<<Pixel detectors>> Chapter 2 sensor

Introduction

- The main advantage is that the energy for producing an electron–hole pair is only 3.6 eV in silicon while about 20 eV is required for gas ionization and therefore a much better energy resolution could be reached
- silicon is the preferred material because it is the most intensively studied semiconductor and its electrical properties are well known
- it is cheaply available in large quantities and its processing is well developed thanks to the progress in electronics industry

Device Physics and Fundamental Sensor Properties

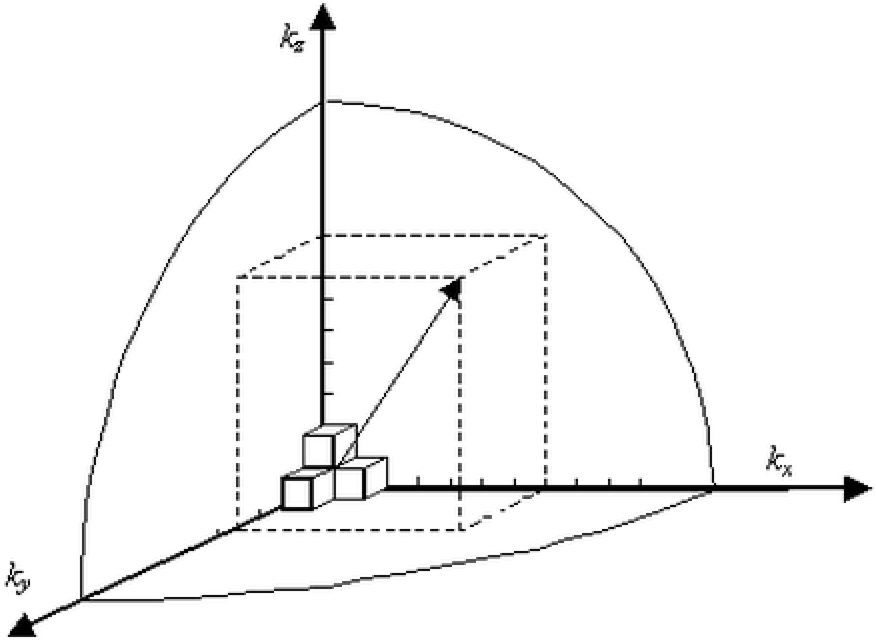
- Carrier Concentration
  - A piece of semiconductor is called *intrinsic* if the concentration of impurities is negligible compared to the thermally generated free electrons and holes
  - number of free electrons *n,* the density of states in the conduction band *N,* Fermi–Dirac function *F(E), EC* is the energy of the lower bound of the conduction band

$$n = \int_{E_C \equiv 0}^{\infty} N(E) F(E) \, \mathrm{d}E \, ,$$

Calculation of the density of states

- the volume of one eighth of a sphere with radius *k* and dividing it by the volume corresponding to a single solution (π/L)^3

$$N = 2\times\frac{1}{8}\times\left(\frac{L}{\pi}\right)^3\times\frac{4}{3}\times\pi\times k^3$$



- A factor of two is added to account for the two possible spins of each solution

$$\frac{dN}{dE} = \frac{dN}{dk}\frac{dk}{dE} = \left(\frac{L}{\pi}\right)^3 \pi k^2 \frac{dk}{dE}$$

$$E(k) = \frac{\hbar^2 k^2}{2m^*}, \text{ providing } \frac{dk}{dE} = \frac{m^*}{\hbar^2 k} \text{ and } k = \frac{\sqrt{2m^* E}}{\hbar}$$

$$g(E) = \frac{1}{L^3}\frac{dN}{dE} = \frac{8\pi\sqrt{2}}{h^3} m^{*3/2} \sqrt{E}, \text{for } E \geq 0$$

$$g_c(E) = \frac{8\pi\sqrt{2}}{h^3} m^{*3/2} \sqrt{E - E_c}, \text{for } E \geq E_c$$

$$g_c(E) = 0, \text{for } E < E_c$$

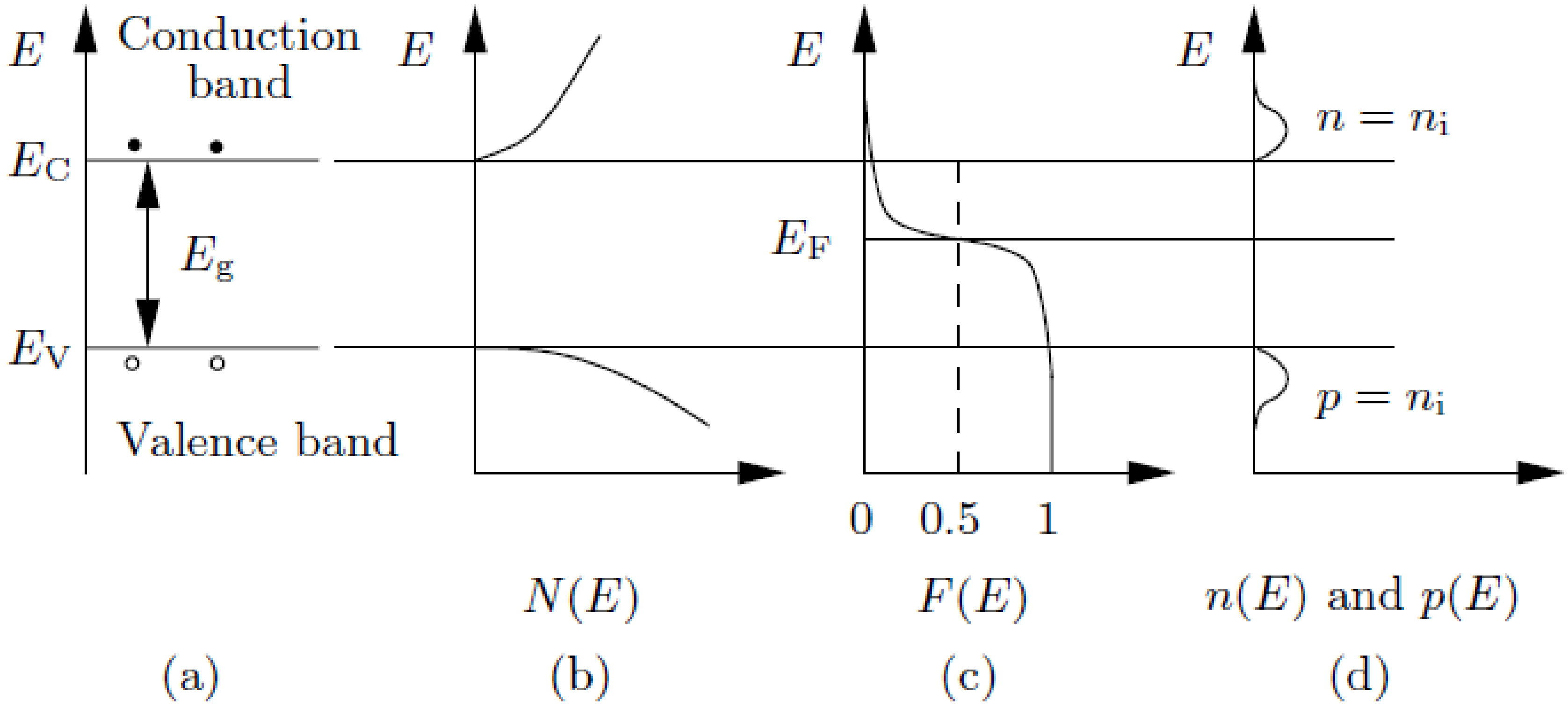


Fig. 2.1. Intrinsic semiconductor: (**a**) schematic band diagram, (**b**) density of states, (**c**) Fermi function, and (**d**) carrier concentration

- the Fermi function can be approximated by an exponential function in the conduction band

$$F(E)=\frac{1}{1+\mathrm{e}^{(E-E_\mathrm{F})/kT}}\approx \mathrm{e}^{-(E-E_\mathrm{F})/kT}$$

- free charge carriers

$$n=\underbrace{2\left(\frac{2\pi m_\mathrm{n}kT}{h^2}\right)^{3/2}}_{N_\mathrm{C}}\mathrm{e}^{-(E_\mathrm{C}-E_\mathrm{F})/kT}$$

$$p=\underbrace{2\left(\frac{2\pi m_\mathrm{p}kT}{h^2}\right)^{3/2}}_{N_\mathrm{V}}\mathrm{e}^{-(E_\mathrm{F}-E_\mathrm{V})/kT}$$

$$np=n_\mathrm{i}^2=N_\mathrm{C}N_\mathrm{V}\,\mathrm{e}^{-E_\mathrm{g}/kT}$$

- The *intrinsic* Fermi level Ei

$$E_\mathrm{i}=\frac{E_\mathrm{C}-E_\mathrm{V}}{2}+\frac{3kT}{4}\ln\left(\frac{m_\mathrm{p}}{m_\mathrm{n}}\right)$$

doping

- dope silicon are either from the third group of the periodic table (e.g. boron) or from the fifth group (e.g. phosphorus, arsenic, antimony)
- The latter ones , called *n-material* ,release their “extra” electron easily into the conduction band and are therefore called *donors*

$$E_F = E_i + kT \ln\left(\frac{N_D}{n_i}\right)$$

- The former ones , called *p-material* produces a free hole and boron is called an *acceptor*

$$E_F = E_i - kT \ln\left(\frac{N_A}{n_i}\right)$$

Charged Particles

- *Bethe–Bloch Formula*

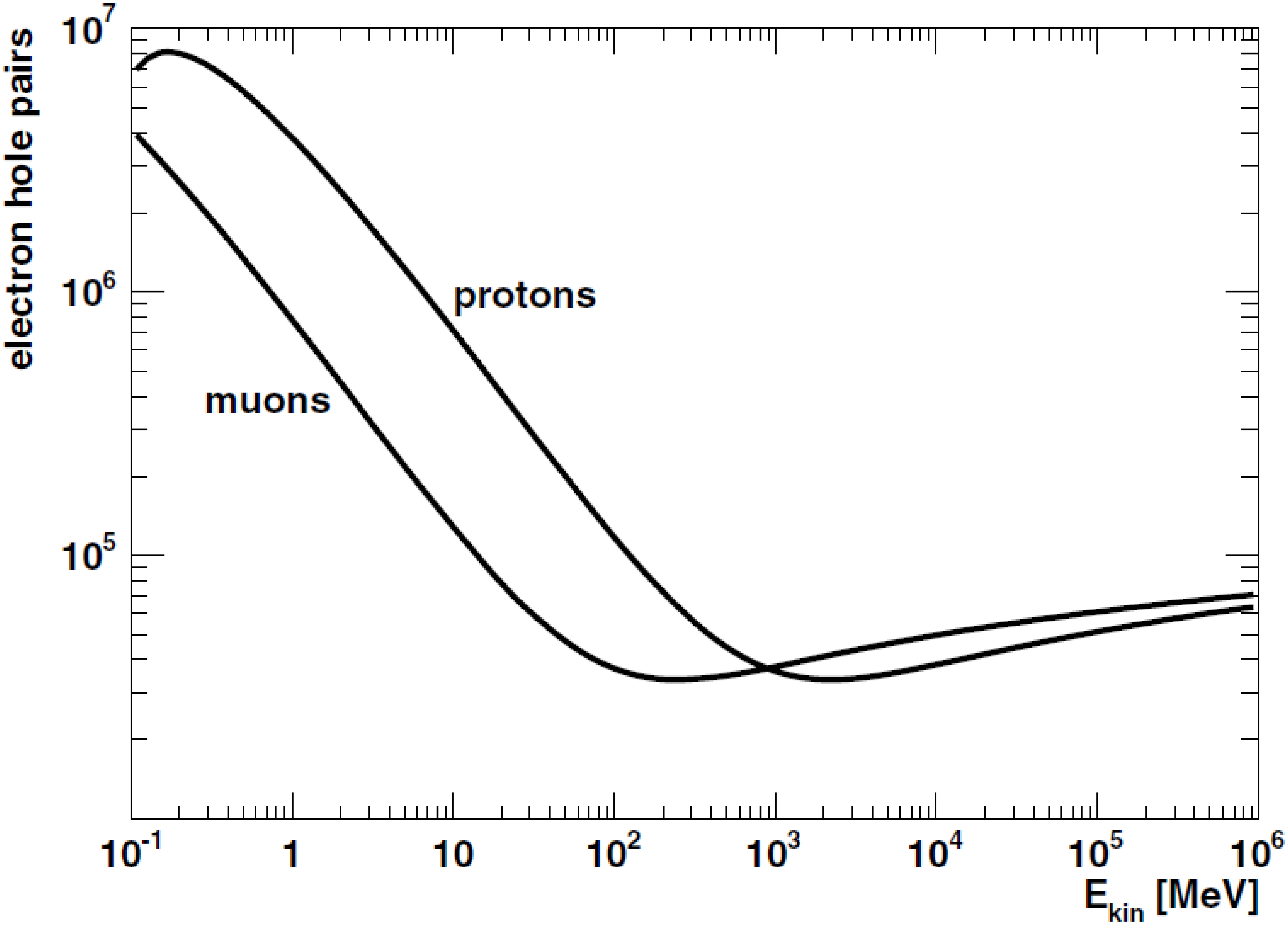
$$-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left(\frac{1}{2} \ln \frac{2m_\mathrm{e}c^2\beta^2\gamma^2T_\mathrm{max}}{I^2} - \beta^2 + \cdots \right), \qquad (2.9)$$

with

$\frac{\mathrm{d}E}{\mathrm{d}x}$	energy loss of the particle usually given in $\frac{\mathrm{eV}}{\mathrm{g/cm^2}}$
K	$4\pi N_\mathrm{Av} r_\mathrm{e}^2 m_\mathrm{e} c^2 = 0.307075\ \mathrm{MeV\ cm^2}$
z	charge of the traversing particle in units of the electron charge
Z	atomic number of absorption medium (14 for silicon)
A	atomic mass of absorption medium (28 for silicon)
$m_\mathrm{e}c^2$	rest energy of the electron (0.511 MeV)
β	velocity of the traversing particle in units of the speed of light
γ	Lorentz factor $1/\sqrt{1-\beta^2}$
I	mean excitation energy (137 eV for silicon)

