Detector Physics

Ionisation Detectors I - Semiconductor Detectors

Alfredo Davide Ferella

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Lecture Summary

Semiconductor Detectors

Introduction

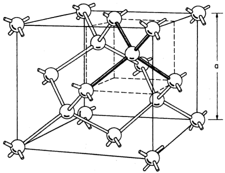
- Main applications:
  - γ-ray spectroscopy with very high energy resolution
  - vertex detectors with high spatial resolution
  - very accurate energy measurements of charged particles
  - PID via dE/dx (multiple layers)

  Many great advantage:
  - 1000 times more dense than gases therefore compact
  - Best resolution in routine use radiation detectors
  - Relatively fast timing characteristics
- Also few disadvantages:
  - Limitation to small size
  - Relatively high radiation damage susceptibility
- Same principles of ionisation detectors: no ion pairs but electron-hole pairs
- Technology started in early 1960s. Originally "crystal counters", nowadays "semiconductor" or "solid state detectors".
- Of all the semiconductors existing the main ones used in radiation detection are:
  - Silicon, used in charged particles spectroscopy
  - Germanium, widely used in gamma-ray measurements

Band Structure

Band Structure in Solids

- Most commonly used semiconductors are single crystals with diamond (with Si and Ge) or zinc blende (e.g. GaAs) structure



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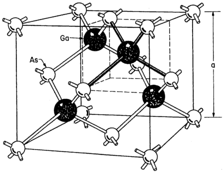

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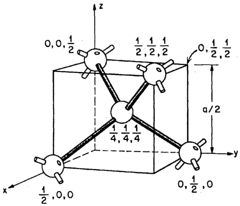
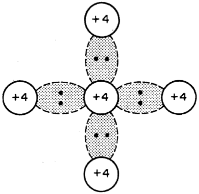


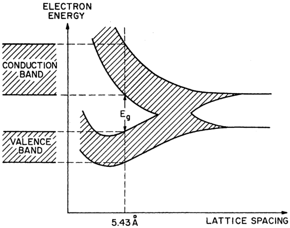


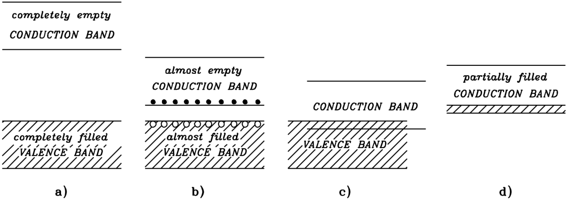
- All atoms in the diamond lattice are identical, while the two fcc sublattices are built of different atoms in the case of III-V compounds such as GaAs
- The atoms are arranged in a tetrahedron and each atom shares its four outer (valence) electrons with those of the neighbours, thus forming covalent bonds
- Each tetrahedron repeats itself
- At low temperatures all valence electrons remain bound in their respective tetrahedral lattice.
- At higher temperatures thermal vibrations may break the covalent bond and a valence electron may become a free electron, leaving behind a free place or hole

Both the electron and the hole are available for conduction

Band Structure in Solids

- Quantum mechanical calculations of the energy levels of the atoms as a function of the lattice spacing (for Si) (left):





- The spacing corresponding to silicon is indicated in the Figure above and corresponds to the minimum total energy of the electrons and the lattice, not very far from the minimum energy of the electrons in the filled valence band.
- The difference between the valence and the conduction band is called bandgap (E_g).
- In the Figure on the right the different energy band structures of the different solids are displayed.

Charge Carriers in an Electric Field

- As for gases, both charge carriers migrate with a combined random thermal velocity and a net drift velocity parallel to $\mathscr{E}$ direction.
- Contrarily to gases, the hole mobility is of the same order as for electrons
- At low-moderate fields the drift velocity is proportional to $\mathscr{E}$. For high $\mathscr{E}$ the drift velocity reaches a saturation velocity.
- Semiconductor detectors when operated at saturation have drift velocities of the order of 10^7 cm/s
- For a 0.1 cm thick silicon detector (typical dimension) the charge collection time is in the order of $\lesssim 10$ ns (fastest!)
- The diffusion of the free electron-hole pairs is characterised by the standard deviation of the Gaussian distributed arrival positions at the electrodes, given by:

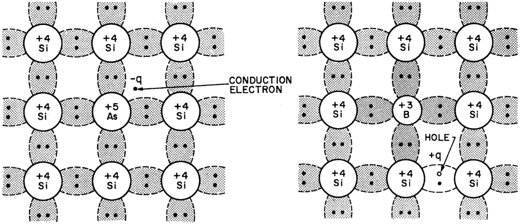
$$\sigma = \sqrt{\frac{2kTx}{e\mathscr{E}}} \tag{1}$$

Carefull! Diffusion broadening can limit precision of position reconstruction.

