n^2 + (N_a - N_d)n - n_i^2 = 0 \\ p^2 + (N_d - N_a)p - n_i^2 = 0 \end{aligned}$$

- Let's consider three cases:
  - $N_a = N_d$
  - $N_d > N_a$
  - $N_a > N_d$

Extrinsic semiconductors

- $N_a = N_d$ compensated semiconductor: $n_i = n = p$
- $N_d > N_a$ n-type semiconductor

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

$$p \simeq \frac{n_i^2}{N_d - N_a}$$

  - $n >> p$
  - Electrons: majority charge carriers
  - Holes: minority charge carriers

- $N_a > N_d$ p-type semiconductor

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

$$p \simeq \frac{n_i^2}{N_a - N_d}$$

  - $p >> n$
  - Holes: majority charge carriers
  - Electrons: minority charge carriers

Extrinsic Semiconductors: n-type

- Charge carriers wrt intrinsic semiconductors

$$n_c(T) = N_c(T)e^{-(E_c-E_F)/kT}$$

$$\Big\downarrow \times \frac{e^{E_i/kT}}{e^{E_i/kT}}$$

$$= \underbrace{N_c(T)e^{-(E_c-E_i)/kT}}_{n_i(T)} e^{(E_F-E_i)/kT}$$

$$n_c(T) = n_i(T)e^{(E_F-E_i)/kT}$$

- Fermi level

$$n = N_d - N_a$$

$$E_F^{(n)} = E_c - kT\ln\frac{N_c}{N_d - N_a}$$

$$E_F^{(n)} = E_i + kT\ln\frac{N_d - N_a}{n_i}$$

Extrinsic Semiconductors: p-type

- Charge carriers wrt intrinsic semiconductors

$$p_v(T) = N_v(T)e^{(E_v - E_F)/kT}$$

$$\Big\downarrow \times \frac{e^{E_i/kT}}{e^{E_i/kT}}$$

$$= \underbrace{N_v(T)e^{(E_v - E_i)/kT}}_{n_i(T)} e^{(E_i - E_F)/kT}$$

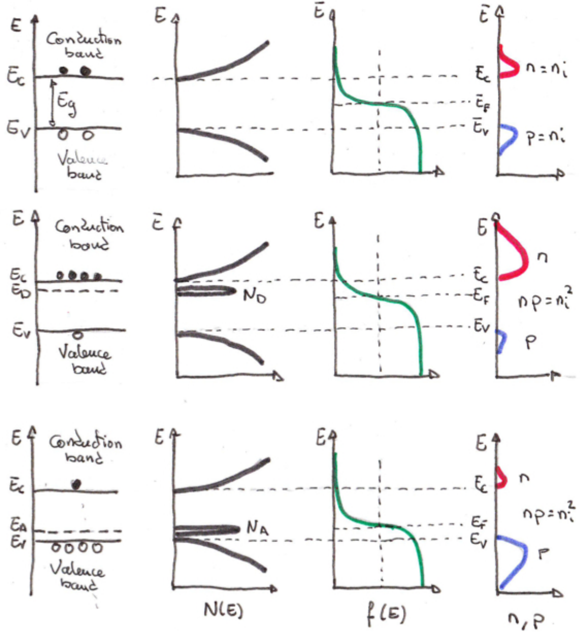
$$p_v(T) = n_i(T)e^{(E_i - E_F)/kT}$$

- Fermi level

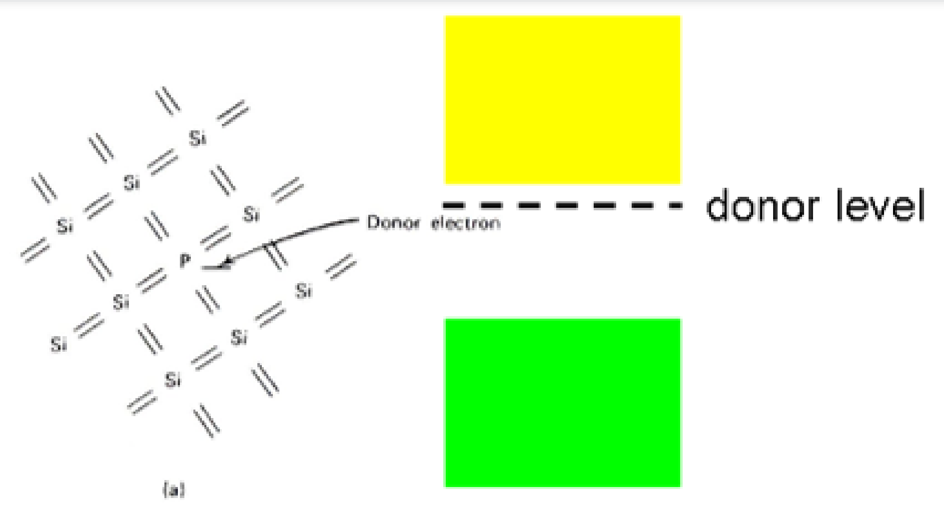
$$n = N_a - N_d$$

$$E_F^{(p)} = E_v + kT \ln \frac{N_v}{N_a - N_d}$$

$$E_F^{(p)} = E_i - kT \ln \frac{N_a - N_d}{n_i}$$


E
Conduction band
Ec
Eg
Ev
Valence band
n = ni
p = ni
EF
ED
ND
np = ni²
n
p
EA
NA
N(E)
f(E)
n, p

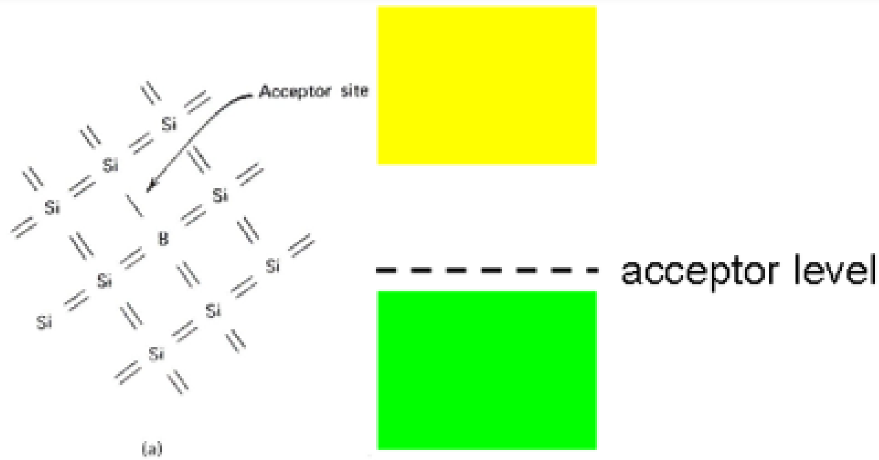
n-type semiconductor



- pentavalent elements (group V/15, e.g. P, As, Sb) have one electron too much to fit in: "donor impurities"
- extra electrons are lightly bound
  - energy level close to the conduction band
  - thermally excited into the conduction band
  - recombination with holes: $n_e >> n_h$

→ n-type semiconductors
  - electrons are the majority charge carriers
  - holes are the minority charge carriers

P-type semiconductor



- trivalent elements (group III/13, e.g. Ga, B, In) have one electron too little to fit in: "acceptor impurities"
- electrons in missing bond slightly less bound
  - energy level close to the valence band
  - thermally excited electrons fill the acceptor level creating holes
  - holes recombine with conduction band electrons: $n_h >> n_e$

→ p-type semiconductors

  - holes are the majority charge carriers
  - electrons are the minority charge carriers

Currents in semiconductors

- Currents in semiconductors can be generated both by majority and and minority charge carriers.
  - Most of the times current is dominated by majority carriers
  - Under some conditions minority charge carrier current is relevant
- Currents can be generated by:
  - Presence of an external electric field: drift, displacement current
  - Existence of a gradient concentration: diffusion current
- In absence of these causes, free charge carriers moves because thermal excitation
  - Free charge carriers collide with atoms in the materisl
  - Between two collisions they follow a rectilinear path
  - Kinetic energy is equal to thermal energy

$$\frac{1}{2}m^* v_{th}^2 = \frac{3}{2}kT$$

$$v_{th} = \sqrt{\frac{3kT}{m^*}}$$

$$l = v_{th}\tau_c$$

$$v_{th} \sim 10^7 \; cm/s$$

$$\tau_c \sim 10^{-12} - 10^{-13}$$

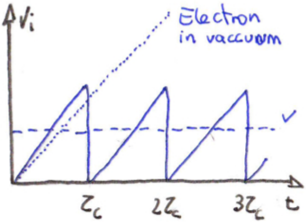
$$l \sim 0.1 - 1 \, \mu m$$

Conduction current: Drift

- In presence of an electric field charges carriers:
  - are accelerated: $\vec{F} = q\vec{E}$
  - acquire an instantaneous velocity

$$qE = m^* \frac{dv_i(t)}{dt} \quad \longrightarrow \quad v_i(t) = \frac{qE}{m^*} t$$ Grows linearly with time

- When charge carriers collides with atoms they stop
- We can imagine $v_i(t)$ as being periodical with period τ_c=collision time



$$v = \frac{1}{\tau_c}\int_0^{\tau_c} v_i(t)dt = \frac{qE}{m^*}\frac{\tau_c}{2}$$

$$v = \pm\mu E$$

$$\tau = \frac{\tau_c}{2}$$ Relaxation time

$$\mu = \left|\frac{q\tau}{m^*}\right|$$ *mobility*

Conduction current: Drift

- Mobility measures the ability of charge carriers to move into a material in presence of an electric field
  - By definition always positive
  - Constant
  - Units: $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$

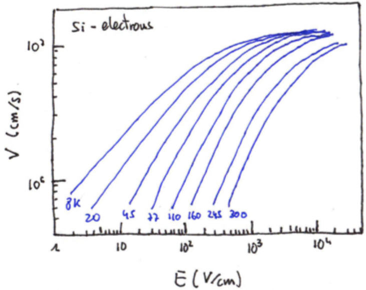
$$\vec{v}_n = -\mu_n \vec{E}$$

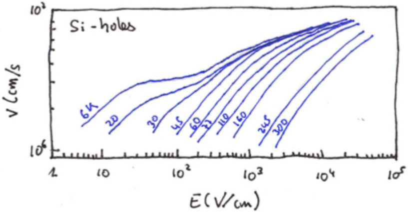
$$\vec{v}_p = +\mu_p \vec{E}$$

Mobility ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)	Si	Ge	GaAs	Diamond
Electrons μ_n	1450	3900	8300	1800
Holes μ_p	505	1800	320	1600