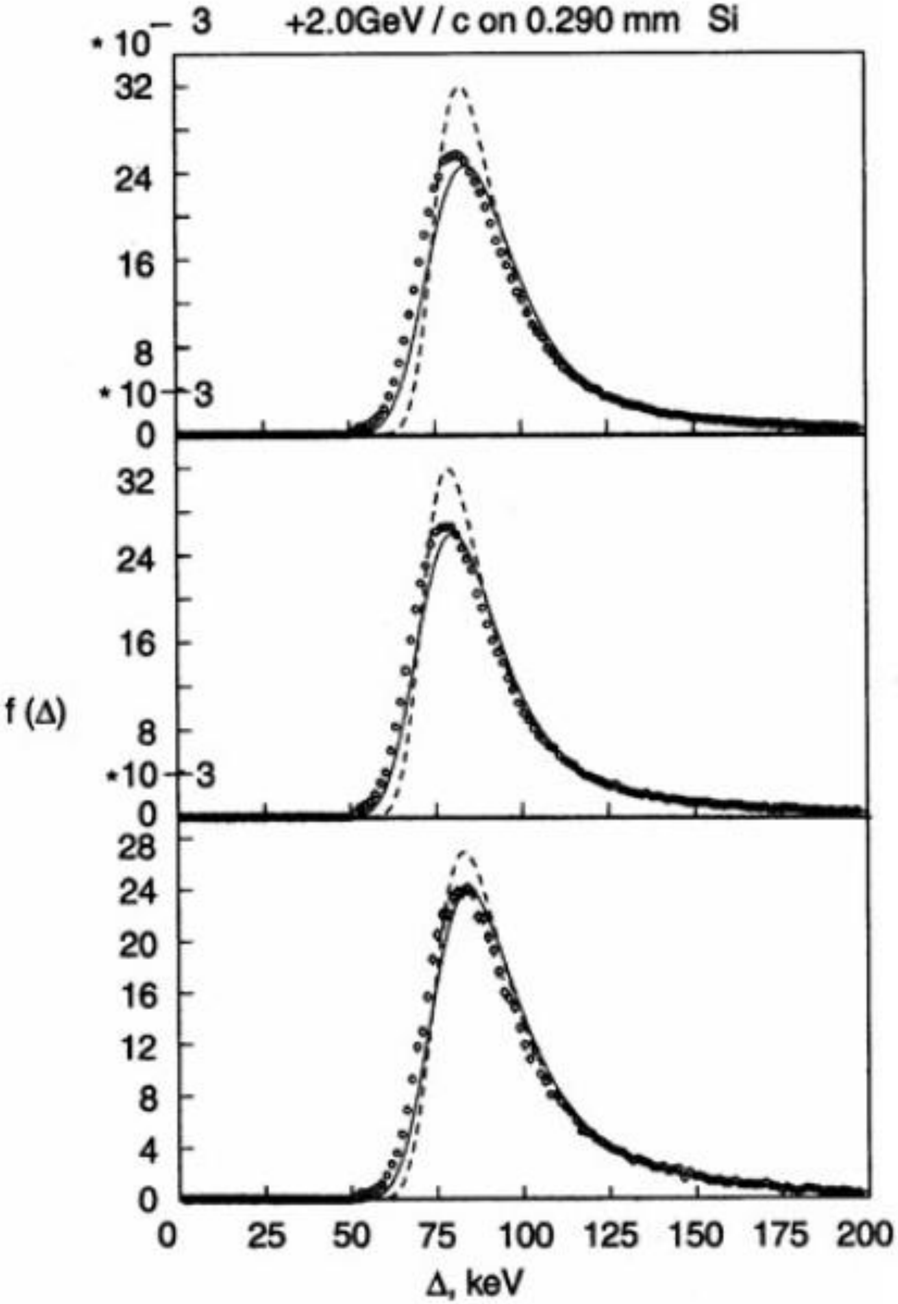
- Note that the dependence of (2.9) on the properties of the absorbing medium is fairly weak, as *Z/A ≈ 1/2 for most materials and* the other material-dependent quantities appear in the logarithmic term

- A particle with an energy loss in the minimum of the Bethe–Bloch formula is called a *minimum ionizing particle* (m.i.p.)
  - The value of the minimum depends on the square of the particle charge but very weakly on the particle mass
  - also used for all particles with $\beta > 0.96$
- Bethe–Bloch formula's use is therefore limited
- to the range of particle velocities $\beta > 0.1$


electron hole pairs
10^7
10^6
10^5
protons
muons
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
E_{kin} [MeV]

Landau distribution

- It is important to mention that the ionization is subject to statistical fluctuations and the value returned by (2.9) is only the average value of the so called *Landau distribution*
- The main reason for the Landau fluctuation is the rare but measurable occurrence of the so-called δ-electrons or knock-on electrons which obtain enough energy by the interaction to become ionizing particles themselves
- Due to this tail the average value is higher than the most probable value of the distribution
- The fluctuation around the maximum of this distribution becomes higher for thinner sensors


+2.0GeV / c on 0.290 mm Si
* 10⁻ 3
32
24
16
8
* 10 − 3
0
32
24
16
8
* 10 − 3
0
28
24
20
16
12
8
4
0
f (Δ)
0
25
50
75
100
125
150
175
200
Δ, keV

Shape of Ionization Path

- A minimum ionizing particle with unit charge generates a signal of about 23,000 electrons (most probable value) in 300 µm of silicon
- If the total charge can be collected in about 5 ns, it will produce a current of the order of 1 µA which by far exceeds the leakage current of a single cell in a pixel detector
- β-Particles produce a uniform charge cloud as long as their velocity remains relativistic. For this reason β-sources are often used in the laboratory to test silicon detectors.

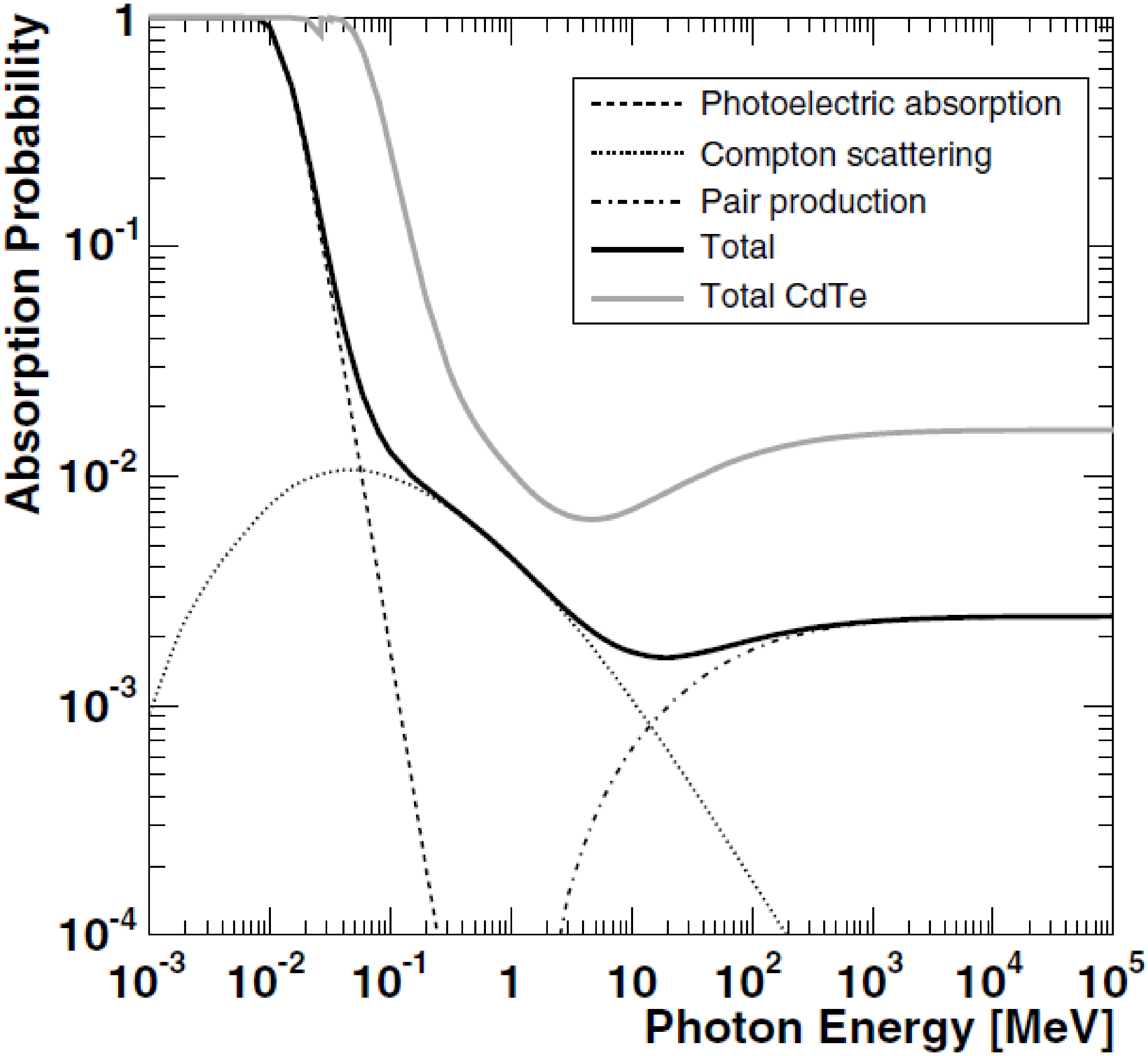
Multiple Scattering

$$\theta_{\rm plane}^{\rm rms} = \frac{13.6\ {\rm MeV}}{\beta p c} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

- θ is expressed in rad, the particle momentum p in MeV, The radiation length X0 of silicon is 9.36 cm which corresponds to a superficial density of 21.82 g/cm^2
- If one needs to calculate the scattering angle of a sample composed of several materials and layers, one should add all layers in units of the radiation length and apply (2.11) only once

Electromagnetic Radiation

- Photons interact with the sensor mainly via three processes, namely photoelectric effect, Compton effect, and pair production
- A monochromatic photon beam penetrating through material is attenuated in intensity according to $I(x) = I_0\, \mathrm{e}^{-x/\mu}$, attenuation length μ is a material property of the absorbing medium and depends on the photon energy


Absorption Probability
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
Photon Energy [MeV]
Photoelectric absorption
Compton scattering
Pair production
Total
Total CdTe

- photoelectric effect
  - below about 100 keV
  - Its cross section is strongly dependent on the nuclear charge *Z* $\sigma_{\text{Photo}} \propto Z^n$;
  - n varying between 4 and 5
- Compton scattering
  - linearly dependent on *Z*
- pair production
  - Energies exceeding twice the electron mass

$$(\text{with } \sigma \propto Z^2)$$

Fano Factor $N = \frac{E}{w}$

- The energy w required to create an electron–hole pair is about 3.6 eV in silicon
- The fraction of deposited energy that is used for electron–hole separation and phonon generation is subject to fluctuations which cause *N* to vary by $\langle \Delta N^2 \rangle = FN = F\frac{E}{w}$
- The experimental determination of this quantity is difficult