Intrinsic and Extrinsic Semiconductors

From now on we will use the following notation:

- ✓ n the concentration of electrons in the conduction band
- ✓ p the concentration of holes in the valence band

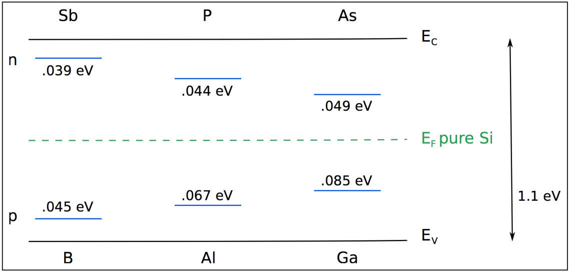


(a) (b)

- intrinsic semiconductors:
  - very pure material, charge carriers are created by thermal or optical excitation of electrons to conduction band $n_i = p_i$

- impurity or extrinsic semiconductors:
  - majority of charge carriers provided by impurity atoms at lattice sites of crystal
  - impurity atoms provide either an extra electron above the number required for covalent bonds $\longrightarrow$ majority charge carriers are electrons 'n-type semiconductor' or
  - impurity atoms have insufficient number of electrons for covalent bonds, free hole at impurity site $\longrightarrow$ majority charge carriers are holes 'p-type semiconductor'

- most common:
  - crystal of element of group IV such as Si or Ge
  - impurities of group V (P, As, Sb) or of group III (Al, Ga, In)
  - but also GaAs or CdS
- in semiconductors like Si, Ge, GaAs, lower edge of conduction band E_c only a few eV above upper edge of valence band E_v .



- The replacement of a proper atom of the lattice by a different atom is accompanied by the creation of localised energy levels in the band gap
- These energy levels may be of the donor (E_D) or acceptor (E_A) type
- donor levels E_D are close to the conduction band

at room temperature donor's electrons will be transported to the conduction band

electron donors (P, Sb, . . .): 5^{th} electron bound only weakly in crystal can easily be promoted ('donated') into conduction band (Li-like)

electron acceptors (B, Al, . . .): only valence electrons, one unsaturated binding in crystal tendency to 'accept' an electron from Si leaving behind a hole in valence band

Law of mass action:

$$np = N_c N_v \exp\left[-(E_c - E_v)/kT\right] = n_i^2 \qquad (2)$$

The product of n and p at a given T is fixed, characterized by effective masses and band gap (often called **law of mass action**)

Typical values at 300 K are:

$$\text{Si:} \qquad n_i = 1.5 \times 10^{10}\ \text{cm}^{-3} \qquad (3)$$

$$\text{Ge:} \qquad n_i = 2.5 \times 10^{13}\ \text{cm}^{-3} \qquad (4)$$

example: at 300 K in Si

$$n_i = p_i = 10^{10}\ \text{cm}^{-3}$$
$$n = 10^{17}\ \text{cm}^{-3} \quad \rightarrow \quad p = 10^{3}\ \text{cm}^{-3}$$

conductivity determined by majority carriers (electrons in n-doped, holes in p-doped)
role of minority carriers negligible with

$$\begin{aligned} n &\cong N_D \\ p &\cong \frac{n_i p_i}{N_D} = \frac{n_i^2}{N_D} \\ \frac{1}{\rho} &= \sigma = e \cdot N_D \cdot \mu_e \end{aligned}$$

typical values:

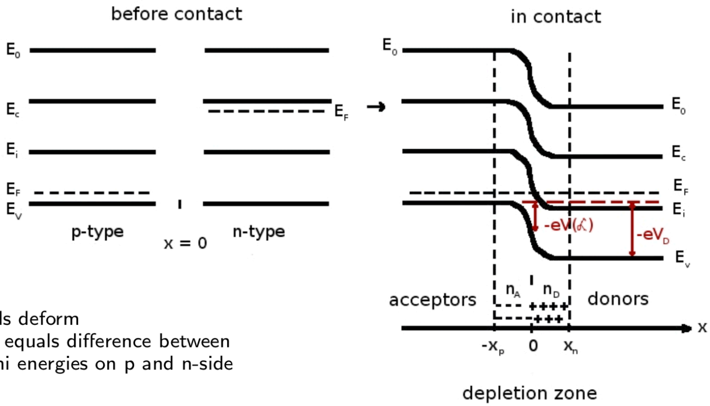
pure Si	Si p-type 10^{13} cm^{-3}
$2.3 \cdot 10^{5}$ Ωcm	500 Ωcm