- If $E \sim 10^4$ V/cm $\rightarrow v_n \sim 10^6$ cm/s

Conduction current: Drift





Conduction current: Drift

- Electron and holes currents can be written as:

$$\vec{j}_n = -ne\vec{v} = ne\mu_n\vec{E}$$
$$\vec{j}_p = +pe\vec{v} = pe\mu_p\vec{E}$$
$$\vec{j}_c = \vec{j}_n + \vec{j}_p = \sigma\vec{E}$$
$$\vec{j}_c = (ne\mu_n + pe\mu_p)\vec{E}$$
$$\sigma = e(n\mu_n + p\mu_p)$$
$$\rho = \frac{1}{e(n\mu_n + p\mu_p)}$$

Silicon	N_a/N_d	n	p	$\rho\ (\Omega\ cm)$
Intrinsic	-	1.45×10^{10}	1.45×10^{10}	219806.91
p-type	1.00×10^{12}	2.10×10^{08}	1.00×10^{12}	13801.53
	1.00×10^{13}	2.10×10^{07}	1.00×10^{13}	1381.11
	1.00×10^{14}	2.10×10^{06}	1.00×10^{14}	138.11
	1.00×10^{15}	2.10×10^{05}	1.00×10^{15}	13.81
	1.00×10^{16}	2.10×10^{04}	1.00×10^{16}	1.38
n-type	1.00×10^{12}	1.00×10^{12}	2.10×10^{08}	4143.10
	1.00×10^{13}	1.00×10^{13}	2.10×10^{07}	414.34
	1.00×10^{14}	1.00×10^{14}	2.10×10^{06}	41.43
	1.00×10^{15}	1.00×10^{15}	2.10×10^{05}	4.14
	1.00×10^{16}	1.00×10^{16}	2.10×10^{04}	0.41

- For detectors we will need high resistivity ($\sim$few kΩ cm)
- Low doping in the bulk

Diffusion current

- If charge carriers are not uniformly distributed
  - Charge carriers move to uniform the charge carrier distributions
  - Current that appears is called diffusion current
  - According to Fick's law this current is proportional to gradient concentration

$$\Phi_n = -D_n \vec{\nabla} n$$
$$\Phi_p = -D_p \vec{\nabla} p$$

$$\vec{j}_{d,n} = -e\Phi_n = +eD_n \vec{\nabla} n$$
$$\vec{j}_{d,p} = +e\Phi_p = -eD_p \vec{\nabla} p$$
$$\vec{j}_d = \vec{j}_{d,n} + \vec{j}_{d,p} = eD_n \vec{\nabla} n - eD_p \vec{\nabla} p$$

  - Negative sign because carriers move in direction of weaker concentration
  - D_p,D_n are called diffusion constants and are different for electrons and holes
- Mobility and diffusion constants are not independent:

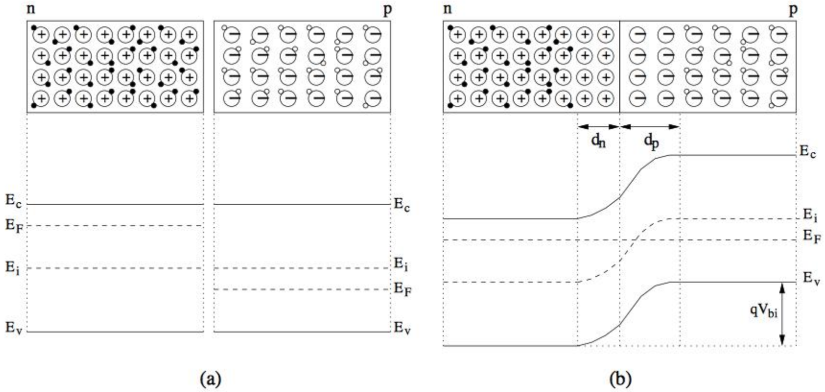
$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} + \frac{kT}{e} \qquad \text{Einstein relation}$$

p-n Junction

- One of the most important electronic structures
- Obtained by joining same intrinsic semiconductor with opposite doping
- It shows diode characteristics: conducts current only in one direction

- Excess electrons on n-side diffuse to p-side
  - Creation of positive ions in n-side
  - Recombine with a hole
  - Creation of negative ion in p-side
- Excess holes on p-side diffuse to n-side
  - Creation of negative ion in p-side
  - Recombine with an electron
  - Creation of positive ions in n-side
- This process continue till all electron-holes around junction recombine

p-n Junction



p-n Junction

	n-side	p-side
Majority carriers	$n_n = N_d$	$p_p = N_a$
Minority carriers	$p_n = n_i^2/N_d$	$n_p = n_i^2/N_a$

- Polarization in the junction
  - Positive charge in n-side
  - Negative charge i p-side
- Creation of a built-in voltage
  - Opposes to drift of majority carriers
  - Enhances drift of minority carriers
- Charge density:

$$\rho(x) = \begin{cases} -eN_A & \text{p-side} \\ eN_D & \text{n-side} \end{cases} \qquad V_b = \frac{E_c^p - E_c^n}{e}$$

p-n Junction

Electric field and Potential:

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

p-side $x_p < x < 0$

$x = x_p \quad E = 0$

$V = V_p$

n-side $0 < x < x_n$

$x = x_n \quad E = 0$

$V = V_n$

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

$$\frac{dV(x)}{dx} = \frac{eN_a}{\varepsilon}(x - x_p)$$

$$V(x) = \frac{eN_a}{2\varepsilon}(x - x_p)^2 + V_p$$

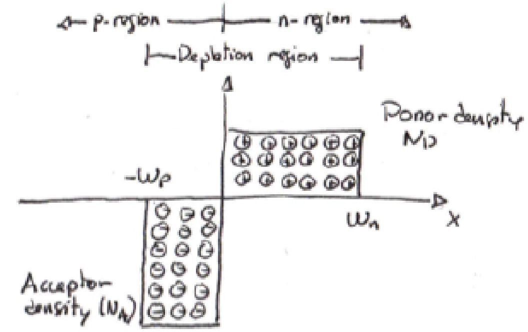
$$E(x) = -\frac{eN_a}{\varepsilon}(x - x_p)$$

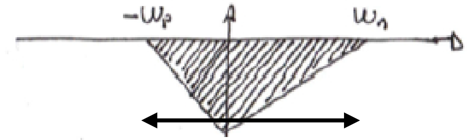
$$\frac{d^2V(x)}{dx^2} = -\frac{eN_d}{\varepsilon}$$

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

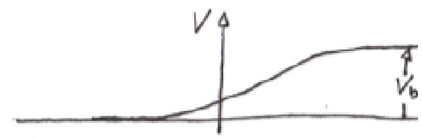
$$V(x) = -\frac{eN_d}{2\varepsilon}(x - x_n)^2 + V_n$$

$$E(x) = \frac{eN_d}{\varepsilon}(x - x_n)$$

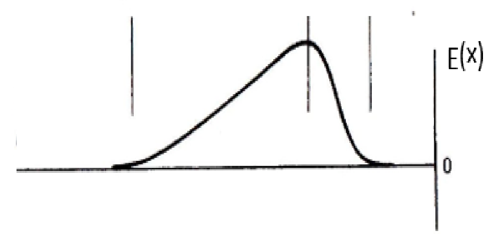




depletion region



contact potential



p-n Junction: Built-in potential

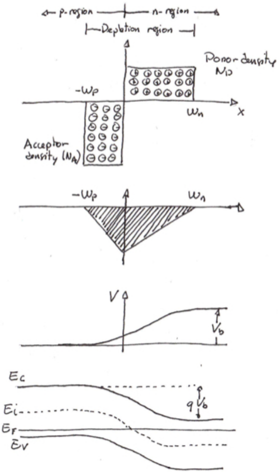
- E_F is the same in the whole structure
- Electron densities in both sides

$$n_n = N_c e^{-(E_{cn}-E_F)/kT} = N_d$$
$$n_p = N_c e^{-(E_{cp}-E_F)/kT} = n_i^2/N_a$$

$$E_{cp} - E_{cn} = kT \ln \frac{N_d N_a}{n_i^2}$$

$$E_{cp} = -eV_p$$
$$E_{cn} = -eV_n$$

$$V_d = V_n - V_p = \frac{E_{cp} - E_{cn}}{e} = \frac{kT}{e} \ln \frac{N_d N_a}{n_i^2}$$



p-n Junction: Depletion depth

At $x = 0 \rightarrow$ continuity of displacement vector and potential

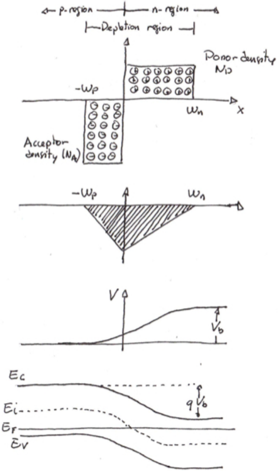
$$\varepsilon E_{0-} = \varepsilon E_{0+} \qquad \frac{eN_a}{2\varepsilon} W_p^2 + V_p = -\frac{eN_d}{2\varepsilon} W_n^2 + V_n$$
$$N_d W_n = N_a W_p$$

$$V_d = V_n - V_p = \frac{e}{2\varepsilon}\left(N_d W_n^2 + N_a W_p^2\right)$$

$$W_n = \sqrt{\frac{2\varepsilon}{e}\frac{N_a}{N_d(N_a+N_d)}V_d} = 2\sqrt{\frac{\varepsilon kT}{2e^2 N_d}}\left(\frac{1}{1+N_d/N_a}\ln\frac{N_d N_a}{n_i^2}\right)^{\frac{1}{2}}$$

$$W_p = \sqrt{\frac{2\varepsilon}{e}\frac{N_d}{N_a(N_a+N_d)}V_d} = 2\sqrt{\frac{\varepsilon kT}{2e^2 N_a}}\left(\frac{1}{1+N_a/N_d}\ln\frac{N_d N_a}{n_i^2}\right)^{\frac{1}{2}}$$

$$W = W_n + W_p = \sqrt{\frac{2\varepsilon}{e}\frac{N_a+N_d}{N_a(N_a+N_d)}V_d}$$



p-n Junction: Depletion depth

- If a voltage (V) is applied to the junction the total voltage drop is:

$$V_0 = V_d - V$$

- V is positive for FORWARD bias: $V_{p-side} > V_{n-side}$
- V is negative for REVERSE bias: $V_{n-side} > V_{p-side}$
  - Depletion region increases

$$W = \sqrt{\frac{2\epsilon}{q}\frac{N_a + N_d}{N_a N_d}(V_d - V)}$$

$$N_a >> N_d = N \rightarrow x_n >> x_p \rightarrow W = x_n$$
$$N_d >> N_a = N \rightarrow x_p >> x_n \rightarrow W = x_p$$