Generation and Recombination

- The thermal generation rate *Gth of* charge carriers, with *τg* being the generation lifetime

$$G_{\mathrm{th}} = \frac{n_{\mathrm{i}}}{\tau_{\mathrm{g}}}$$

- The recombination rate

$$R = \frac{p}{\tau_{\mathrm{r,n}}} \quad \text{for n-material} ,$$

$$R = \frac{n}{\tau_{\mathrm{r,p}}} \quad \text{for p-material} ,$$

- These excess carriers might be introduced by injection or radiation
- After injection or radiation has stopped, a thermal equilibrium leads to an exponential decay with the characteristic time *τr* removal of carriers will be unaffected, the equilibrium state is never reached

Transport of Charge Carriers

- Diffusion

$$J_{\mathrm{n,diff}} = -D_{\mathrm{n}}\boldsymbol{\nabla} n = -\frac{kT}{e}\mu_{\mathrm{n}}\boldsymbol{\nabla} n \quad \text{for electrons,}$$

$$J_{\mathrm{p,diff}} = D_{\mathrm{p}}\boldsymbol{\nabla} p = \frac{kT}{e}\mu_{\mathrm{p}}\boldsymbol{\nabla} p \quad \text{for holes,}$$

- Drift

$$v_{\mathrm{n}} = -\frac{e\tau_{\mathrm{c}}}{m_{\mathrm{n}}}\boldsymbol{E} = -\mu_{\mathrm{n}}\boldsymbol{E} \quad \text{for electrons,}$$

$$v_{\mathrm{p}} = \frac{e\tau_{\mathrm{c}}}{m_{\mathrm{p}}}\boldsymbol{E} = \mu_{\mathrm{p}}\boldsymbol{E} \quad \text{for holes,}$$

- τc isdependent on temperature, doping concentration, and the concentration of other lattice imperfections

- **At higher fields the charge carriers acquire a higher acceleration**
  - the number of random collision per unit time becomes higher
  - leads to a saturation of the drift velocity at saturation values

$$\mu = \frac{v_\mathrm{s}/E_\mathrm{c}}{\left[1+(E/E_\mathrm{c})^{\beta}\right]^{1/\beta}}$$

- **The low field mobility for intrinsic silicon at 300 K**

$$\mu_\mathrm{n} = 1,415 \pm 46\ \mathrm{cm}^2/(\mathrm{Vs}),$$

$$\mu_\mathrm{p} = \quad 480 \pm 17\,\mathrm{cm}^2/(\mathrm{Vs})\,.$$

  - Holes more prone to trapping especially in the irradiated material

Effect of Magnetic Field

$$\tan\theta_{\mathrm{L,n}} = \mu_{\mathrm{Hall,n}} B_{\perp} xs \quad \text{for electrons,}$$

$$\tan\theta_{\mathrm{L,p}} = \mu_{\mathrm{Hall,p}} B_{\perp} \quad \text{for holes,}$$

with $B_{\perp}$ being the magnetic field perpendicular to the drift velocity.

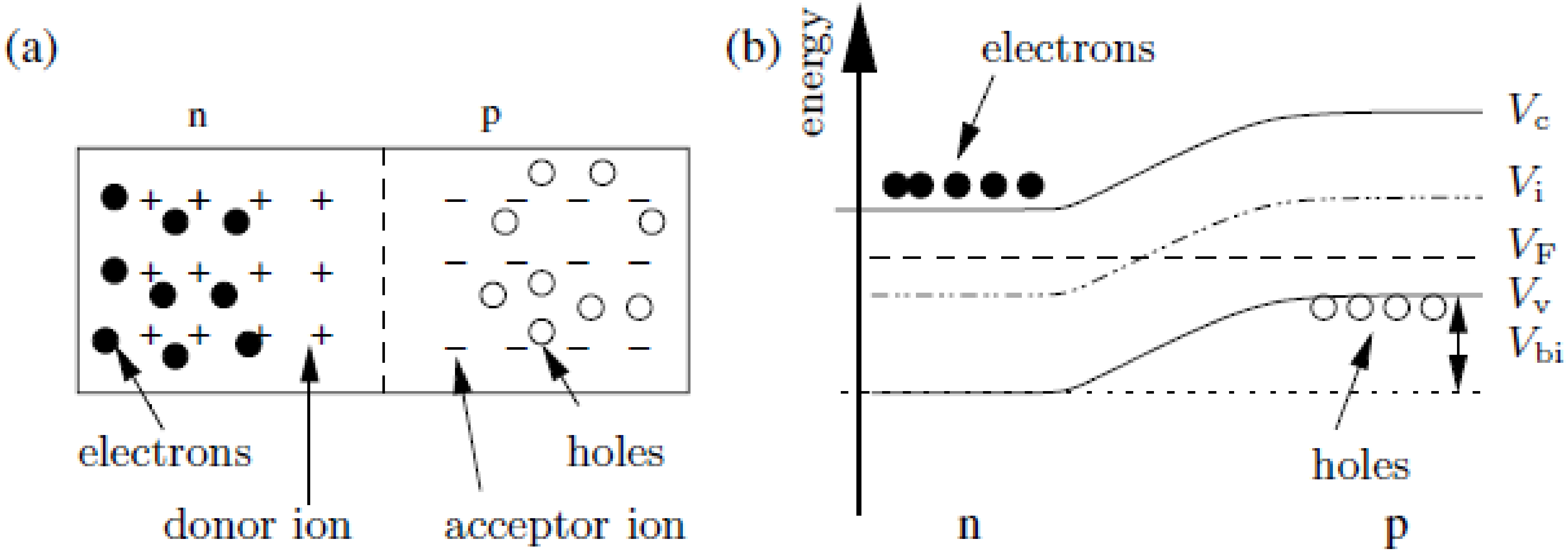
$$\mu_{\mathrm{Hall}} = r\mu$$

with values for r of 1.15 for electrons and 0.72 for holes at 0°C.

The pn-Junction

- **Thermal Equilibrium**
  - diffusion and drift current cancel each other
  - built-in voltage

$$V_{\mathrm{bi}} = \frac{kT}{e} \ln\left(\frac{n_{0,\mathrm{n}}\, p_{0,\mathrm{p}}}{n_{\mathrm{i}}^2}\right) \approx \frac{kT}{e} \ln\left(\frac{N_{\mathrm{D}} N_{\mathrm{A}}}{n_{\mathrm{i}}^2}\right)$$



$$W = x_{\mathrm{n}} + x_{\mathrm{p}} = \sqrt{\frac{2\varepsilon_0\varepsilon_{\mathrm{Si}}}{e}\left(\frac{1}{N_{\mathrm{A}}}+\frac{1}{N_{\mathrm{D}}}\right)(V+V_{\mathrm{bi}})}\,,$$

- proof

$$\oint_S \vec{D}\cdot d\vec{A} = Q$$

$$\frac{d\mathcal{E}}{dx} = \frac{q}{\epsilon}\left(p - n + N_d^{+} - N_a^{-}\right)$$

Within the depletion region, $n = p = 0$

$$\begin{cases} \dfrac{d\mathcal{E}}{dx} = \dfrac{q}{\epsilon}N_d\,, & 0 < x < x_{n0} \\[2ex] \dfrac{d\mathcal{E}}{dx} = -\dfrac{q}{\epsilon}N_a\,, & -x_{p0} < x < 0 \end{cases}$$

$$\mathcal{E}_0 = \frac{-q}{\epsilon} N_d x_{n0} = \frac{-q}{\epsilon} N_a x_{p0}$$

$$V_0 = \frac{-1}{2}\mathcal{E}_0 W = \frac{1}{2}\cdot\frac{q}{\epsilon} N_d x_{n0} W = \frac{1}{2}\frac{q}{\epsilon} N_a x_{p0} W$$

$$x_{n0} = \frac{N_a}{N_a + N_d} W$$

$$\boxed{W = \left[\frac{2\epsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{\frac{1}{2}} = \left[\frac{2\epsilon V_0}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{\frac{1}{2}}}$$

- highly doped (NA > 10^18 cm^−3) p+-implant in a low-doped (ND ≈ 10^12 cm^−3) bulk material
- built-in voltage of the order of 0*.5 V is small* compared to typical operation voltages exceeding in most cases 50 V

$$W \approx x_{\mathrm{n}} \approx \sqrt{\frac{2\varepsilon_0\varepsilon_{\mathrm{Si}}}{eN_{\mathrm{D}}}V}$$

- thermal generation in the depleted volume

$$J_{\mathrm{vol}} \approx -e\frac{n_{\mathrm{i}}}{\tau_{\mathrm{g}}}W \approx -e\frac{n_{\mathrm{i}}}{\tau_{\mathrm{g}}}\sqrt{\frac{2\varepsilon_0\varepsilon_{\mathrm{Si}}}{eN_{\mathrm{D}}}V}$$

- current doubles every 8 K

$$J_{\mathrm{vol}} \propto T^2 \mathrm{e}^{-E_{\mathrm{g}}(T)/2kT}$$

Forward Bias

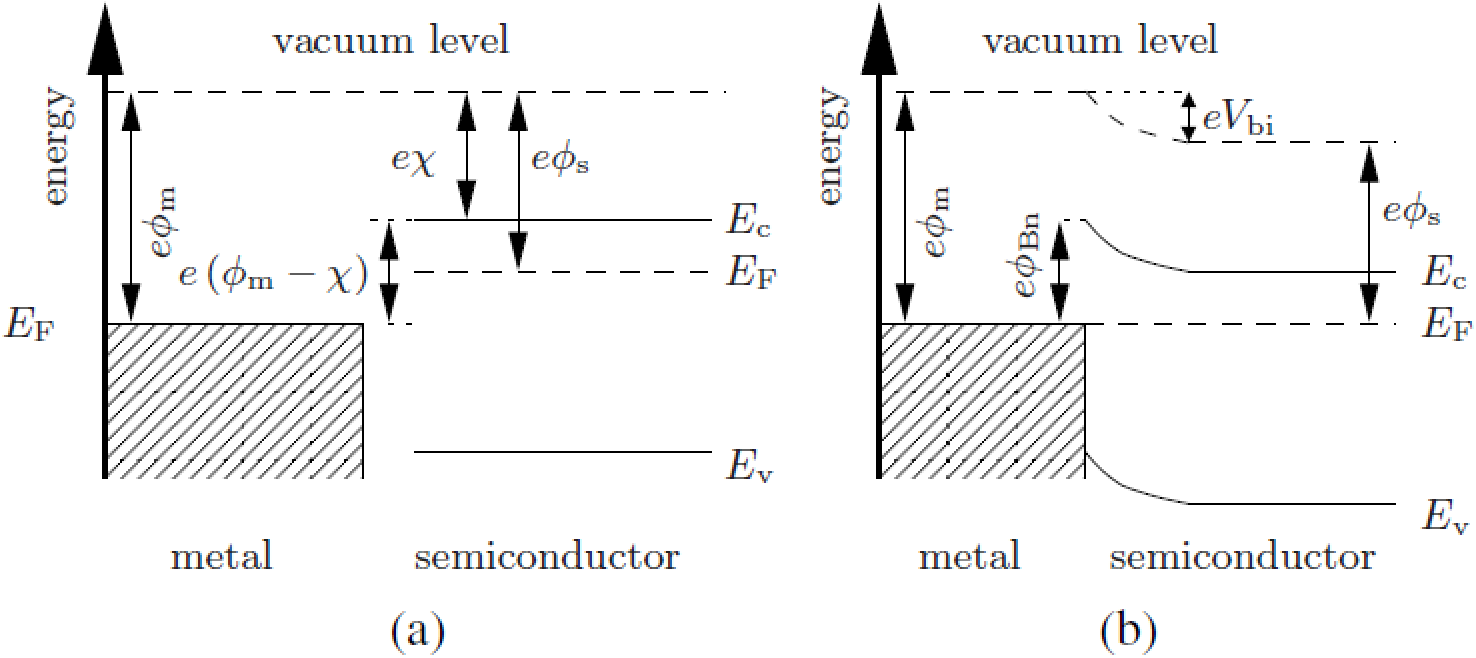
$$n_{\mathrm{p}} = n_{\mathrm{n}}\, \mathrm{e}^{-e(V_{\mathrm{bi}}+V)/kT} = n_{0,\mathrm{p}}\, \mathrm{e}^{-eV/kT} \qquad \text{for electrons,}$$

$$p_{\mathrm{n}} = p_{\mathrm{p}}\, \mathrm{e}^{-e(V_{\mathrm{bi}}+V)/kT} = p_{0,\mathrm{n}}\, \mathrm{e}^{-eV/kT} \qquad \text{for holes,}$$