		Si	Ge
Atomic number		14	32
Atomic weight	u	28.09	72.60
Stable isotope mass numbers		28-29-30	70-72-73-74-76
Density (300 K)	g/cm^3	2.33	5.32
Atoms/cm^3	cm^{-3}	$4.96 \cdot 10^{22}$	$4.41 \cdot 10^{22}$
Dielectric constant		12	16
Forbidden energy gap (300 K)	eV	1.115	0.665
Forbidden energy gap (0 K)	eV	1.165	0.746
Intrinsic carrier density (300 K)	cm^{-3}	$1.5 \cdot 10^{10}$	$2.4 \cdot 10^{13}$
Intrinsic resistivity (300 K)	Ωcm	$2.3 \cdot 10^5$	47
Electron mobility (300 K)	cm^2/Vs	1350	3900
Hole mobility (300 K)	cm^2/Vs	480	1900
Electron mobility (77 K)	cm^2/Vs	$2.1 \cdot 10^4$	$3.6 \cdot 10^4$
Hole mobility (77 K)	cm^2/Vs	$1.1 \cdot 10^4$	$4.2 \cdot 10^4$
Energy per electron-hole pair (300 K)	eV	3.62	
Energy per electron-hole pair (77 K)	eV	3.76	2.96

Source: G. Bertolini an A. Coche (eds.), Semiconductor Detectors, Elsevier-North Holland, Amsterdam, 1968

p-n Junction

- bring p- and n-semiconductors into contact; thermodynamic equilibrium → Fermi-energies of both systems become equal

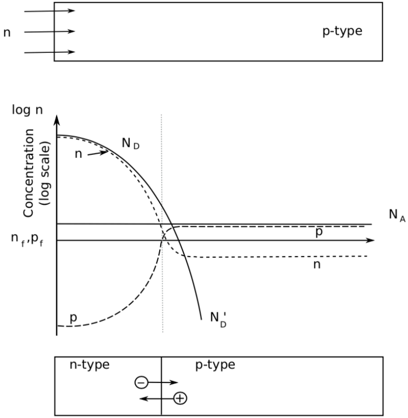


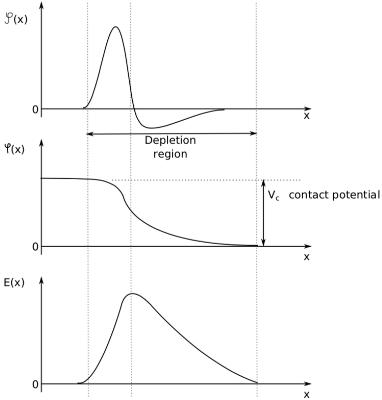
- bands deform
  eV_D equals difference between Fermi energies on p and n-side

- equilibration is achieved by electrons diffusing from n to p semiconductor and holes from p to n
- at the boundary a zone with few free charge carriers (electrons and holes) builds up 'depletion layer'
- fixed charges are left behind (ionized donors and acceptors) $\rightarrow$ space charge
  E-field builds up and counteracts the diffusion which stops eventually (like Hall effect)
  with $n \approx N_D$ and $p \approx N_A$, difference between Fermi energies on both sides gives

$$\begin{aligned} eV_D &= E_c - kT \ln \frac{N_c}{N_D} - E_v - kT \ln \frac{N_v}{N_A} \\ &= E_{gap} - kT \ln \frac{N_c\, N_v}{N_D\, N_A} \end{aligned}$$

V_D: diffusion/contact potential





$$\begin{aligned} \text{n-region} \qquad \rho &= e(N_D^+ - n_n(x) + p_n(x)) \\ \text{p-region} \qquad \rho &= -e(N_A^- + n_p(x) - p_p(x)) \end{aligned}$$

density of majority carriers $n_n, p_p \quad \gg \quad$ density of minority carriers n_p, p_n