$$W = \sqrt{\frac{2\epsilon V}{qN}}$$

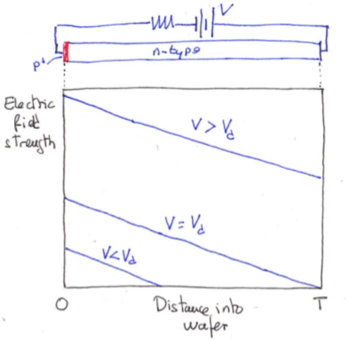
- Maximum depletion depth is limited by breakdown voltage $\sim 1 - 3 \times 10^5$ V/cm

$$W_{max} = \frac{\varepsilon E_{break}}{eN_{min}}$$

$$N_{min}(Si) = 10^{12} \rightarrow W_{max}(Si) \sim 1\ cm$$
$$N_{min}(Ge) = 10^{11} \rightarrow W_{max}(Ge) \sim 10\ cm$$

p-n Junction: Depletion depth

- Depletion region is important for detectors
  - There no free charges in this region
  - Only free charges created from radiation
  - There is an electric field present that will make drift the charge carriers
  - It defines the active volume sensor
- If W >thickness of the semiconductor $\rightarrow$ overdepletion
  - Usual operation of the semiconductor detectors
  - Maximal active volume achievable



p-n junction: Capacitance

- The junction depletion layer capacitance per unit area can be defined as

$$C = \frac{\varepsilon A}{d}$$

  - If d=depletion depth (W)

$$\frac{C}{A} = \frac{\varepsilon}{W} = \sqrt{\frac{\varepsilon e N}{2V}}$$

$$\frac{1}{C^2} \propto V$$

- In case of overdepletion:
  - we will get the minimal possible value of capacitance
  - Limited by the thickness (t) of the material

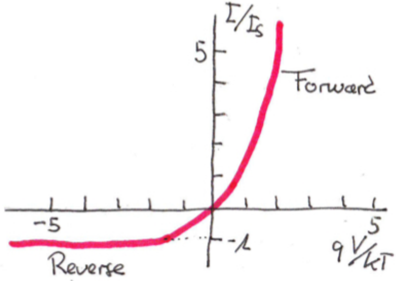
$$\frac{C}{A} = \frac{\varepsilon}{t}$$

p-n Junction: Current-Voltage characteristics

$$I = I_s\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

$$I_s = \frac{qD_p p_{no}}{L_p} + \frac{qD_n p_{po}}{L_n}$$

$$I_s = T^{(3+\gamma/2)}\exp\left(-\frac{E_g}{kT}\right)$$



I_s = Saturation current (due to minority carriers)

$L_{p,n}$ = Diffusion length of minority carriers

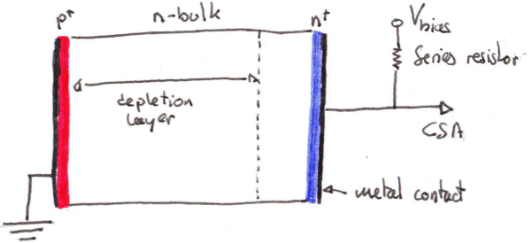
γ = Temperature dependence of $L_{p,n}$

Section 3

Semiconductor Detectors characteristics

Semiconductor Detectors characteristics

- The basis of any semiconductor detector is a pn-junction polarized in reverse mode.
- In the depletion layer:
  - No free charge carriers
  - There is an electric field
- If radiation pass:
  - Generate charge carriers in the depletion layer
  - Charge carriers drift thanks to electric field



Average energy per e-h pair

- Average energy to create an e-h pair (w) is $\sim$10 times less than in gasses

	Si	Ge
300 K	3.62 eV	–
77 K	3.81 eV	2.96 eV

  - Same ΔE will provide a larger number of charge carriers
  - Better energy resolution
  - w is independent of the nature of the particle

- Energy gap is $\sim$1 eV.
- Rest of energy is lost in non-ionizing energy loss $\rightarrow$ lattice vibration

Linearity

$$V = \frac{Q}{C} = e\frac{\Delta E}{wC}$$

- If particle stops: $\Delta E = E$
  $V \propto E$
- If particle does not stops: $V \propto \Delta E$
  Suffers from Landau fluctuations

Fano Factor. Energy resolution

- Fano Factor $\sim$0.12

$$R = 2.35\sqrt{\frac{F}{N}} = 2.35\sqrt{\frac{Fw}{E}}$$

- In case of an α, all energy deposited in the sensor

$$\left.\begin{aligned} E_\alpha &= 5\,\text{MeV} \\ R &= 0.07\% \end{aligned}\right\} \quad \rightarrow \quad \sigma_E \sim 3\,\text{keV!!!!}$$

- Measured σ_E $\sim$20 keV. Mostly due to electronic noise

Leakage current

- A leakage current is intrinsic to reverse bias diodes

$$I = I_s \left(e^{-\frac{eV}{kT}} - 1 \right)$$

- Appears as noise in the detectors
- Origin of leakage current is multiple:
  - Minority carriers (nA/cm^2)
  - Thermal generation. Recombination centers acts as cathalyzers
  - Surface effects (μA/cm^2)
    - surface chemistry
    - contaminants (oxide, dust, ...)
    - mounting techniques
    - Can be reduced working in clean environments and passivating surfaces

Sensitivity and Intrinsic Efficiency

- For charged particles $\varepsilon \sim 100\%$
  Very few particles fail to create ionization
- Limiting factors:
  - Noise (leakage current, electronics)
  - Depletion depth. Thick enough to separate signal from noise
- Figure of merit $S/N > 8$

- For γ's.
  - Indirect ionization
  - Preferred materials with high Z: Germanium

Pulse shape

- Electrical pulses in electrodes arises from induction caused by charge carriers movement
- Most of semiconductors detectors behave as ionization chambers (no multiplication)
  - Main difference $\mu_e \simeq \mu_h$
- Let's consider the case of a parallel plate geometry with uniform field. The sensor has a thicknes d and a voltage V is applied

$$E = \frac{V}{d} \qquad E_w = \frac{1}{d}$$

$$v = \mu \frac{V}{d}$$

- According with Ramo theorem

$$i = qvE_w = q\mu \frac{V}{d}\frac{1}{d} = q\mu \frac{V}{d^2}$$

Pulse shape

- The maximum collection time for charge carrier (generated in the opposite electrode) is

$$t_c = \frac{d}{v} = \frac{d}{\mu \frac{V}{d}} = \frac{d^2}{\mu V}$$

- The induced charge is

$$Q = it_c = q\,\mu \frac{V}{d^2}\,\frac{d^2}{\mu V} = q$$

- Now let's assume the electron-hole pair is formed at coordinate x from positive electrode
  - The drift time and charge collected for electrons are

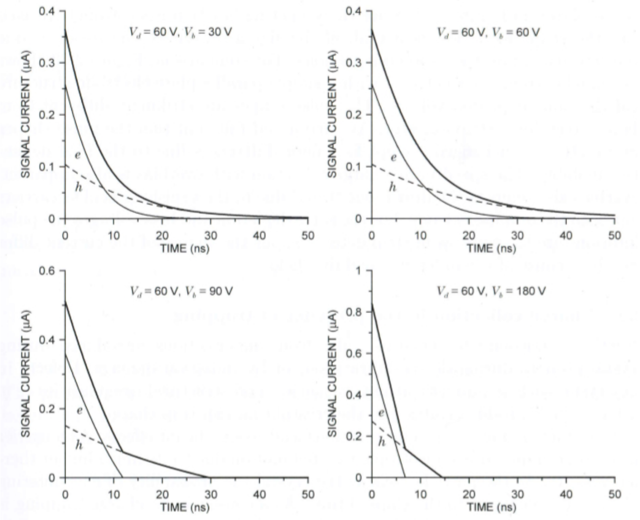
$$t_{ce} = \frac{x}{v_e} = \frac{xd}{\mu_e V} \qquad\qquad Q_e = e\mu_e \frac{V}{d^2}\,\frac{xd}{\mu_e V} = e\frac{x}{d}$$

  - And for the holes

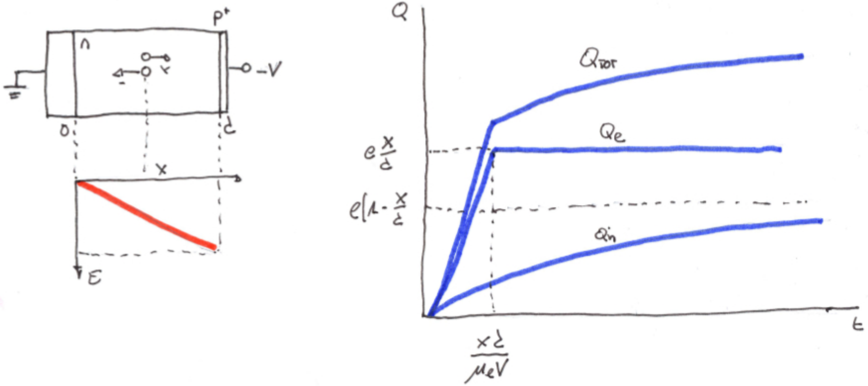
$$t_{ch} = \frac{d-x}{v_h} = \frac{(d-x)d}{\mu_h V} \qquad\qquad Q_h = e\mu_h \frac{V}{d^2}\,\frac{(d-x)d}{\mu_h V} = e\left(1 - \frac{x}{d}\right)$$

Pulse shape

Integrating for all possible charge carriers generated we obtain



Pulse shape



Section 4

Silicon Detectors

Silicon Detectors

- By far the most commonly used material in radiation detectors

$$E_g = 1.17 - 4.73 \times 10^{-4} \frac{T^2}{T + 636}$$

$$n_i = 4.66 \times 10^{15} T^{3/2} e^{-E_g/2kT}$$

- Forbidden gap large enough to operate it at normal temperatures.
- T^2 dependence make it sensitive to non-linearities
- Often operated at -3C - -10C
- High resistivity easily achieved

Property	Symbol	Value
Electron mobility	μ_e	$\leq$1400 cm^{2}V^{-1}s^{-1}
Hole mobility	μ_h	$\leq$450 cm^{2}V^{-1}s^{-1}
Electron Thermal velocity	v_e	2.3$\times$10^7 cm/s
Hole Thermal velocity	v_h	1.7$\times$10^7 cm/s
Electron Diffusion Coefficient	D_e	$\leq$36 cm^{2}s^{-1}
Hole Diffusion Coefficient	D_h	$\leq$12 cm^{2}s^{-1}