Surface Barrier

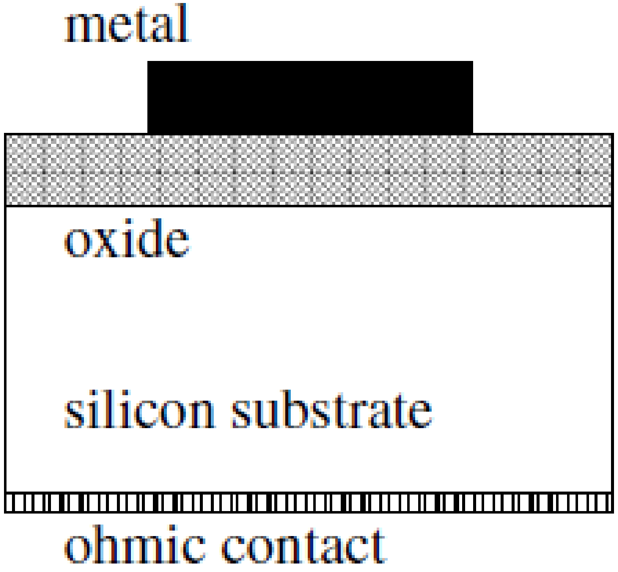
$$V_{\mathrm{bi}} = e(\phi_{\mathrm{m}} - \phi_{\mathrm{s}})\,.$$

$$\phi_{\mathrm{Bn}} = \phi_{\mathrm{m}} - \chi = V_{\mathrm{bi}} + \frac{1}{e}\left(E_{\mathrm{c}} - E_{\mathrm{F}}\right)$$



Metal Oxide Semiconductor Structure

- widely used in microelectronics
- In strip sensors MOS structures are often used as coupling capacitors while in charge coupled devices they are used for charge storage and transfer
- In pixel detectors, which are directly coupled to the readout electronics



- no direct current will flow thanks to the insulating oxide layer
- *surface field effect* :Due to the potential change at the surface of the silicon the bands will be moved relative to the Fermi level, causing a change in the distribution of free charge carriers

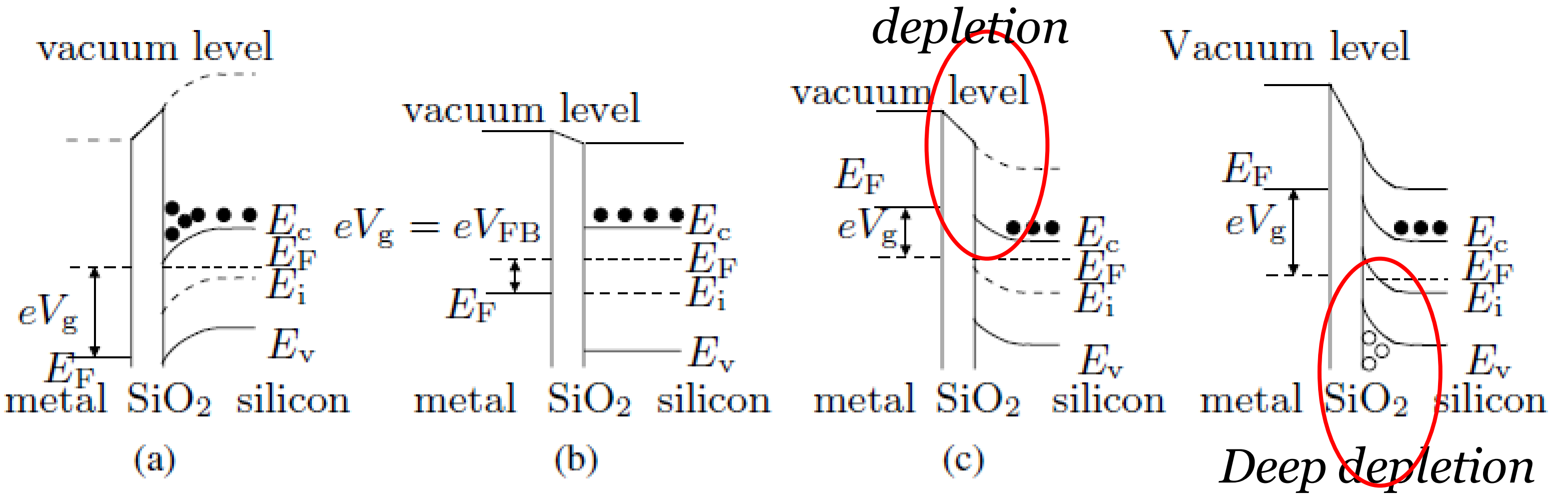


Fig. 2.10. Band diagram of a MOS structure in accumulation (a), flat band condition (b), depletion (c), and inversion (d). The *filled circles* indicate electrons, and the *open circles* holes

$$V_{\mathrm{FB}} = \underbrace{\phi_{\mathrm{m}} - \phi_{\mathrm{s}}}_{=:\phi_{\mathrm{ms}}} - \frac{ed}{\varepsilon_0 \varepsilon_{\mathrm{ox}}} N_{\mathrm{ox}} \ ,$$

with ϕ_{m} and ϕ_{s} being the work functions of the metal and semiconductor, d the thickness of the oxide, and N_{ox} the number of oxide charges per unit area.

$$W_{\text{deep depletion}} = \frac{\varepsilon_{\mathrm{Si}} d_{\mathrm{ox}}}{\varepsilon_{\mathrm{ox}}} \left[\sqrt{1 + \frac{2(V - V_{\mathrm{FB}})}{e N_{\mathrm{d}} \varepsilon_0 \varepsilon_{\mathrm{Si}}} \left(\frac{\varepsilon_0 \varepsilon_{\mathrm{ox}}}{d_{\mathrm{ox}}} \right)^2} - 1 \right]$$

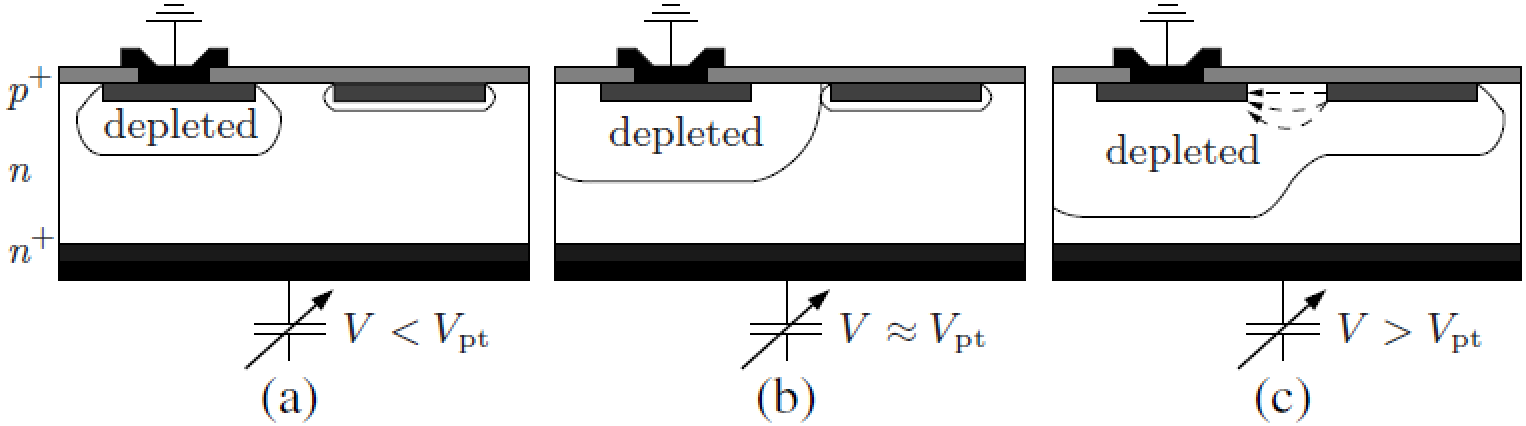
- **hole concentration exceed the electron concentration in the bulk and *strong inversion is reached***

$$d_{\max} = \sqrt{\frac{4\varepsilon_0 \varepsilon_{\mathrm{si}} \Psi_{\mathrm{B}}}{e N_{\mathrm{D}}}}, \ \Psi_{\mathrm{B}} = \frac{E_{\mathrm{F}} - E_{\mathrm{i}}}{e} = \frac{kT}{e} \ln \frac{N_{\mathrm{D}}}{n_{\mathrm{i}}}$$

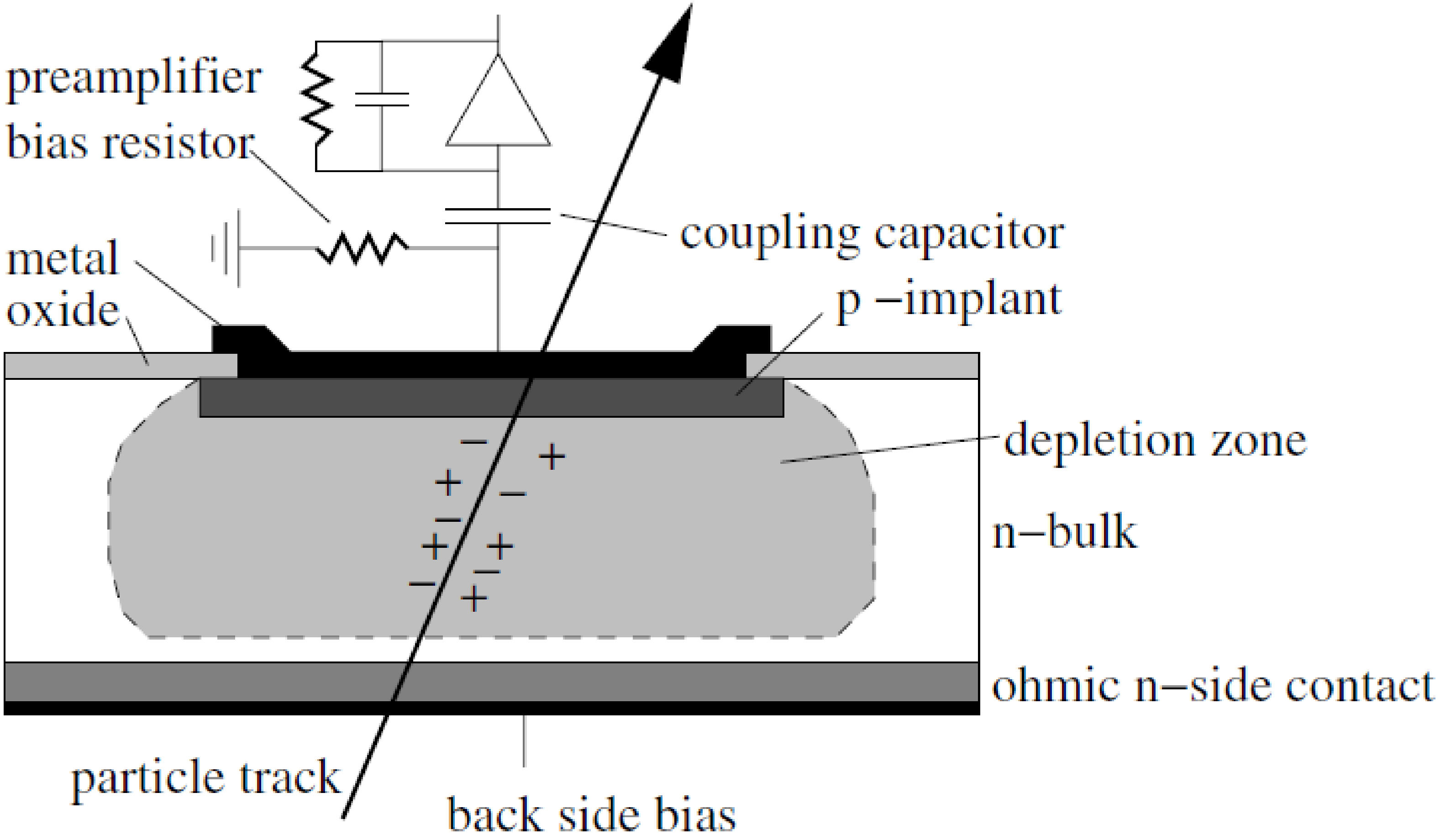
- The voltage at which strong inversion occurs is called, following MOS electronics nomenclature, threshold voltage *Vth*

$$V_{\mathrm{th}} = V_{\mathrm{FB}} - 2\Psi_{\mathrm{B}} - \frac{d_{\mathrm{ox}}}{\varepsilon_0 \varepsilon_{\mathrm{si}}} \sqrt{4eN_{\mathrm{D}}\varepsilon_0\varepsilon_{\mathrm{si}}\Psi_{\mathrm{B}}}$$