potential and space charge related by Poisson equation

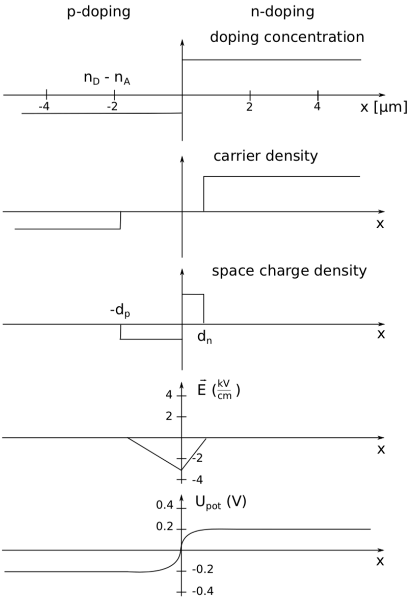
$$\frac{\partial^2 V(x)}{\partial x^2} = -\frac{\rho(x)}{\epsilon \cdot \epsilon_0}$$

but $\rho(x)$ depends on the potential, need to solve self-consistently

approximation: concentration of free charge carriers in depletion layer very small (approx. 0), abrupt change
$n > 0 \;\rightarrow\; n = p = 0 \;\rightarrow\; p > 0$
in reality over small length (Debye length, $0.1 - 1\,\mu$m)

for steps in density: Schottky model
area of rectangles such, that overall region space-charge neutral

$$\rho(x) = \begin{cases} 0 & \text{for} \quad x < -d_p \\ -eN_A & \quad -d_p < x < 0 \\ +eN_D & \quad 0 < x < d_n \\ 0 & \quad d_n < x \end{cases}$$



thickness of depletion layer d_p and d_n: integrate Poisson equation in pieces
n-doped region:

$$\begin{aligned} \frac{\partial^2 V(x)}{\partial x^2} &= -\frac{eN_D}{\epsilon\epsilon_0} \\ E_x &= -\frac{\partial V}{\partial x} = -\frac{e}{\epsilon\epsilon_0} N_D(d_n - x) \\ V(x) &= V_n(\infty) - \frac{e}{2\epsilon\epsilon_0} N_D(d_n - x)^2 \end{aligned}$$

p-doped region equivalently

condition of neutrality: $N_D d_n = N_A d_p$

continuity of potential $V(x)$ at $x = 0$

$$\frac{e}{2\epsilon\epsilon_0}(N_D d_n^2 + N_A d_p^2) = V_n(\infty) - V_p(-\infty) = V_D$$

$$\Rightarrow \quad d_n = \sqrt{\frac{2\epsilon\epsilon_0 V_D}{e} \frac{N_A/N_D}{N_A + N_D}} \quad \text{and} \quad d_p = \sqrt{\frac{2\epsilon\epsilon_0 V_D}{e} \frac{N_D/N_A}{N_A + N_D}}$$

$$\text{e.g.} \quad \left.\begin{array}{ccccc} eV_D & \cong & E_{gap} & \cong & 1\ \text{eV} \\ N_A & \cong & N_D & = & 10^{14}\ \text{cm}^{-3} \end{array}\right\} \begin{array}{c} d_n \cong d_p \cong 1\,\mu\text{m} \\ E \cong 10^6\ \text{V/m} \end{array}$$

to achieve large width on one side choose asymmetric doping,
e.g. $N_D = 10^{12}/\text{cm}^3$ and $N_A = 10^{16}/\text{cm}^3$ (need very pure material to start with)

External Bias

in presence of external field
most of the voltage drop U occurs in depletion layer (very few free carriers, large ρ)

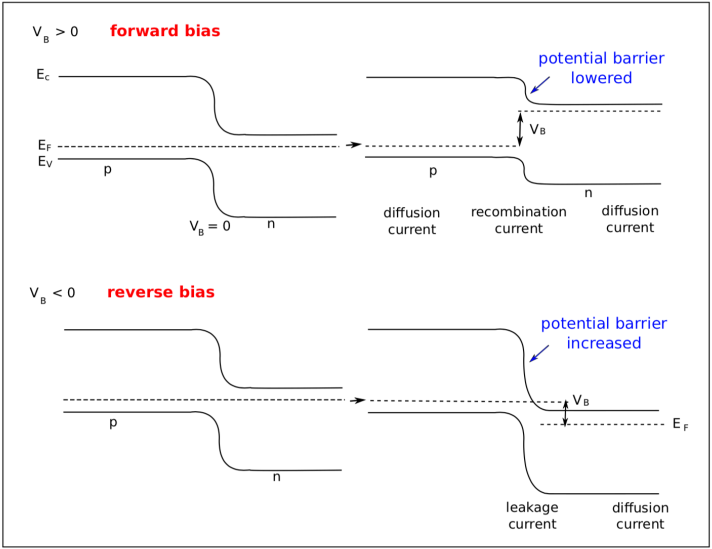
$$V_n(\infty) - V_p(\infty) = V_D - U$$

choose sign such that positive U is opposite to diffusion potential (contact potential)
Forward bias $U > 0$:
holes diffuse in n-direction electrons diffuse in p-direction, potential barrier is lowered