Silicon Detectors

Element	Type	ΔE(eV)
As	Donor	0.054
P	Donor	0.045
Sb	Donor	0.043
Al	Acceptor	0.072
B	Acceptor	0.045
Ga	Acceptor	0.074
In	Acceptor	0.157

Silicon Detectors

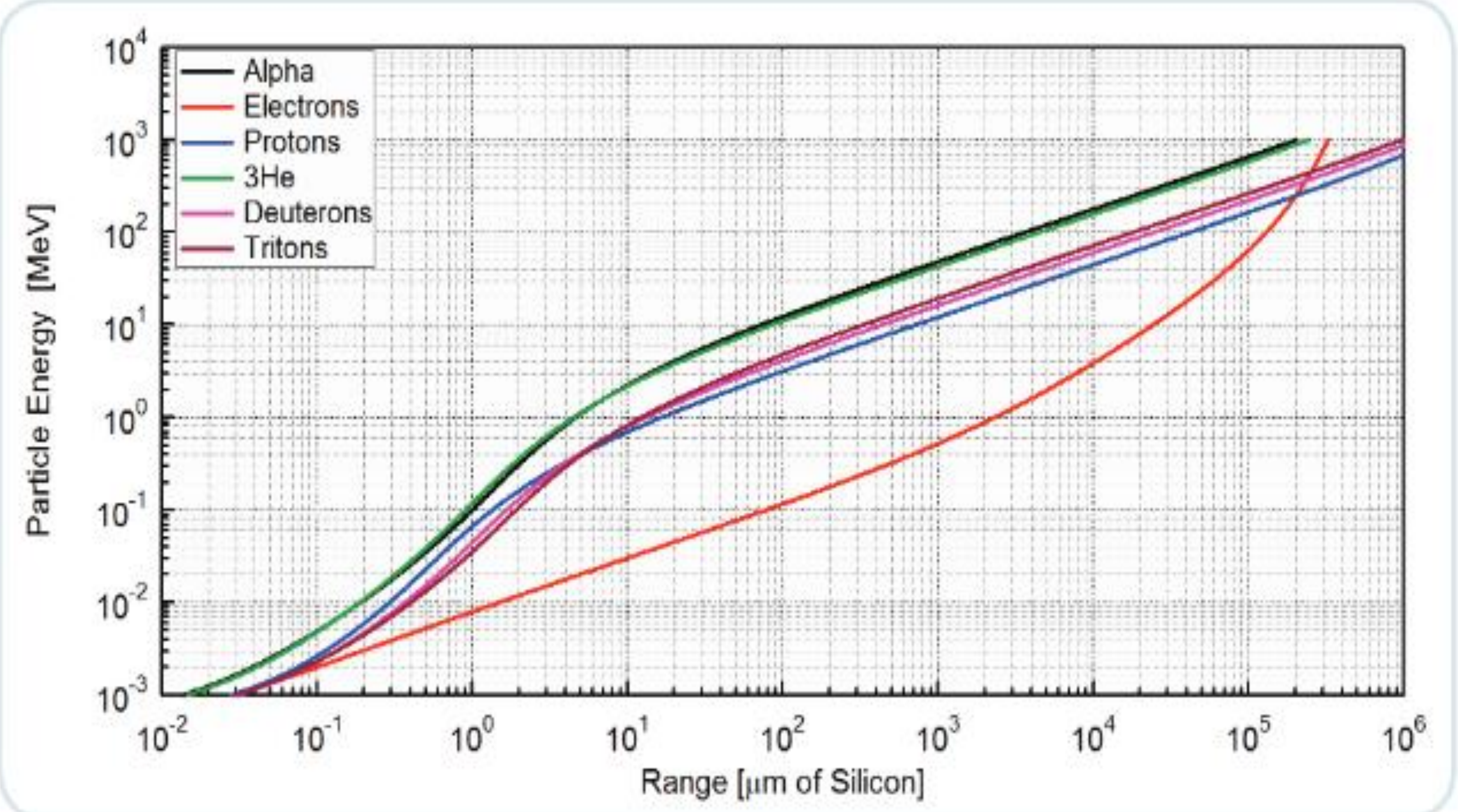
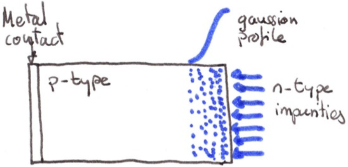


Figure 1
Range-Energy Curves in Silicon

Diffused Junction Detectors

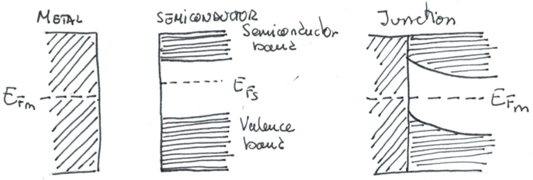
- One of the earliest fabrication methods
- Diffuse n-type impurites (typically P) in p-type bulk at high temperature ($\sim$ 1000 C)



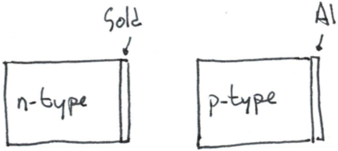
- A junction is formed at a certain distance ($\sim$0.1-2μm) from the surface
- As n-side is heavily doped, depletion region extends mainly on p-side
  - Much of the surface remains out of the depletion region
  - This region is known as dead layer
  - Main drawback if used in spectroscopy
- On the other hand they are quite robust against contamination
- Not often used (mainly because the dead layer)

Surface Barrier Detectors

- p-n junction is substituted by a metal-semiconductor junction (Schottky barrier)

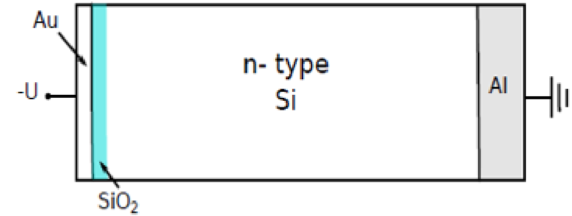


  - In a n-type bulk, the role of p-type can be assumed by high density electron traps at the surface
  - In a p-type bulk, the role of n-type can be assumed by high density electron donor at the surface



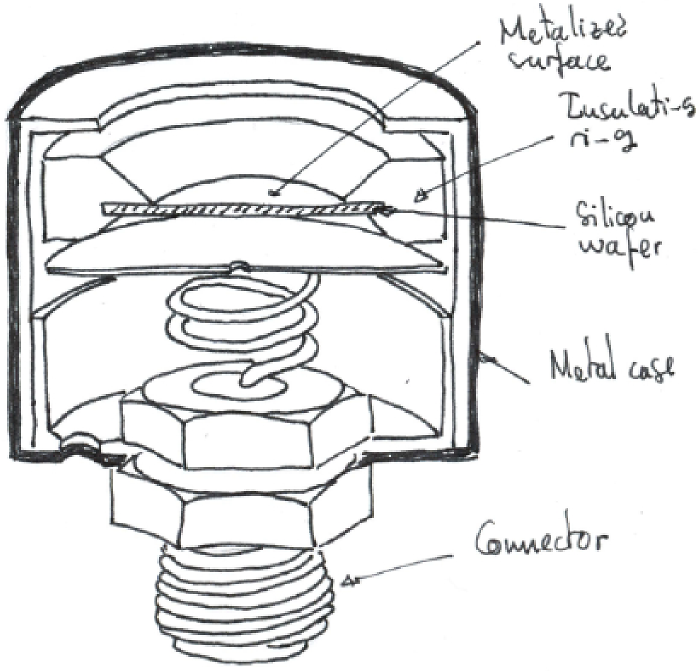
Surface Barrier Detectors

contacts are very thin evaporated metal layers, 40 $\mu g/cm^2 \triangleq$ 20 nm



- "Easy" fabrication at room temperature.
- Deposited metal layer by metal evaporation
  - "Black magic" recipes
  - Industrial processes, most of the times kept secret

- Thin metal layers ~40 $\mu gr/cm^2$
- Few mm thick, and easily fully depleted
- Main drawbacks are
  - High sensibility to light. Metal layer is not light tight
  - Metal surface can be contaminated. It should be handle with care.
- Mostly used for charged particle spectroscopy



Ion-implanted Diodes

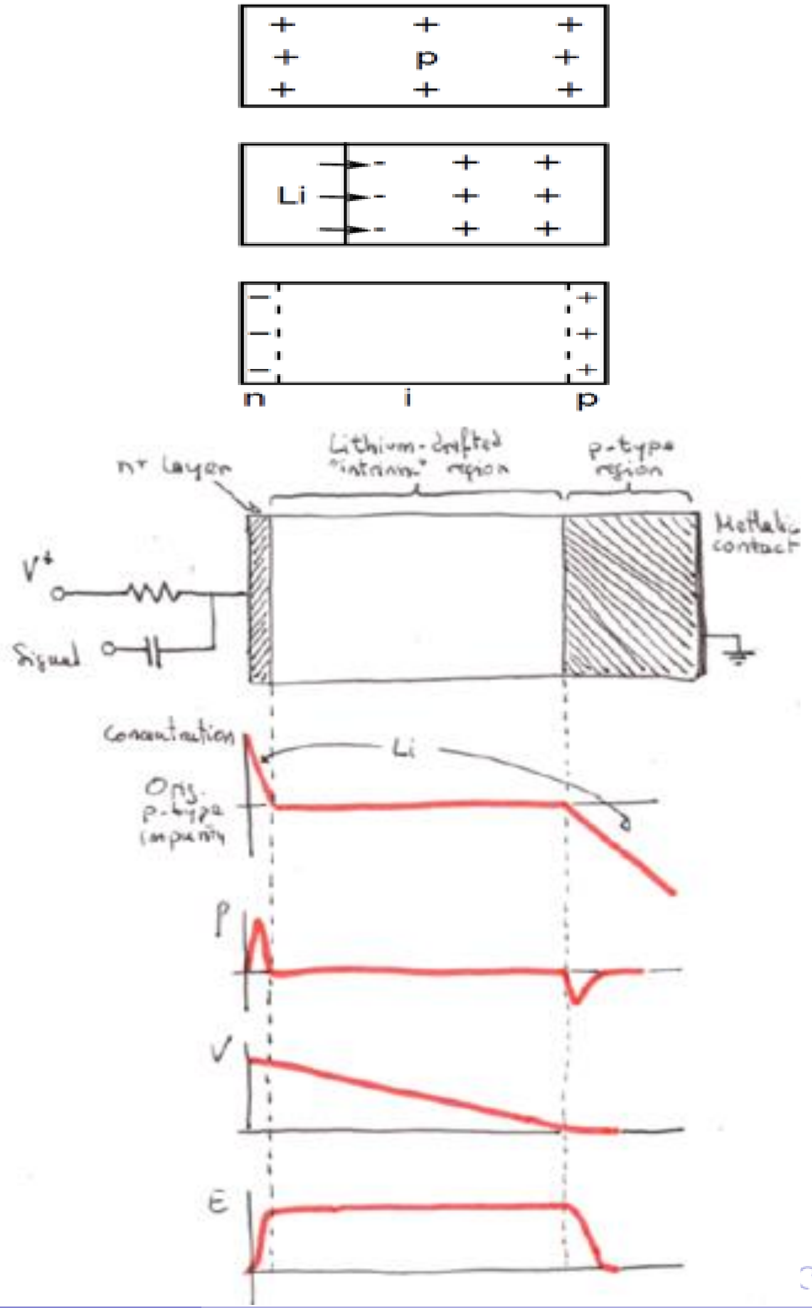
- Doping impurities introduced in the bulk with a beam of ions produced by an accelerator, typically ∼10's of kV
- Adjusting the energy → change ion range → depth profile can be controlled
- During fabrication $T \sim 500^o$C
  - Annealing of radiation damage produced by the beam
  - Temperature much lower than for thermal diffusion
- Thin entrance windows (dead layers) are obtained, ∼30 nm
  - More stable than SSB
  - Expensive fabrication
- Main technique for ion doping in position sensitive sensors.