Punch Through

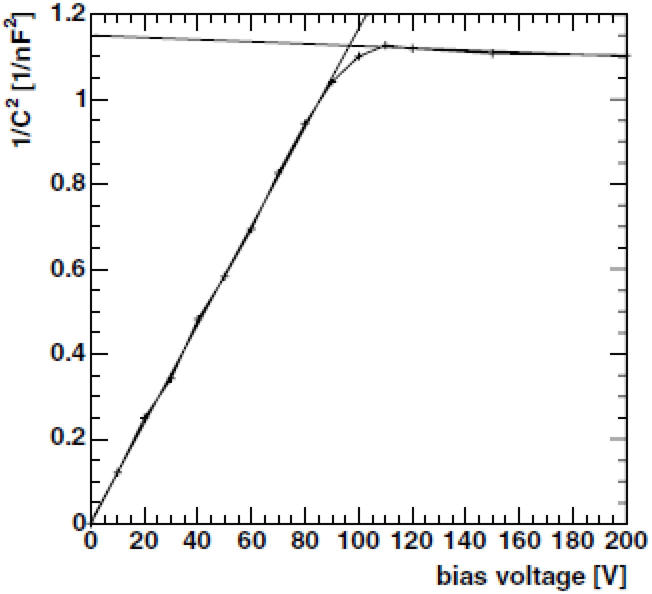


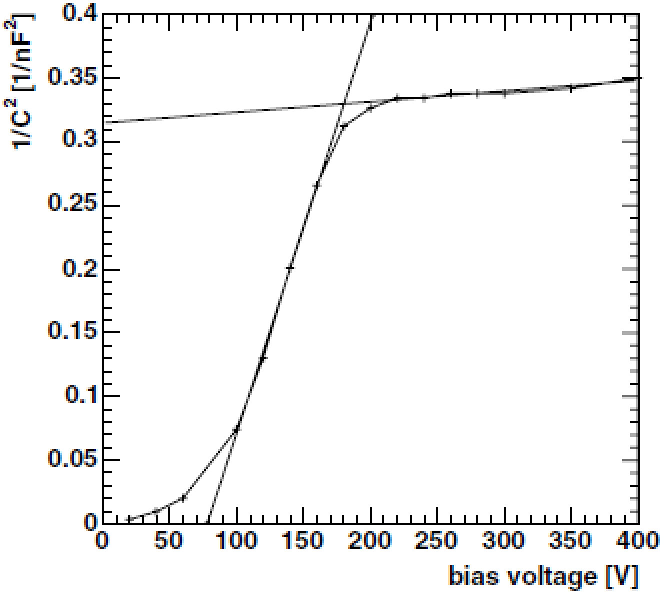
The simplest geometry Silicon Sensors



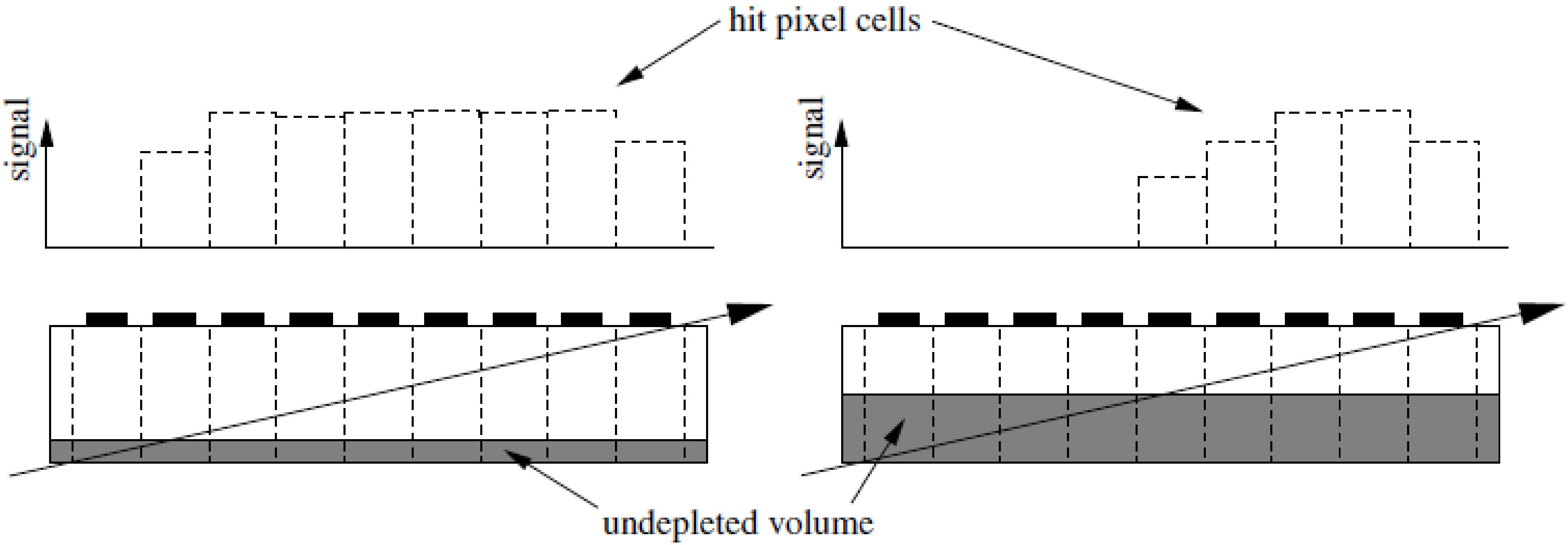
Full Depletion Voltage and Substrate Doping

$$C(V) = \frac{\varepsilon_0 \varepsilon_{\mathrm{Si}}}{W(V)} \approx \begin{cases} \sqrt{\dfrac{\varepsilon_0 \varepsilon_{\mathrm{Si}} e N_{\mathrm{D}}}{2V}} & \text{for } V < V_{\mathrm{depl}}, \\ \dfrac{\varepsilon_0 \varepsilon_{\mathrm{Si}}}{d} & \text{for } V > V_{\mathrm{depl}} . \end{cases}$$

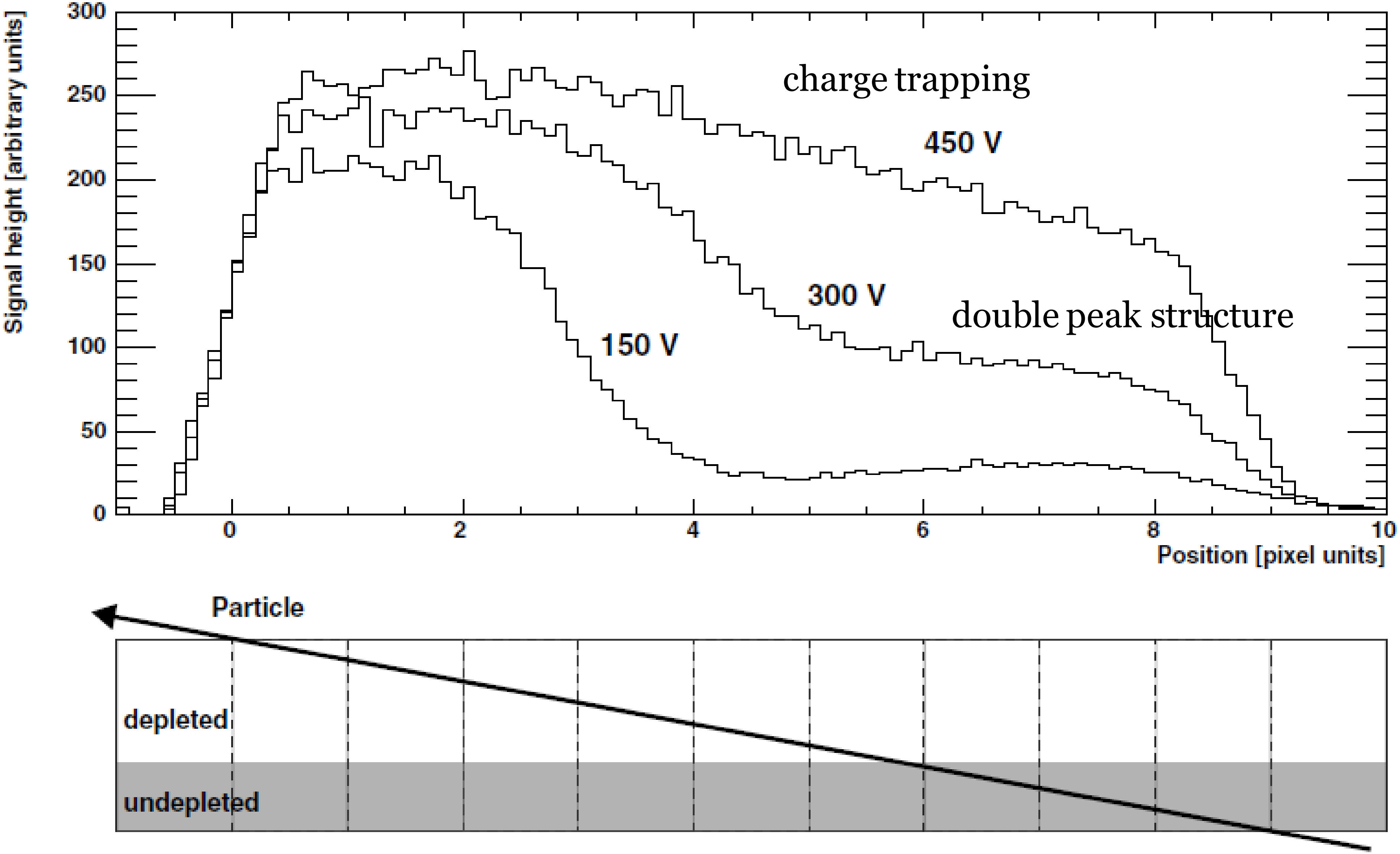




- After attaching the sensor to the readout chip



n+-in-n- sensor


Signal height [arbitrary units]
300
250
200
150
100
50
0
0
2
4
6
8
10
Position [pixel units]
charge trapping
450 V
300 V
150 V
double peak structure
Particle
depleted
undepleted

- Plot the response to a β-particle
  - When the full depletion voltage is reached the signal height saturates
- high energetic γ-source
  - The rate of signals delivered by the electronics will be proportional to the sensitive volume
- these three methods only work if the junction depleting the sensor is located at the side of the pixels as is the case in p+-in n sensors and in n+-in-n sensors which have undergone the radiation-induced type inversion.

Pixel Capacitance

$$C = \varepsilon_0 \varepsilon_{\mathrm{Si}} \frac{A}{d}$$

$20,000\,\mu\mathrm{m}^2$ on 300-µm-thick silicon

- Capacitance to the backside

7 fF

- *interpixel capacitance :* Sum of the capacitances to the neighbor pixels

60 fF for a $125 \times 125\,\mu\mathrm{m}^2$ pixel with 20-µm gap

- Capacitance to the ground plane of the (closely spaced) readout chip
- Other (small) contributions, like the capacitance of the bumps

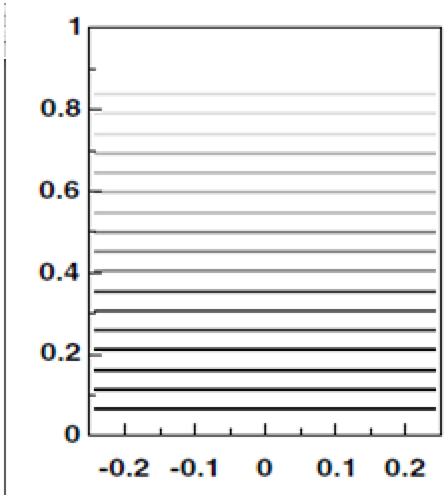
Charge Motion and Signal Formation

$$i = eE_{\mathrm{w}}v \qquad Q = \int^{t_2} i(t)\,\mathrm{d}t = e\left[\phi_{\mathrm{w}}(x_1) - \phi_{\mathrm{w}}(x_2)\right]$$