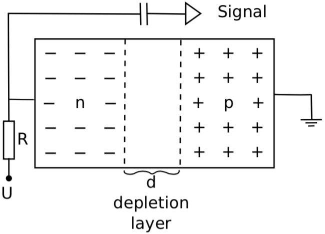
majority carriers recombine in depletion region: ‘recombination current’,
or penetrate to the other side: ‘diffusion current’,
depletion zone narrows

$$\begin{aligned} d_n(U) &= d_n(0)\sqrt{1 - \frac{U}{V_D}} \\ d_p(U) &= d_p(0)\sqrt{1 - \frac{U}{V_D}} \end{aligned}$$

reverse bias $U < 0$:
electron-hole pairs generated in or near the depletion layer by thermal processes (or in the case of detector by ionization) are separated: ‘leakage current’
depletion zone becomes wider (at 300 V order of 1 mm)

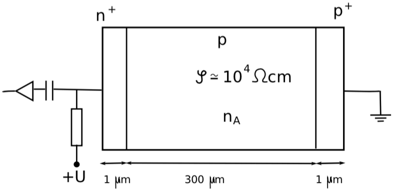


note:
to maximize thickness of depletion layer, need high resistivity (pure material) $d \cong \sqrt{2\epsilon\epsilon_0 U\rho\mu}$



$+++$, $---$: free charge carriers

typical realization:



p^+, n^+: very highly doped, conducting

$d_p + d_n \cong d_p \cong \sqrt{\frac{2\epsilon\epsilon_0}{e}\frac{U}{N_A}}$

since $N_A \ll N_D$, $V_D \ll U$

with $N_A \cong 10^{15}$ cm^{-3} $\Rightarrow$

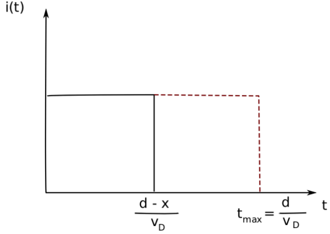
$$U = \frac{e}{2\epsilon\epsilon_0} N_A d_p^2 \cong 100 \text{ V}$$

$$|E| = \frac{100 \text{ V}}{300 \cdot 10^{-6} \text{ m}} = 3 \cdot 10^5 \text{ V/m}$$

(safe; spark limit at 10^7 V/m)

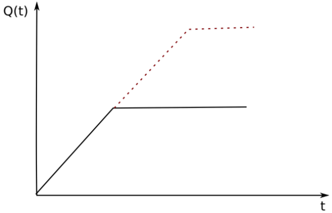
Signal Generation in SD

in principle like ionization chambers:
if E const: each drifting electron contributes to signal current while drifting



$$i = \frac{dq}{dt} = e\frac{dx}{d}\frac{1}{dx/v_D} = e\frac{v_D}{d}$$

d: width of depletion zone
x: location where electron was generated



capacitor charges:

$$Q = e\frac{v_D}{d}\cdot t = e\frac{v_D}{d}\frac{d-x}{v_D}$$

line charge of electrons across the depletion layer (constant ionization along track):

$$
\begin{aligned}
i &= N_0 e \frac{v_D}{d}\left(1-\frac{tv_D}{d}\right)\Theta\left(1-\frac{tv_D}{d}\right) \\
Q(t) &= N_0 e \frac{v_D}{d}\left(t-\frac{t^2 v_D}{d}\right)\Theta\left(1-\frac{tv_D}{d}\right)
\end{aligned}
$$

integrated:

$$
Q\left(t=\frac{d}{v_D}\right) = \frac{N_0 e}{2}
$$

same signal for positive carriers (holes), thus in total

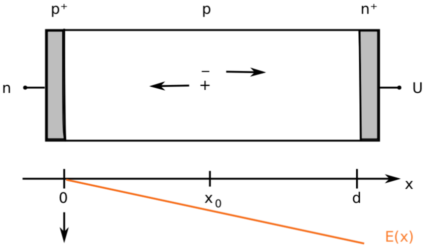
$$
\boxed{N_0 \cdot e = Q_{tot}}
$$

more realistic treatment: E-field depends on x

simple ansatz: $|\vec{E}| = \frac{e\,N_A}{\epsilon\epsilon_0} \cdot x$

and with $\sigma = \frac{1}{\rho} = e\,N_A\,\mu_+$ and $\tau = \frac{\epsilon\epsilon_0}{\sigma}$