Lithium-Drifted Detectors

- The depletion depth achieved with silicon with the highest available purity is limited to few mm.
- If thicker detectors are needed (spectroscopy), the usual approach is the creation of a large zone free of charge carriers with the Lithium-drifted process
  - Creation of a compensated "intrinsic" area
  - 5-10 mm depletion depth easily achieved
- Such detectors are known as Si(Li), lithium-drifted silicon detectors
- Lithium-drifted process can be applied to both Si and Ge bulks
  - For Ge (Z=32), gamma interactions are important $\rightarrow$ used mainly for γ-spectroscopy
  - For Si (Z=14), the gamma-ray full-energy peak efficiency is very low.
- Mainly two applications for Si(Li) detectors
  - LEPS: Low Energy Photon Spectrometer
    Efficiency is high in case of X-ray, low energy photons
    Secondary X-rays with lower energy. Less backscattering than Ge
  - Measurement in mixed fields with gamma-rays and X-rays
    Si(Li) will be blind to high energy photons

Lithium-Drifted Detectors

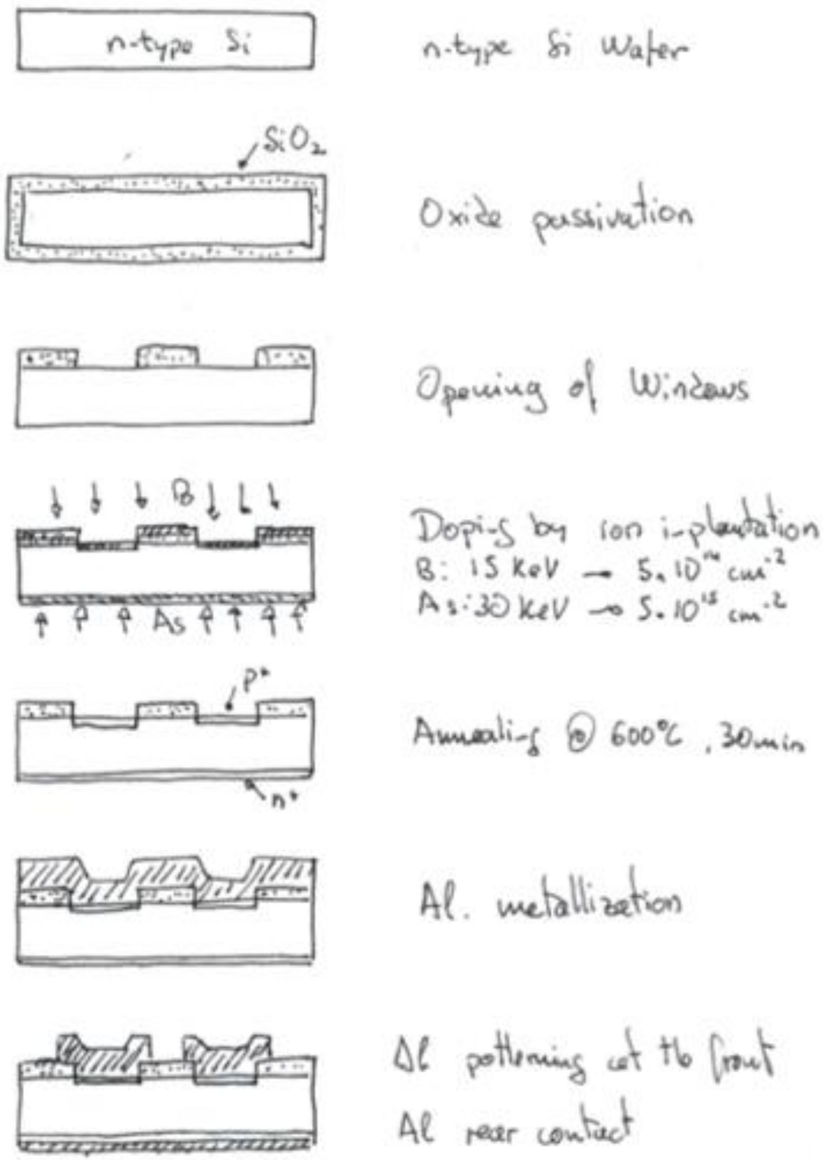
- Lithium Drift process consists in:
  - Diffuse lithium (donor) on p-type semiconductor
  - The p-n junction formed is heavily reversed bias
  - Lithium is "forced" to diffuse in the p-type material (for weeks)
  - Diffusion assure an almost exact compensation
- The structure obtained is known as p-i-n junction
  - Essential structure for photodetectors!!!!
  - As depletion depth increases → detector capacitance decreases



Passivated Planar Detectors

- Application of microelectronic fabrication techniques:
  - Chemical etching
  - Ion implantations
- These techniques allow the fabrication of micropatterns $\rightarrow$ position sensitive devices
  - Microstrip detectors
  - Pixel detectors: Hybrid and monolithic
  - Charge Coupling Devices (CCD)
  - Silicon Drift Chambers (SDC)

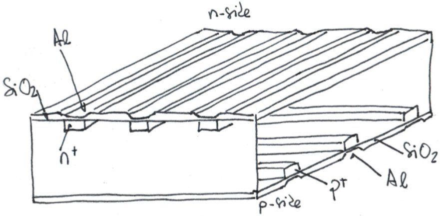
Passivated Planar Detectors



typically 300 μm thick

Microstrip detectors

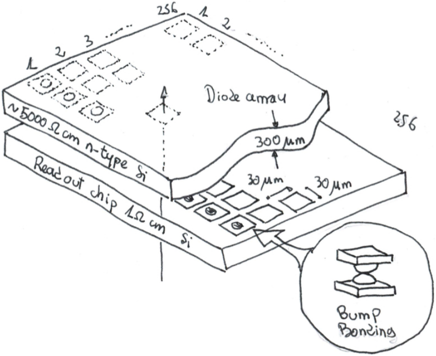
- An straight-forward way to obtain position sensitive device is to divide electrodes into a number of (micro)strips



- Main parameter is strip-pitch (d). Typically $d \sim 50\,\mu m$
- Spatial resolution depends on the readout:
  - Digital readout: $\Delta x = \frac{d}{\sqrt{12}}$
  - Analog readout: $\Delta x = \frac{d}{\sqrt{S/B}}$
- Readout electronics out of sensor

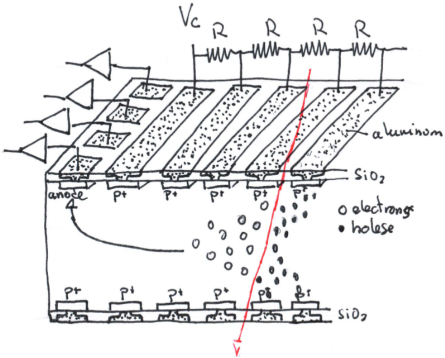
Pixel Detectors

- Two dimensional partitioning of one of the electrons in pads (as checkerboard)
- Typical dimensions $d \sim 20 - 300\,\mu m$
- Main problem is the integration with readout electronics
  - Hybrid pixel sensors (HPS)
  - Monolithic pixel sensors (MPS)



Semiconductor Drift Detectors

- Use the drift time of charge carriers to deduce the position
- Single electrodes on both sides
  - Electrons drift to readout electrodes in a potential well in the middle of the bulk
- Advantages: less readout electronics, and smaller capacitances



Section 5

Germanium Detectors

Germanium Detectors

- Used basically in γ-ray spectroscopy because of its excellent energy resolution
- Forbidden gap:

$$E_g = 0.742 - 4.8 \times 10^{-4} \frac{T^2}{T + 235}$$

$$n_i = 1.38 \times 10^{15} T^{3/2} e^{-E_g/2kT}$$

- It should be operated at cryogenic temperatures
- Germanium can be obtained in extremely pure form

Property	Symbol	Value
Electron mobility	μ_e	$\leq$3900 cm^{2}V^{-1}s^{-1}
Hole mobility	μ_h	$\leq$1900 cm^{2}V^{-1}s^{-1}
Electron Thermal velocity	v_e	3.1$\times$10^7 cm/s
Hole Thermal velocity	v_h	1.9$\times$10^7 cm/s
Electron Diffusion Coefficient	D_e	$\leq$100 cm^{2}s^{-1}
Hole Diffusion Coefficient	D_h	$\leq$50 cm^{2}s^{-1}

Germanium Detectors

Element	Type	ΔE(eV)
As	Donor	0.014
P	Donor	0.013
Sb	Donor	0.010
Bi	Donor	0.013
Li	Donor	0.093
Al	Acceptor	0.011
B	Acceptor	0.011
Ga	Acceptor	0.011
In	Acceptor	0.012
Tl	Acceptor	0.013