E_{w} is the so-called *weighting field.*

ϕ_{w} is *weighting potential*

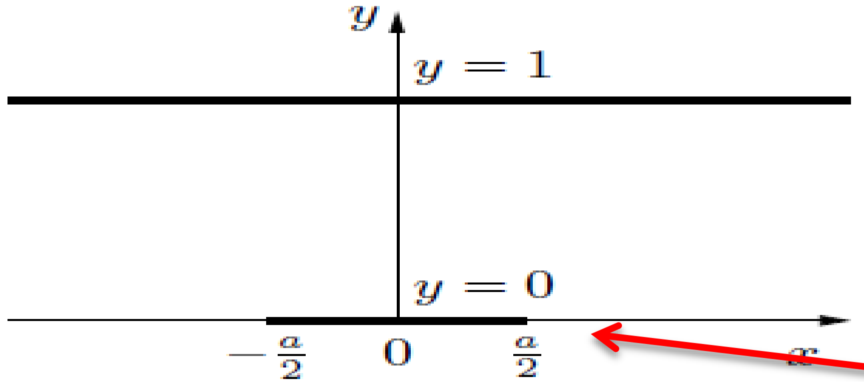
In a pad detector

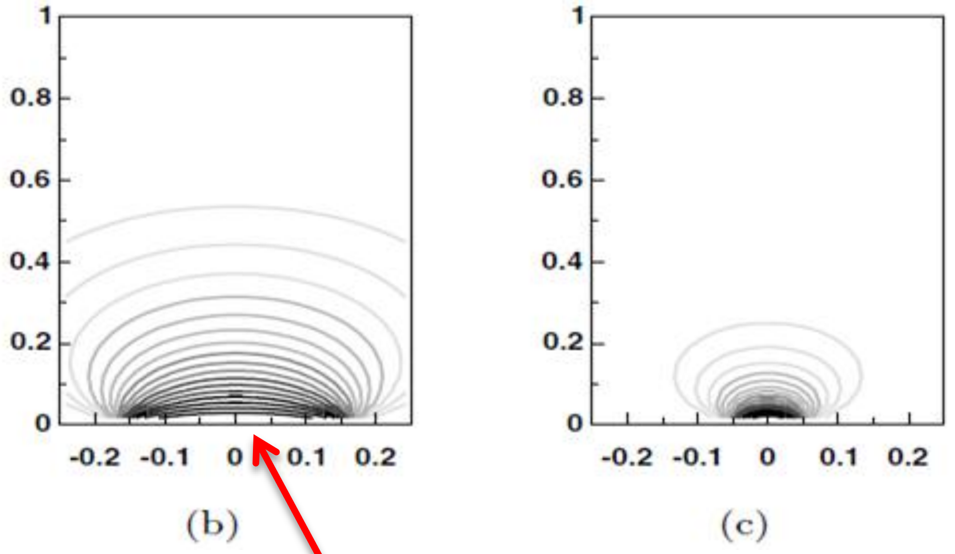


(a)

- **The weighting potential is a linear function of the depth**
  - The charge induced is the same for any part in the drift path.
  - If an electron–hole pair is generated in the middle of the detector, the hole approaching the electrode induces the same signal as the electron departing from it.

$$\phi_{\mathrm{w}} = \frac{1}{\pi}\arctan\left[\frac{\sin(\pi y)\,\sinh\left(\pi\frac{a}{2}\right)}{\cosh(\pi x)-\cos(\pi y)\,\cosh\left(\pi\frac{a}{2}\right)}\right]$$





collecting electrode

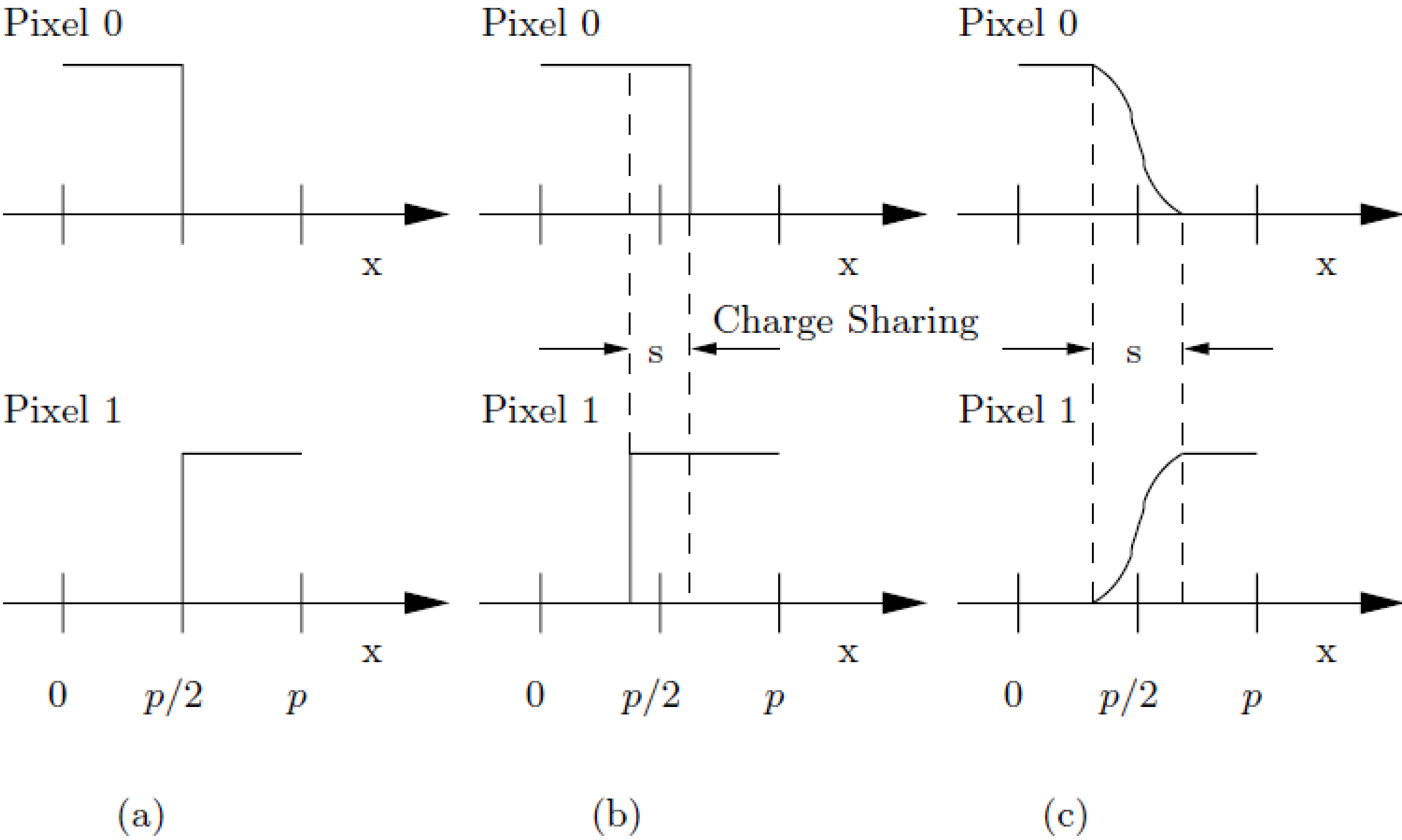
- **small pixel effect**
  - Most of the signal is induced in the last part of the charge drift path
  - Charge carriers drifting toward the backplane do not contribute significantly to the signal

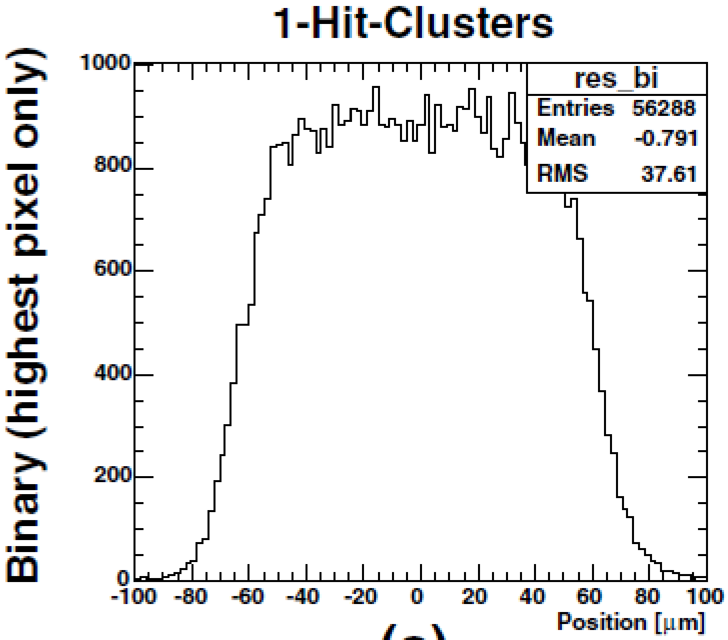
Spatial Resolution

$$\sigma_{\text{position}} = \frac{p}{\sqrt{12}}$$

- **Binary Readout**
  - The threshold is adjusted in such a way that only one pixel per particle track fires.
  - Only particles hitting the detector between −p/2 and p/2 trigger a signal in pixel 0.
  - The detector is hit by a uniform density of particles, $D(x) = 1$
- **two (or more) pixels can be triggered by the same particle**
  - the threshold of the readout electronics is set as low as possible without getting a too high rate of noise hits

Analog Readout





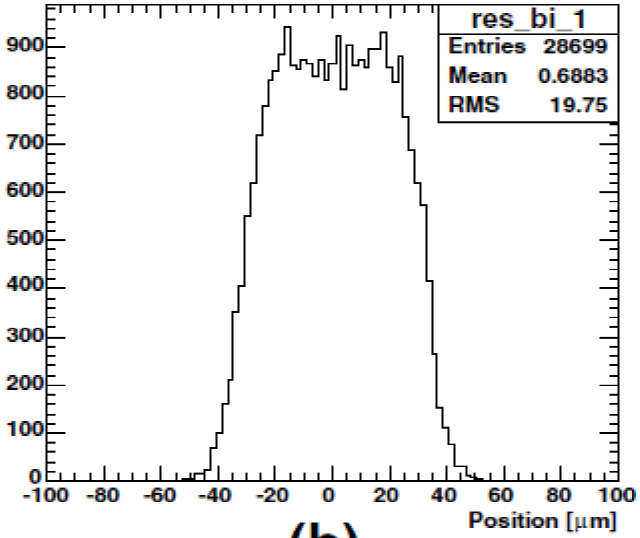
1-Hit-Clusters

(a)

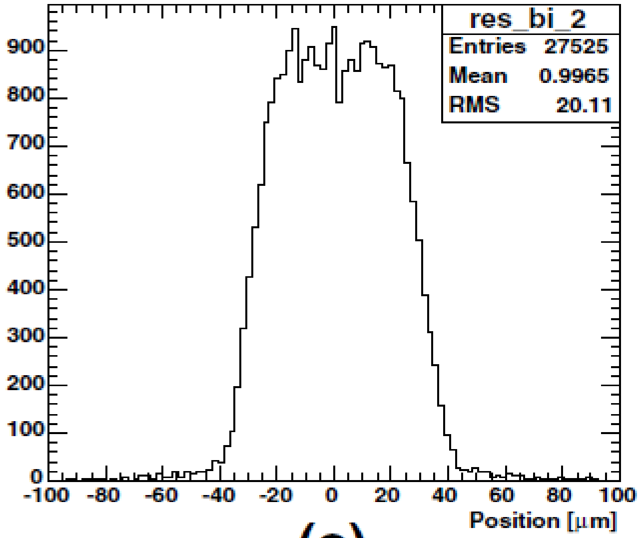
owo-pixel clusters

two-pixel clusters

Binary with double hits

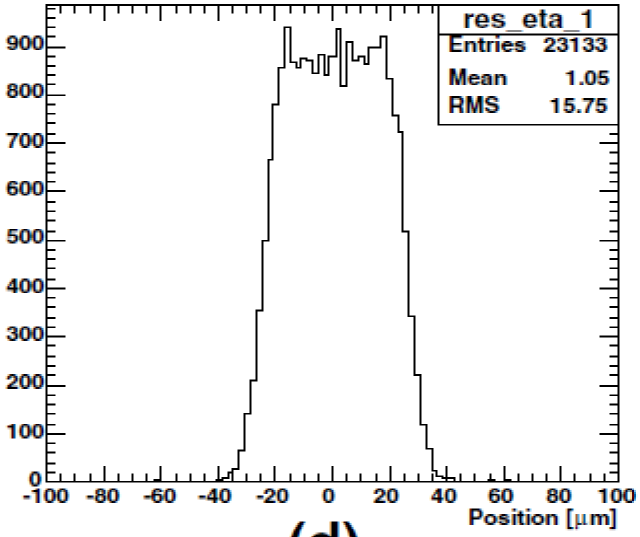


(b)

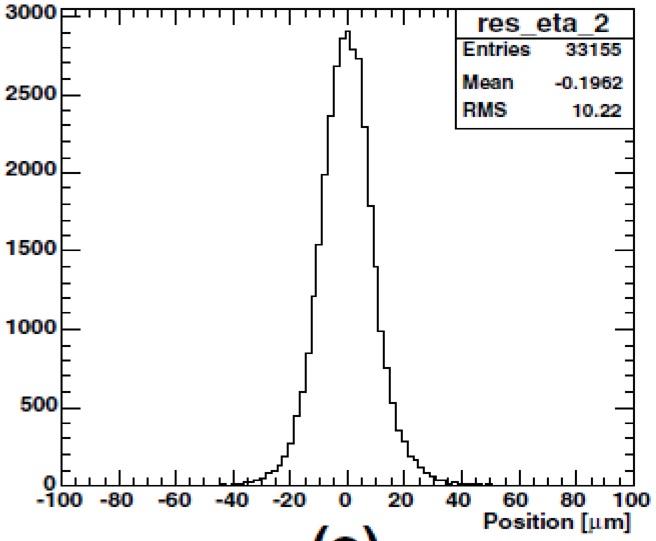


(c)