$$|\vec{E}| = \frac{x}{\mu_+ \tau} \qquad (\tau \cong 1 \text{ ns})$$



for an electron generated at location x inside depletion zone and mobilities independent of E:

$$v_- = -\mu_- E = \frac{\mu_-}{\mu_+}\frac{x}{\tau} \quad \Rightarrow \quad x = x_0 \exp\left(\frac{\mu_- t}{\mu_+ \tau}\right)$$

total drift time of electrons:

$$t_d = \tau \frac{\mu_+}{\mu_-} \ln\left(\frac{d}{x_0}\right)$$

charge signal for $t < t_d$

$$Q_-(t) = -\frac{e}{d}\int \frac{dx}{dt} dt = \frac{e}{d} x_0 \left(1 - \exp\left(\frac{\mu_- t}{\mu_+ \tau}\right)\right)$$

analogously for hole

$$v_+ = \mu_+ E = -\frac{x}{\tau} \quad \Rightarrow \quad x = x_0 \exp\left(-t/\tau\right)$$

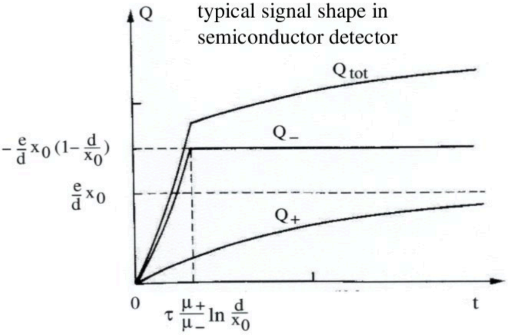
$$Q_+(t) = -\tfrac{e}{d} x_0 \left(1 - \exp\left(-t/\tau\right)\right)$$

Total charge signal:

$$Q_-(t_d) + Q_+(t \to \infty) = -e$$

signal rise time essentially determined by

$$\tau = \rho \cdot \epsilon \cdot \epsilon_0$$



in reality a bit more complicated:

- track not exactly a line charge (distributed over typically 50 μm width)
- $\mu_\pm \neq$ constant
- some loss of charges due to recombination at impurities

  for Si $\tau = \rho \cdot 10^{-12}$ s (ρ in Ωcm), $\rho = 1000\ \Omega$cm $\to \tau = 1$ ns

Ionisation Yield and Fano Factor

mean energy per electron-hole pair

	$E_0^{300\ \mathrm{K}}$	$E_0^{77\ \mathrm{K}}$	E_{gap}
Si	3.6 eV	3.8 eV	1.1 eV
Ge	-	2.9 eV	0.7 eV

$\sim \frac{2}{3}$ goes into excitation of crystal lattice

Energy loss ΔE $\Rightarrow$
- lattice vibrations: generation of phonons, typical quantum energy $E_x = 0.037$ eV
- ionization: characteristic energy $E_i = E_{\mathrm{gap}} = 1.1$ eV in Si
- total: $\Delta E = E_i N_i + E_x N_x$

assume Poisson distributions for both processes with $\sigma_i = \sqrt{N_i}$ $\quad \sigma_x = \sqrt{N_x}$

for a fixed energy loss ΔE:
sharing between ionization and lattice excitation varies as $\quad E_x \Delta N_x + E_i \Delta N_i = 0$

on average: $\quad E_i \sigma_i = E_x \sigma_x$

$$\sigma_i = \frac{E_x}{E_i}\sigma_x = \frac{E_x}{E_i}\sqrt{N_x}$$

using $N_x = (\Delta E - E_i N_i)/E_x$

$$\sigma_i = \frac{E_x}{E_i}\sqrt{\frac{\Delta E}{E_x} - \frac{E_i}{E_x}N_i}$$

$$N_i = \frac{\Delta E}{E_0}$$ in case of ideal charge collection without losses

$$\rightarrow \qquad \sigma_i = \frac{E_x}{E_i}\sqrt{\frac{\Delta E}{E_x} - \frac{E_i}{E_x}\frac{\Delta E}{E_0}} = \underbrace{\sqrt{\frac{\Delta E}{E_0}}}_{\sqrt{N_i}} \; \underbrace{\sqrt{\frac{E_x}{E_i}\left(\frac{E_0}{E_i} - 1\right)}}_{\sqrt{F}}$$