Germanium detectors

- Two types of Germanium detectors:
  - Lithium-drifted Detectors
  - High Purity Germanium detectors
- Nowadays only HPG used, less than 10^{10} impurities per cm^3
- Depletion depth of few cm
- Because of the relatively low energy gap of Ge should be operated at cryogenic temperatures (77 K)
- Basically used for gamma spectroscopy because of:
  - Small radiation length (23 mm) (because of his high Z)
  - Excellent energy resolution

$$\mathrm{FWHM[eV]} = 2.35\sqrt{\frac{2.96F}{E[\mathrm{eV}]}}$$

$$E_\gamma = 1.33\,\mathrm{MeV} \rightarrow \Delta E = 1.33\,\mathrm{eV}$$

Germanium detectors

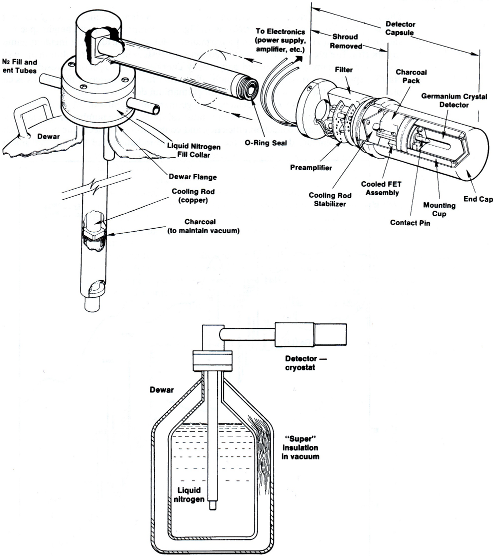


Figure 12.6 Diagram showing the location of a HPGe detector within its vacuum capsule. In this design, the capsule can be connected, without using vacuum pumps, to a variety of cryostats or cryostat–dewar

Germanium detectors

- resolution much better than NaI
- efficiency significantly lower

Germanium detectors

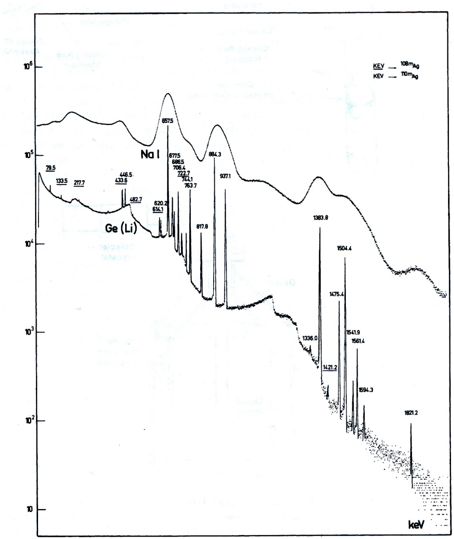
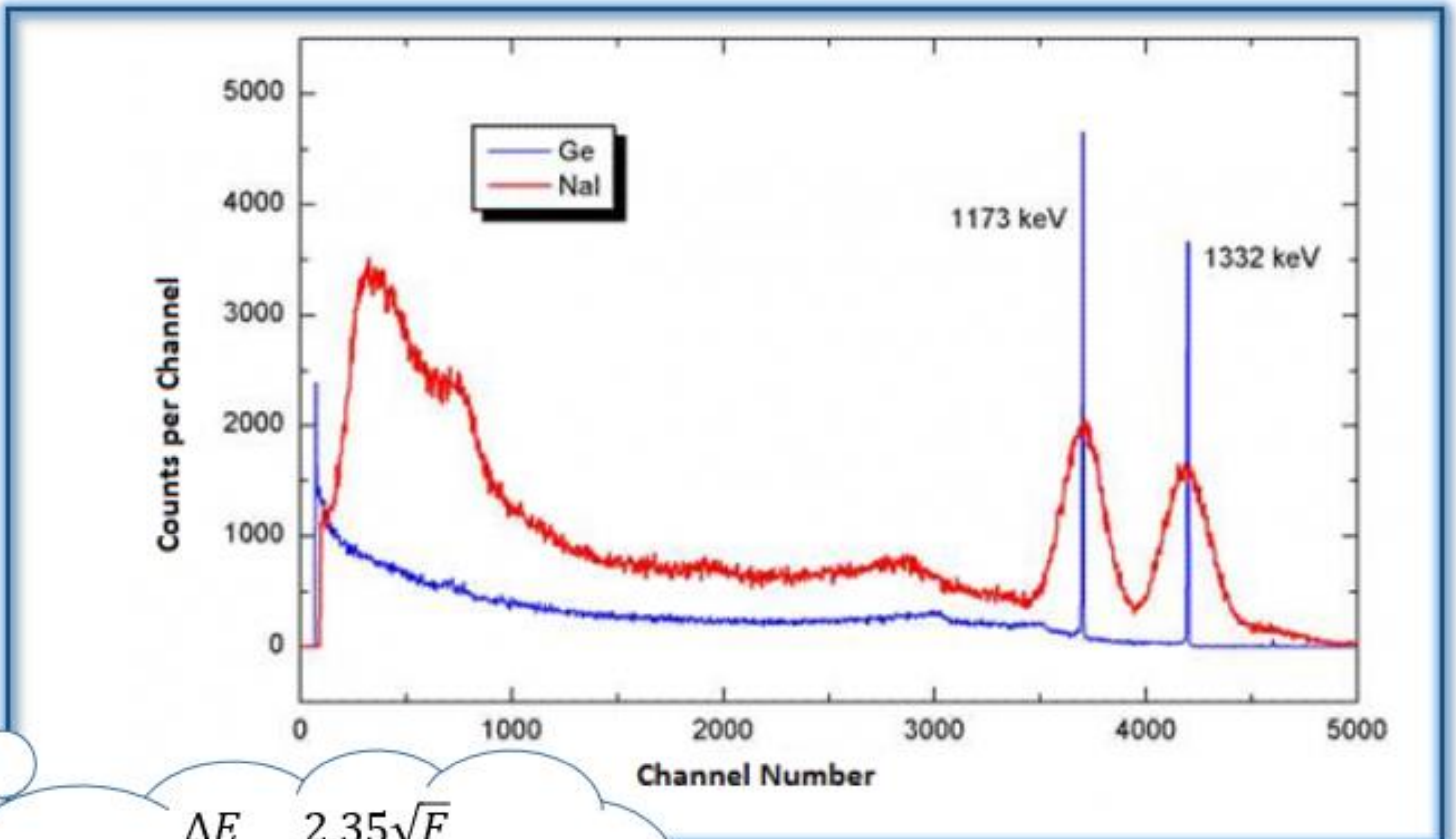


Figure 12.7 Comparative pulse height spectra recorded using a sodium iodide scintillator and a Ge(Li) detector. The source was gamma radiation from the decay of ^{108m}Ag and ^{110m}Ag. Energies of peaks are labeled in keV. (From Philippot.[13])

Germanium detectors



$$R \equiv \frac{\Delta E}{E_0} = \frac{2.35\sqrt{F}}{\sqrt{N}}$$

Scintillation detectors: R ~ 5 - 10 %

Semiconductor detectors: R ~,< 1 %

Germanium detectors

Feeling of efficiency

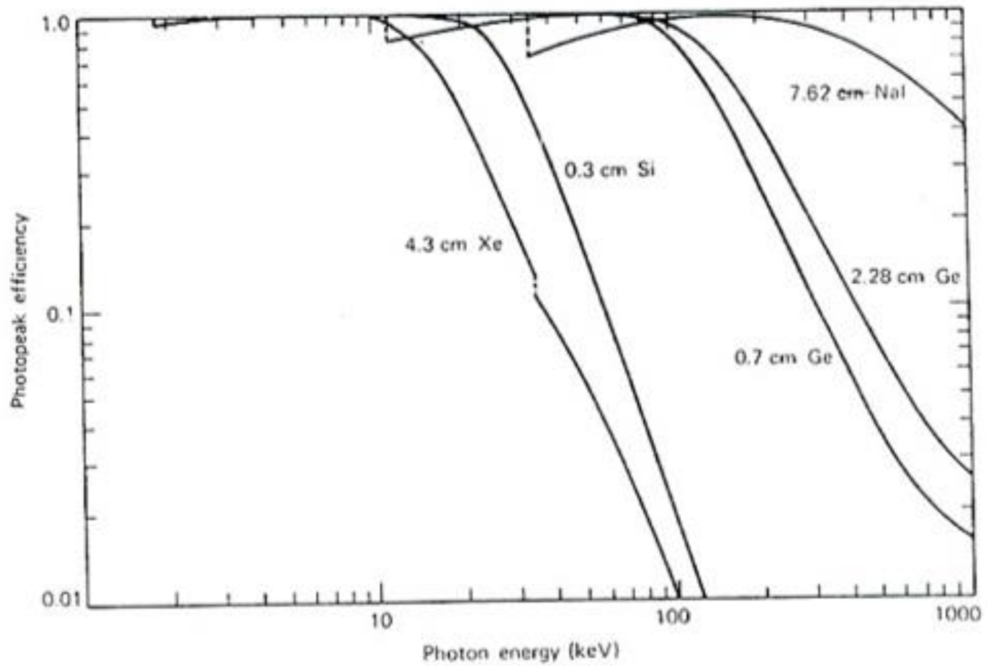


Figure 13-15 Calculated peak efficiency for five different detectors as a function of incident X- or gamma-ray energy. The thicknesses in the direction of the incident radiation are indicated on the figure. The detectors are a xenon-filled proportional counter, an Si(Li) detector, two different germanium detectors, and an NaI(Tl) scintillator. (From Israel et al.[26])

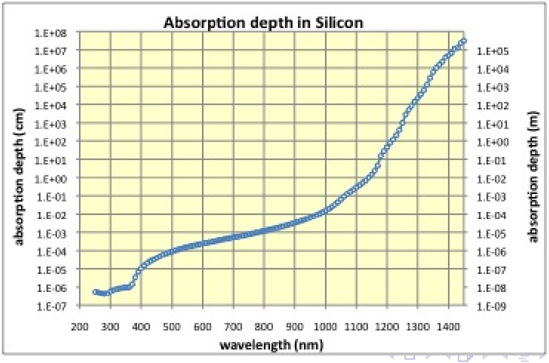
Section 6

Semiconductor Photodetectors

Semiconductor-based Photodetectors: Photodiodes

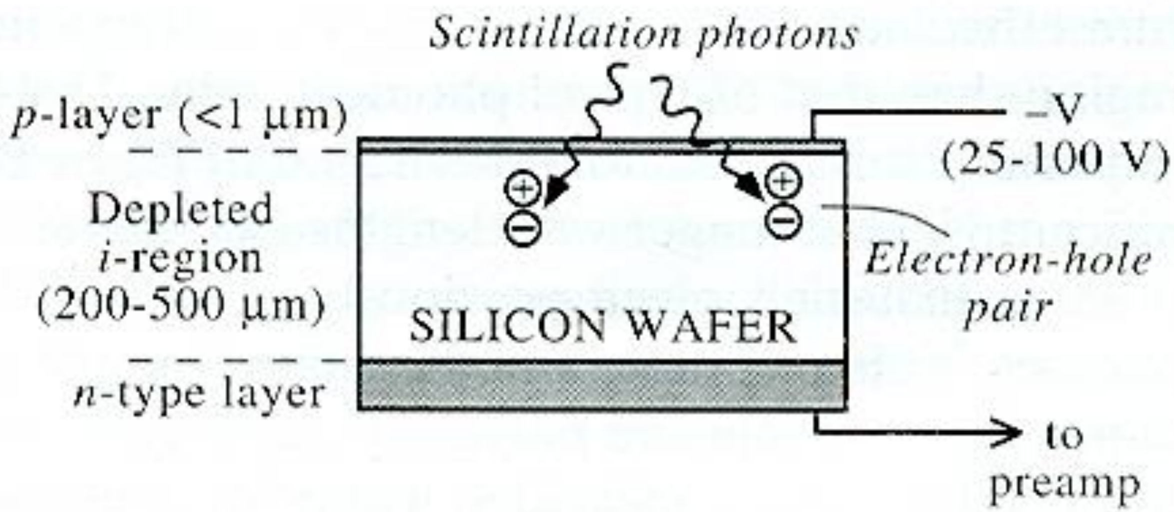
- (Visible) light is converted into e-h pairs in the depletion region