Analogue reconstruction

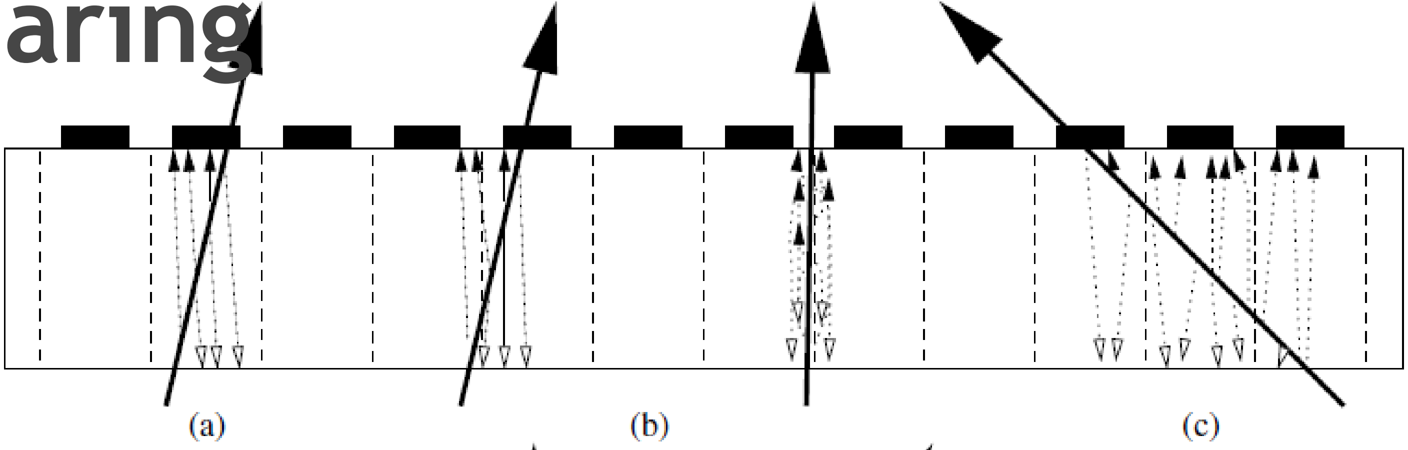


(d)

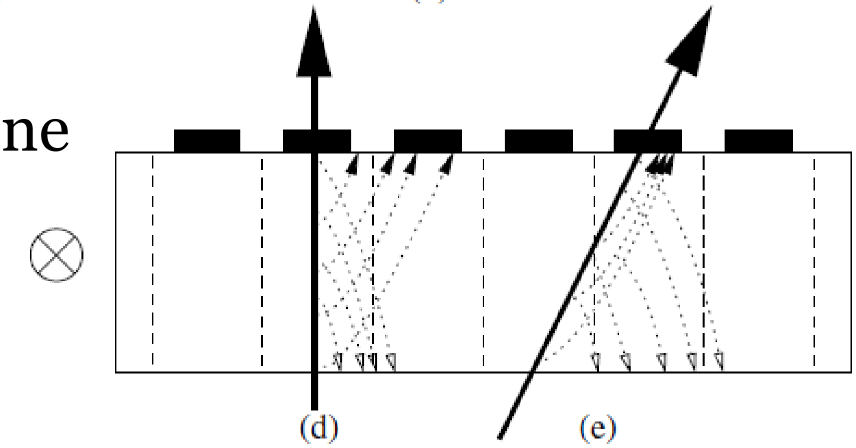


(e)

Charge Sharing



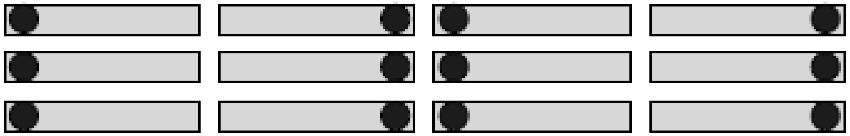
In order to guarantee track efficiency, at least one pixel in a cluster must collect enough charge to overcome its threshold.



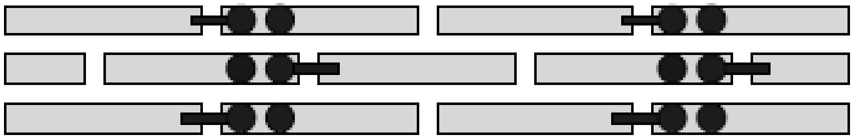
- after irradiation,higher voltage necessary to operate the detector
- The Lorentz angle decreases

Pixel Pattern

- Reducing the probability for four-pixel clusters



(a)



(b)

Bulk Damage

- To remove a silicon atom from its lattice position
  - Electrons need an energy of at least 260 , while protons and neutrons require only 190 eV.
- If energy exceeds about 2 keV, it will creat a cluster of defects
- cause energy levels in the band gap
- have an impact on the space charge in the depletion zone

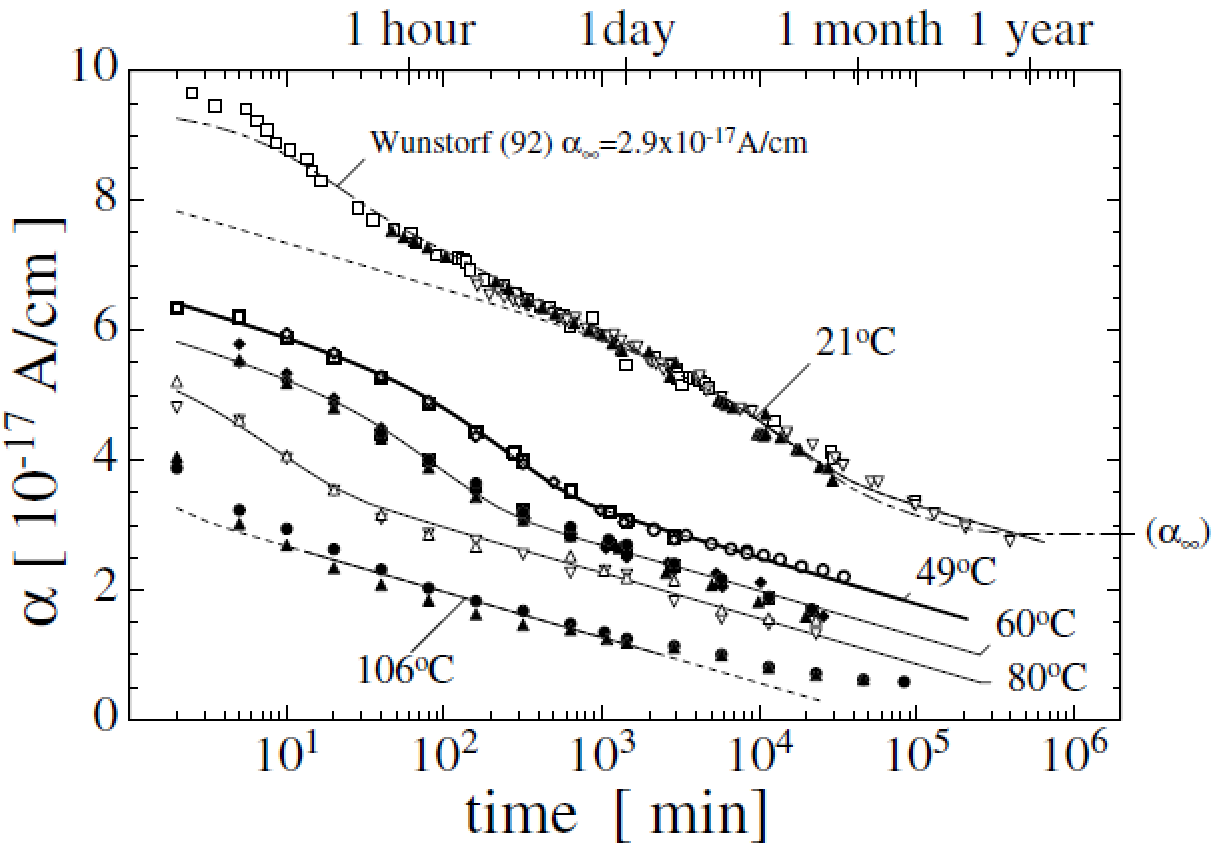
Leakage Current

- decrease of the generation lifetime τg and an increase of the volume generation current Ivol proportional to the fluence Φ:

$$\frac{1}{\tau_\mathrm{g}} = \frac{1}{\tau_{\mathrm{g},\Phi=0}} + k_\tau \Phi$$

$$\frac{I_\mathrm{vol}}{V} = \frac{I_{\mathrm{vol},\Phi=0}}{V} + \underbrace{\alpha\Phi}_{\Delta I_\mathrm{vol}/V} ,$$

$$\alpha = e n_\mathrm{i} k_\tau$$



$$\alpha(t) = \alpha_{\rm i} \exp\left(-\frac{t}{\tau_{\rm i}}\right) + \alpha_0 - \beta \ln\left(\frac{t}{t_0}\right)$$

t_0 arbitrarily set to 1 min

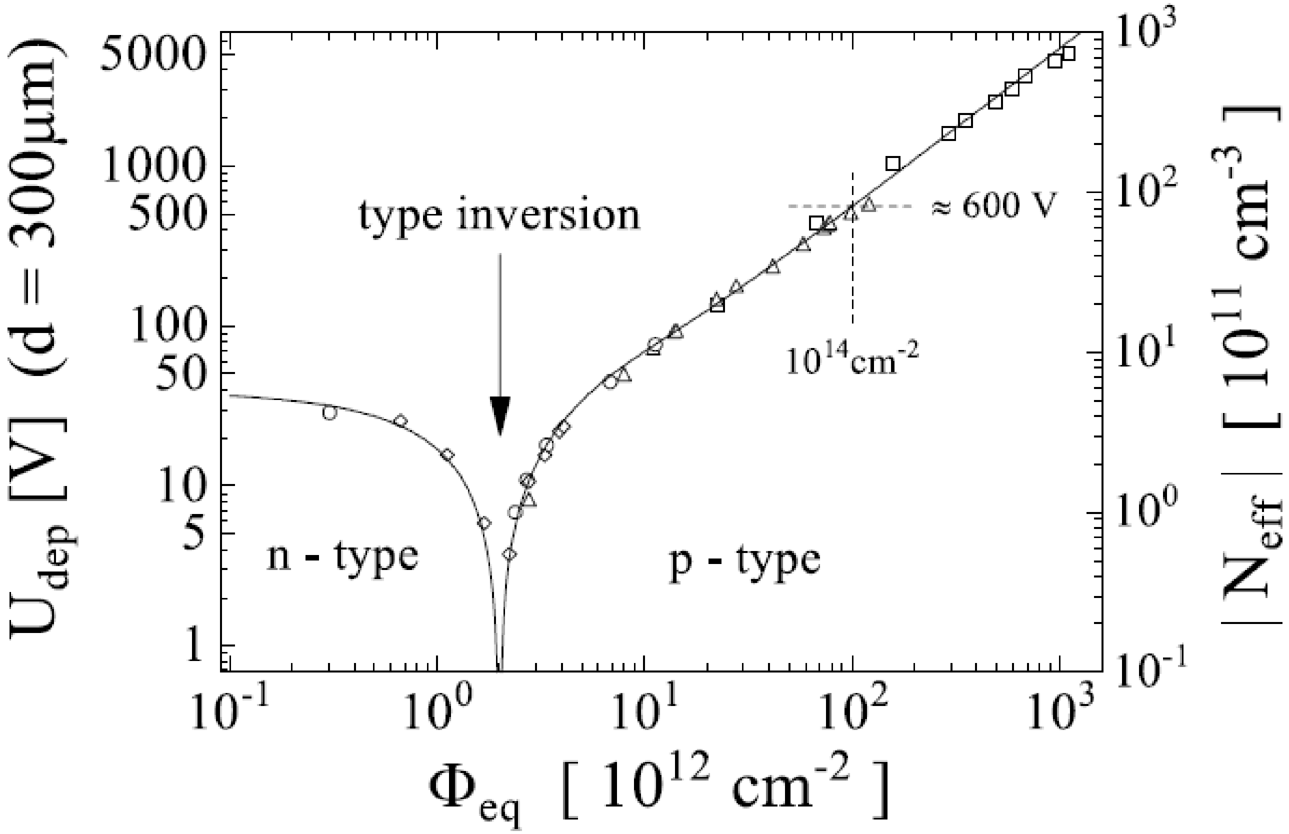
$$\frac{1}{\tau_{\rm i}} = k_{0,{\rm i}} \exp\left(-\frac{E_{\rm i}}{kT_{\rm a}}\right)$$ dependence on the annealing temperature $T_{\rm a}$