F: Fano factor

Si: $E_0 \cong 3.6$ eV $\quad F \cong 0.1$
Ge: $E_0 \cong 2.9$ eV $\quad F \cong 0.1$

$$\boxed{\sigma_i = \sqrt{N_i}\sqrt{F}}$$

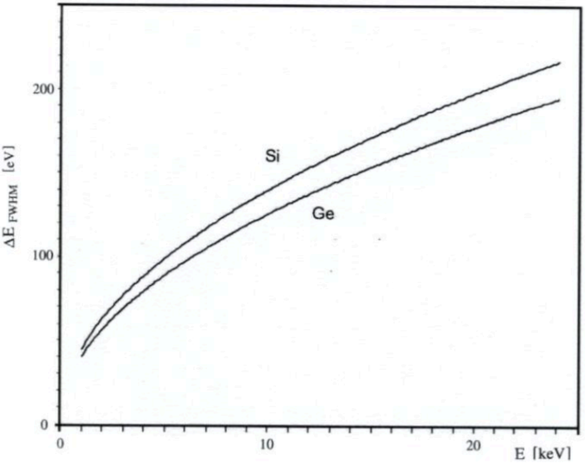
smaller than naive expectation

due to energy conservation, fluctuations are reduced for a given energy loss ΔE (the total absorbed energy does not fluctuate)

relative energy resolution

$$\boxed{\frac{\sigma_i}{N_i} = \frac{\sqrt{N_i\,F}}{N_i} = \frac{\sqrt{F}}{\sqrt{N_i}} = \frac{\sqrt{F\,E_0}}{\sqrt{\Delta E}} = \frac{\sigma_{\Delta E}}{\Delta E}}$$

example: photon of 5 keV, $E_\gamma = \Delta E$, $\sigma_{\Delta E} = 40$ eV $\cong 1\%$ instead of 2.7% w/o Fano factor



intrinsic resolution due to statistics of charge carriers generated, in addition noise and non-uniformities in charge-collection efficiency

Energy Measurement

Energy Measurement with SD

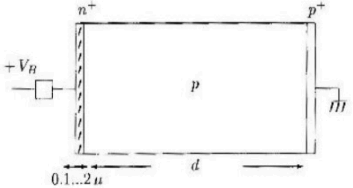
for low energies, e.g. α-particles, low energy electrons or X- and γ-rays

4.5.1 Ion implanted or diffusion barrier detectors

as described in previous paragraph:
p-material with n^+ and p^+ surface contacts of
50 nm (ion implantation) or
$0.1 - 1$ μm (diffusion doping) thickness

$+U$ applied at n$^+$ side

p-layer typically 300 μm thick, usually
'fully depleted' i.e. depletion layer = p-zone

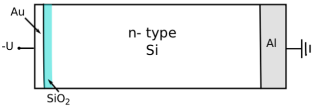


Disadvantage: n$^+$ contact layer acts as dead material for entering particles

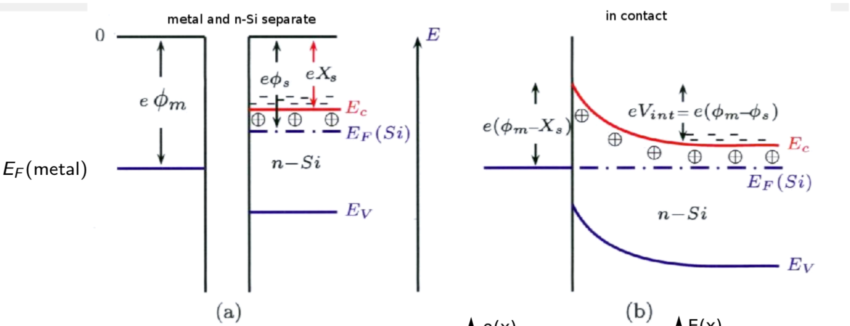
- part of energy loss not measured $\rightarrow$ additional fluctuations
- very soft particles or short range particles like α's may not reach the depletion layer