λ	E	Mean free path
300 nm	4.1327 eV	5.7 nm
400 nm	3.0995 eV	0.1 μm
500 nm	2.4796 eV	0.9 μm
600 nm	2.0663 eV	2.4 μm
700 nm	1.7711 eV	5.2 μm
1050 nm	1.1808 eV	613 μm



Semiconductor-based Photodetectors: Photodiodes

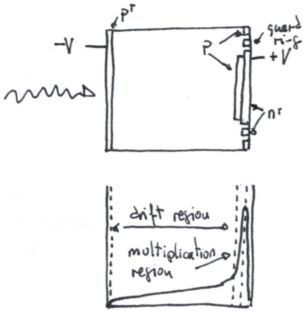
- Silicon photodetectors are also known as photodiodes
- Main characteristics of photodiodes are:
  - Light should reach the depleted region. One of the electrodes should be as thin as possible and transparent to light
  - Insensitive to magnetic fields
  - High quantum efficiency: 60% at 400 m and 80% at 800 nm
  - They have NO internal gain!!!! Useful for high intensity applications, but hard to be used as photodetectors where the number of photons can be quite reduced!!!



Avalanche Photodiode (APD)

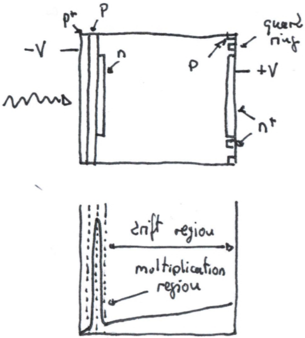
- An avalanche photodiode is a silicon photodiode with internal gain
- To make an avalanche, an special doping profile is needed
  - Electric field $\propto$ doping
  - Gain $\sim 10^{2-3}$. Depends strongly on applied voltage and temperature
- Based in the p-i-n configuration
  - Reduced capacitance ($\Delta V \propto \frac{Q}{C}$)s
  - Intrinsic region used to convert photons to e-h pairs
- Conceptually quite simple but very difficult to realize
  - In order to control fields is needed an extremely good control of doping profiles
  - High purity bulk materials needed
- Two type of APDs:
  - Reach-trhough
  - Reverse type

Reach-trhough APD



- Low field region where photons convert into e-h pairs
- High field region (severe doping) where the field is sufficient to cause electron multiplication
- Main drawback is that the (large) dark current in the drift region is also multiplied
- If the drift region is reduced, detector capacitance is increased

Reverse type APD



- High field region where multiplication takes place close to the entrance window
- Followed by a drift region, mainly to maintain low the capacitance
- Leakeage current is not any more an issue but the material to create e-h pairs is smaller

Excess Noise Factor

- Statistical behavior of the output signal from an APD resembles that of proportional counters
- In both cases pulse-to-pulse fluctuations appears:
  - Variations in the number of initial charges (e-h) pairs in the case of APDs
  - Stochastic differences in the multiplication processes
- Let's assume that on average we have

$$N = n_o M$$

n_0=number of e-h created

M=Gain of the APD

N=Number of the electrons making up the signal

- The relative fluctuations in the output signal are:

$$\left(\frac{\sigma_N}{N}\right)^2 = \left(\frac{\sigma_{n_0}}{n_0}\right)^2 + \left(\frac{\sigma_M}{M}\right)^2$$

Excess Noise Factor

- $\sigma^2_{n_0} = n_0$, just follows Poisson statistics
- The multiplication factor is the sum of the independent avalanches (with gain A_i) triggered by a simple charge carrier

$$M = \frac{1}{n_0}\sum_{i=1}^{n_o} A_i = \overline{A} \qquad \sigma^2_M = \frac{1}{n_0}\sigma^2_A$$

- Then the relative fluctuations can be written as:

$$\left(\frac{\sigma_N}{N}\right)^2 = \frac{1}{n_0}\left[1 + \left(\frac{\sigma_A}{A}\right)^2\right]$$

- For avalanche photodiodes the excess noise is defined as

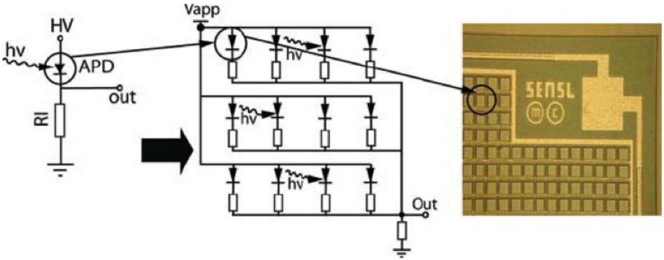
$$J = 1 + \left(\frac{\sigma_A}{A}\right)^2$$

- It reflects the variability of the avalanches
  - If all avalanches are identical $\sigma_A = 0$ and J=1
  - Typically $J \simeq 1.5 - 3$
  - It depends on applied voltage but not on temperature

Silicon Photomultiplier (SiPM)

- It's possible to obtain large electric fields in APD increasing the applied voltage
  - Gain $\sim 10^6$
  - APD goes into discharge in the amplification region as soon as e-h pair is formed
  - In analogy with gas detectors the APD is operated in "Geiger" mode
  - The discharge is quenched with a resistor to the power supply.
- As a result there is a non negligible recovering time
- In order to avoid the whole sensor to be non-operational
  - SiPM have been designed as a matrix of independent pixels, each containing an APD
  - Typical sizes of micropixels is 50μm $\times 50\mu$m
  - When a discharge occurs in a pixel is not spread to the neighbors
- As soon as the number of fired pixels is small response remains linear
- Ideally: 1 (optical) photon = 1 e-h pair = 1 pixel fired
- Quantum efficiencies are smaller than APD because of the unavoidable dead area between pixels

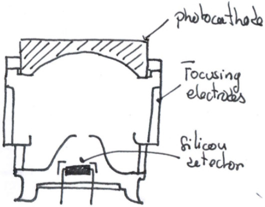
Silicon Photomultipliers (SiPM)



- SiPM are also known as:
  - MPPC: Multipixel Photo Counter
  - SSPM: Solid State Photomultiplier
  - MGMP: Multipixel Geiger Mode Photodetector

Hybrid Photodetector (HPD)

- Photodetectors that combines elements from normal PMs and SiPMs



  - Vacuum tube with a photocathode
  - In front of photocathode there is an APD array
  - Between the cathode and the APD a large HV is applied
- Photons are converted to electrons in the photocathode
- Photoelectrons are accelerated in the HV
- The electrons generate e-h pairs in the APD.
- Gain is directly proportional to HV applied

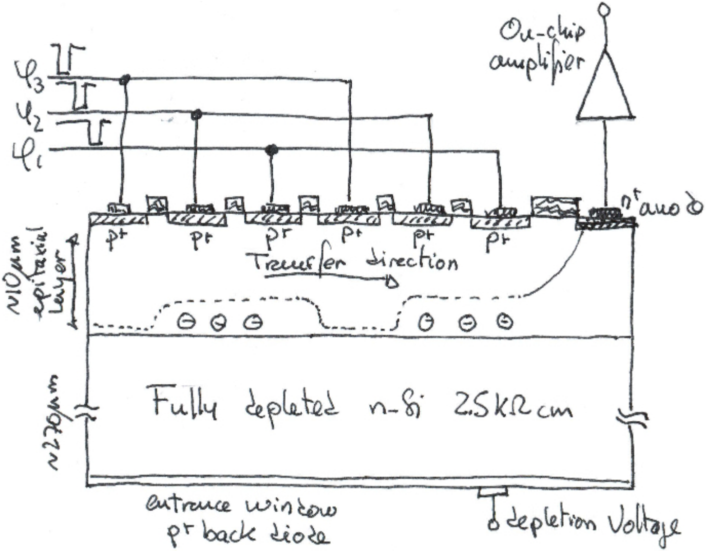
$$G = \frac{E_e}{w} = \frac{V}{3.62eV}$$

i.e. to reach a G=10000, a $V = 36000$ V should be applied
- Technically feasible but the system is complicated to operate and expensive

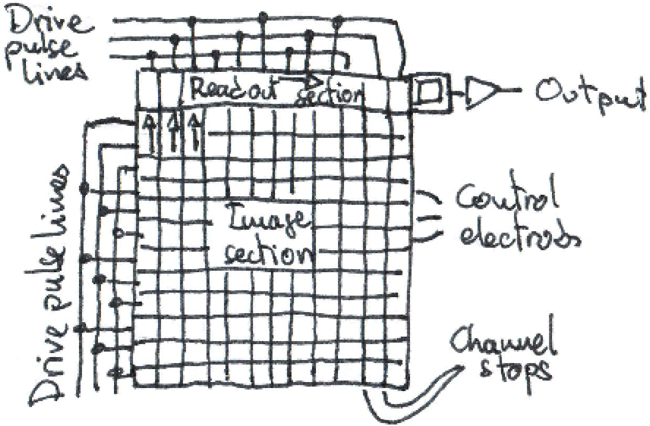
Charge Coupling Device (CCD)

- Introduced in 1970 for visible light: cameras.
- Extended to all wavelenghts
- Used from the 80's as particle detectors (IR,HE, X-ray). Scientific CCD
- "Pixel" sensor fabricated on standard wafers with standard microelectronic techniques
  - Pixel size ~25 μm, total size ~4-9 cm^2
  - Depletion regions created under each pixel
  - Potential wells for electrons created under each pixel (few microns depth) in the so called epitaxial layer
  - Wells generated by MOS structures or p-n junctions controlled by electrodes
- Serial readout:
  - Only one electronic device to readout
  - Charges transported
  - "Slow" readout
- Highly efficient device with low noise