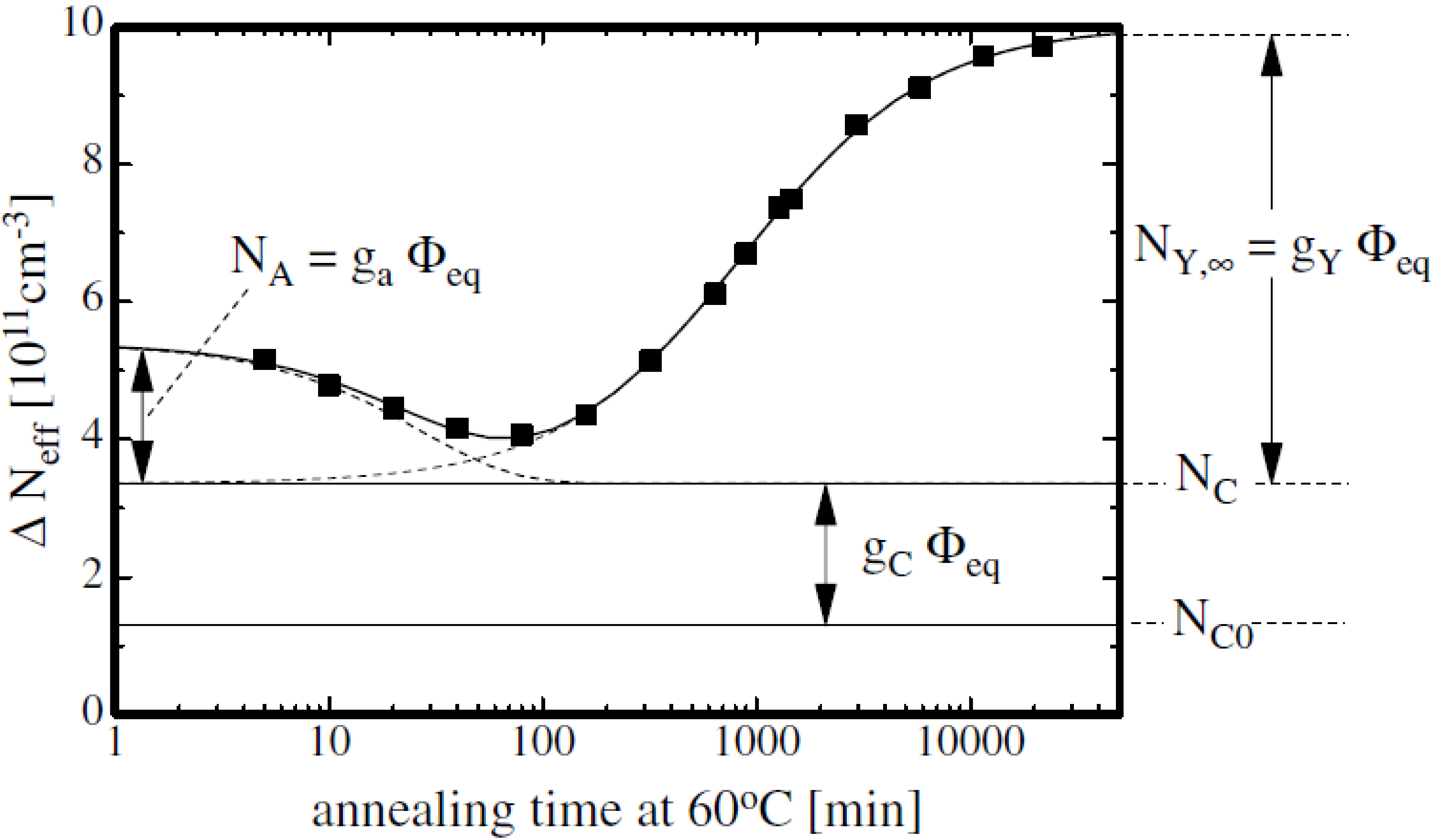
Effective Doping $|N_{\mathrm{eff}}| = \frac{2\varepsilon_0\varepsilon_{\mathrm{si}}V_{\mathrm{depl}}}{ed^2}$

- the doping concentration was equated with the concentration of donors ND or acceptors NA assuming that on each side one of those is so much dominant that all other contributions may be neglected
- If several dopings and electrically active defects are present,these numbers have to be replaced by a quantity called net doping or effective doping Neff , which is the difference of all donor-like states and all acceptor-like states

Fluence Dependence

$$N_{\mathrm{eff}} = N_{\mathrm{eff},\Phi=0} - \underbrace{\left[N_{\mathrm{C}}(\Phi) + N_{\mathrm{a}}(\Phi, T_{\mathrm{a}}, t) + N_{\mathrm{Y}}(\Phi, T_{\mathrm{a}}, t)\right]}_{\Delta N_{\mathrm{eff}}(\Phi, T_{\mathrm{a}}, t)}$$




ΔN_{eff} [10^{11}cm^{-3}]
0
2
4
6
8
10
1
10
100
1000
10000
annealing time at 60°C [min]
$N_A = g_a \Phi_{eq}$
$N_{Y,\infty} = g_Y \Phi_{eq}$
N_C
$g_C \Phi_{eq}$
N_{C0}

$$N_{\mathrm{C}}(\Phi) = N_{\mathrm{C},0}\left(1 - \mathrm{e}^{-c\Phi}\right) + g_{\mathrm{c}}\Phi.$$

- The initial concentration of removable donors

$$N_{\mathrm{C},0} = (0.6\text{–}0.9) \times N_{\mathrm{eff},\Phi=0}.$$

- Initial acceptors will also be removed exponentially with the fluence
- These defects are acceptor-like in a sense that they lead to a negative space charge and hence to an increase of the full depletion voltage
- However, they do not lead to an increase of the conductivity of the material, because the levels caused by these defects are deep in the band gap

Short-Term Annealing

$$N_a = \Phi \sum_i g_{a,i}\, e^{-t/\tau_{a,i}(T_a)} \approx \Phi g_a\, e^{-t/\tau_a(T_a)}$$

- Short annealing times (of the order of hours or less) are not relevant for the operation of the sensors

$$\frac{1}{\tau_a(T_a)} = k_{a,0}\, e^{-E_a/kT_a} \ ,$$

with $k_a, 0 = 2.4^{+1.2}_{-0.8} \times 10^{13}\,\mathrm{s}^{-1}$ and $E_a = (1.09 \pm 0.03)\,\mathrm{eV}$.

Reverse Annealing

- describes the increase of the full depletion voltage after some weeks at room temperature

$$N_{\mathrm{Y}} = \underbrace{g_{\mathrm{Y}} \Phi}_{N_{\mathrm{Y},\infty}} \left(1 - \frac{1}{1 + t/\tau_{\mathrm{Y}}}\right) , \qquad (2.53)$$

with $g_{\mathrm{Y}} = (5.16 \pm 0.09) \times 10^{-2}\,\mathrm{cm}^{-1}$ and a fluence-independent time constant

$$\frac{1}{\tau_{\mathrm{Y}}} = k_{\mathrm{Y},0}\, \mathrm{e}^{-E_{\mathrm{Y}}/kT_{\mathrm{a}}}$$

containing the parameters $k_{\mathrm{Y}},0 = 1.5^{+3.4}_{-1.1} \times 10^{15}\,\mathrm{s}^{-1}$ and $E_{\mathrm{Y}} = (1.33 \pm 0.03)\,\mathrm{eV}$.

Oxygen-Enriched Material

- It was found out that the enrichment of the silicon substrate with oxygen, which is believed to capture vacancies in stable and electrically neutral point defects, leads to a superior postradiation performance

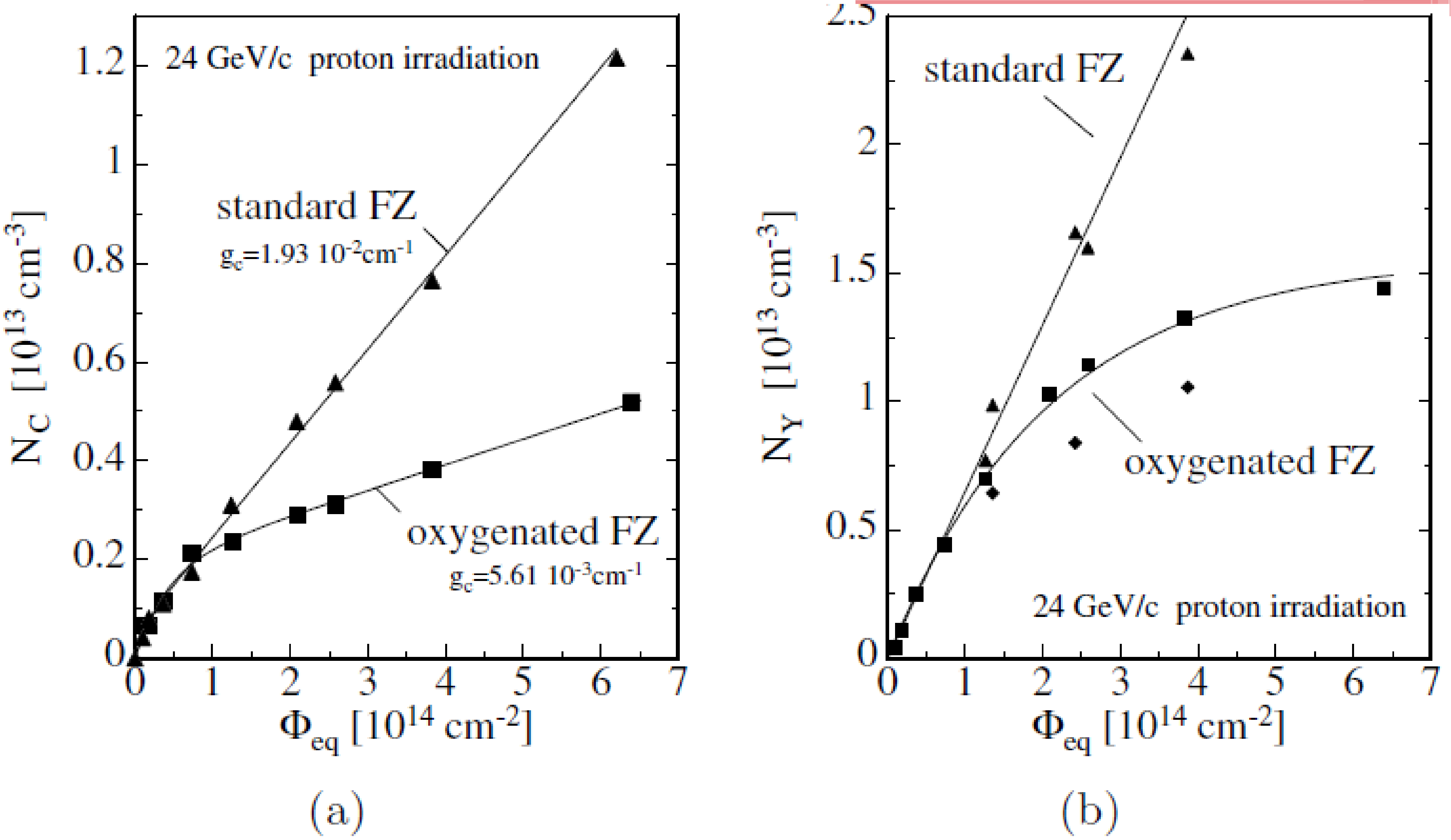


Fig. 2.27. Comparison of oxygenated (DOFZ) and standard(FZ) material. Damage parameters N_C describe the stable damage (a) and the parameters N_Y describe the amplitude of reverse annealing (b) [109]

Noninverted Surface Layer

- Regions close to the sensor's surface do not undergo the process of type inversion and remain n-type
- The reason of this effect is still unclear

Charge Trapping

- Traps are mostly unoccupied in the depletion region due to the lack of free charge carriers and can hold or trap parts of the signal charge for a time longer than the charge collection time and so reduce the signal height

$$\frac{1}{\tau_{\mathrm{t}}(\Phi)} = \frac{1}{\tau_{\mathrm{t},\Phi=0}} + \gamma\Phi\,.$$

- in particle physics this effect is much less of a problem than the other radiation-induced effects already mentioned
- trapping will eventually limit the use of silicon detectors for fluences much beyond

$$10^{15}\,\mathrm{n_{eq}}/\mathrm{cm}^2$$

Influence of Bulk Damage on Sensor Operation