Charge Coupling Device (CCD)

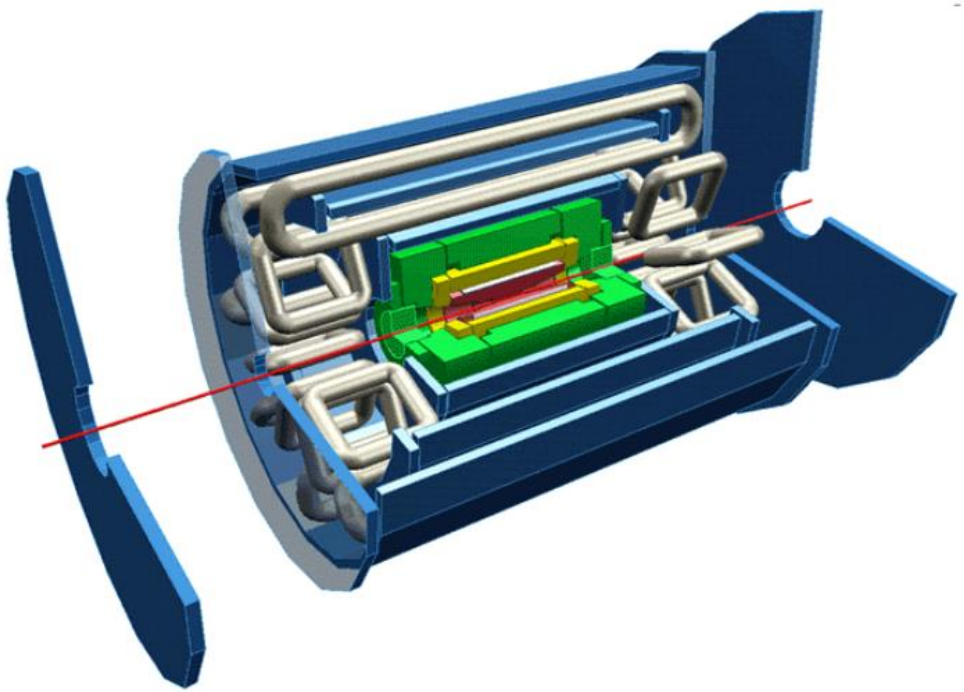


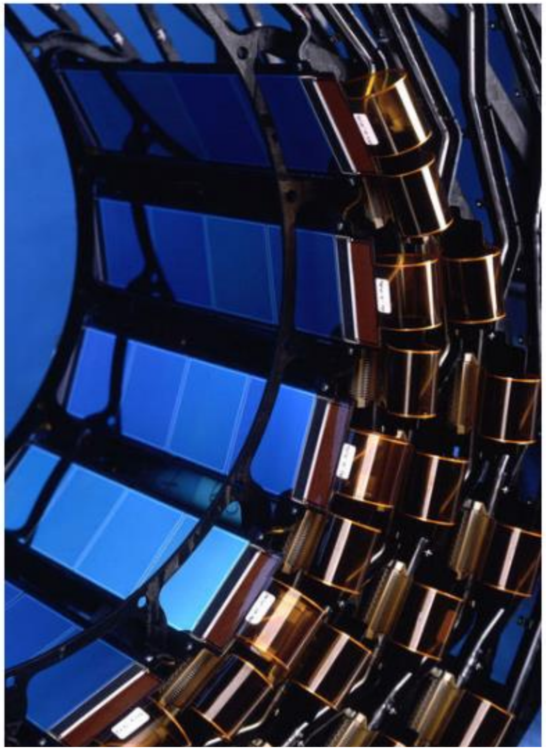
Charge Coupling Device (CCD)



Applications in Basic Research

High Energy Physics



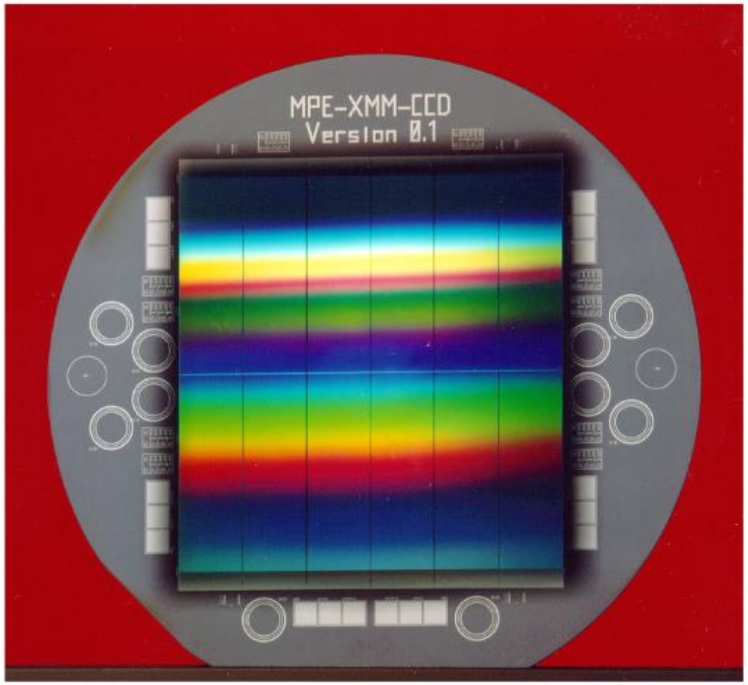


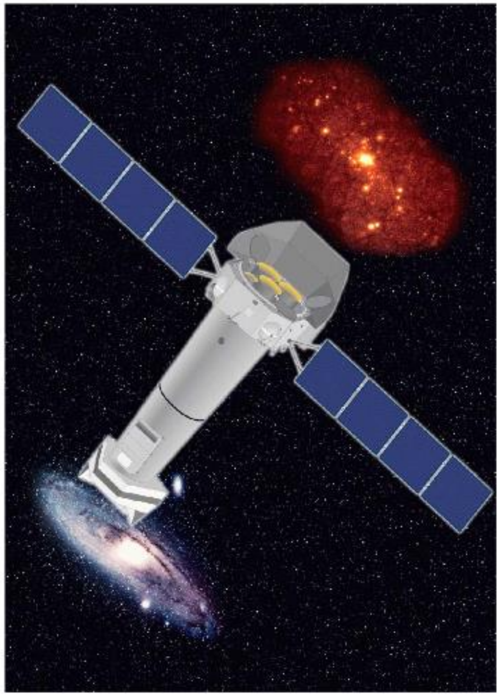
Diode array for position measurement

Strip or pixel detectors as inner trackers → position resolution

Applications in Basic Research

X-Ray Astronomy



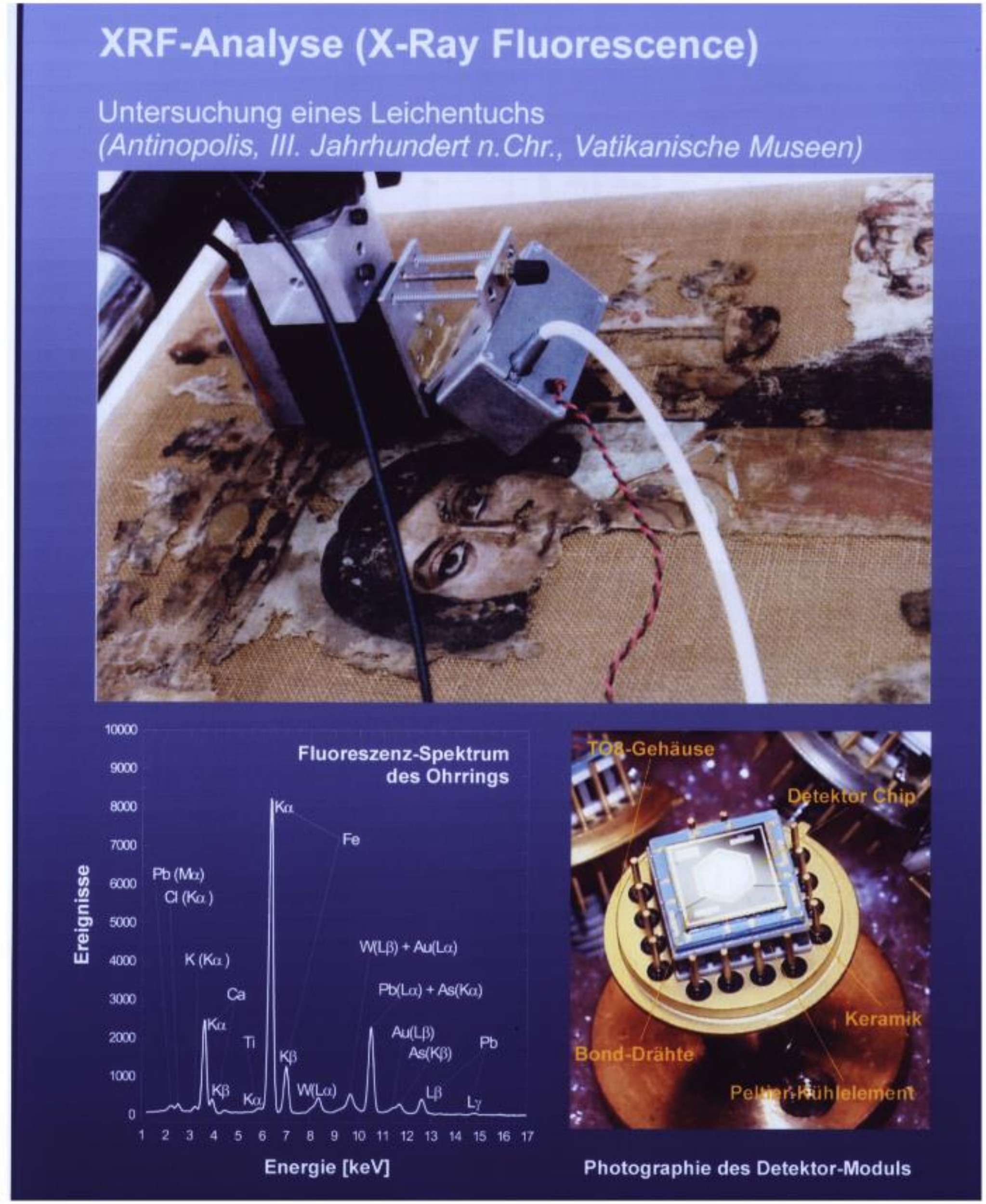


Spectroscopy of cosmic x-ray sources
Fully depleted pn-CCD on ESA's x-ray multi-mirror mission (XMM)

Application

X-Ray Fluorescence Analysis (XRF)

Excitation of sample with X-rays



NASA Mars Rovers