4.5.2 Surface barrier detectors

contacts are very thin evaporated metal layers, 40 μg/cm^2 $\hat{=}$ 20 nm

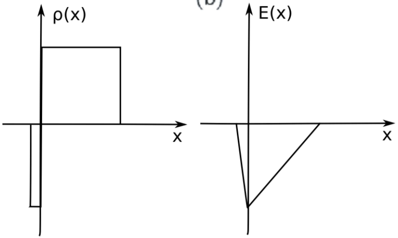


2-band model of Schottky diode



$e\Phi_m$ work function metal
$e\Phi_S$ work function semiconductor $< e\Phi_m$
(otherwise interface would be conducting)
eX_S electron affinity semiconductor

bringing metal in contact with n-Si:
electrons diffuse from Si into metal until
$E_F^{\mathrm{metal}} = E_F^{\mathrm{Si}} \rightarrow$ strong E-field at surface



metal – semiconductor junction acts as diode, region with high resistance

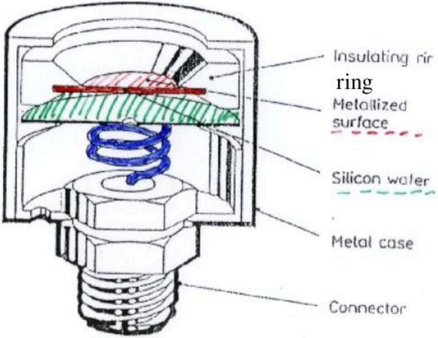
$eV_{int} = e(\phi_m - \phi_S)$ potential barrier at surface for electrons in conduction band in Si

applying $-U$ at metal: this barrier is increased $\rightarrow$ no tunneling (dark current)
current only due to ionization

depletion layer in n-Si up to several mm thick
used since the 1960ies for particle detection

advantage of surface barrier detector:
very thin entrance window

- energy loss negligible
- for detection of photons down to eV energy range
  but usually thickness too small for γ-ray detection above 100 keV,
  i.e. good for X-rays



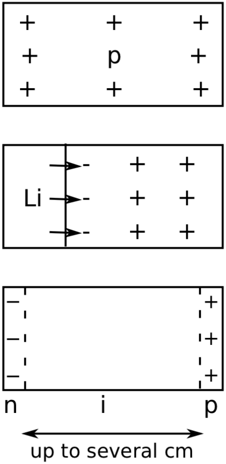
p-i-n detectors Ge(Li), Si(Li)

from 1960ies, trick: create a thick (cm) depletion layer with intrinsic conductivity by compensation

1. start with high-purity p-type Ge or Si, acceptor typically Boron
2. bring in contact with liquid Li bath ($350 - 400^\circ$ C) Li diffuses into Ge/Si
3. apply external field $\rightarrow$ positive Li-ions drift far into crystal and compensate B-ions locally

   typically 10^9 cm^{-3} Li atoms

   p-Si + Li$^+$ $\widehat{=}$ neutral
   $\rho = 2 \cdot 10^5$ Ωcm possible
   i.e like true intrinsic material



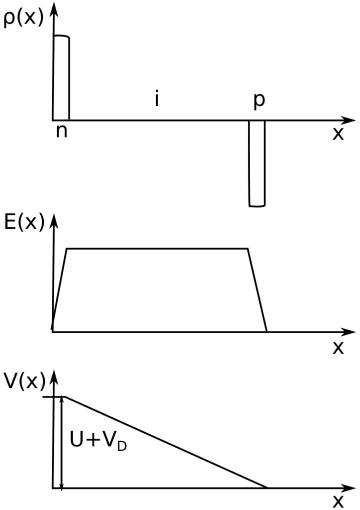
needs to be cooled permanently (liq. N_2) to avoid separation of Li from impurities by diffusion!

application: γ-spectroscopy

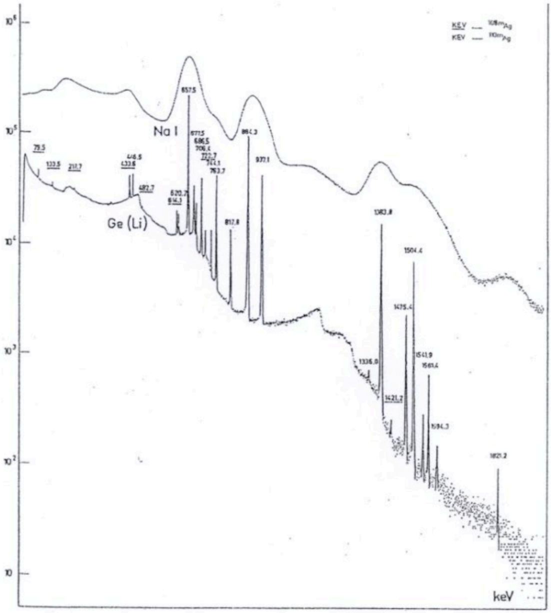
larger cross section for photo effect in Ge as compared to Si
$\rightarrow$ Ge(Li) preferred

however: full energy peak contains only order of 10 % of the signal in a 50 cm^3 crystal (30 % in a 170 cm^3 crystal))

- resolution much better than NaI
- efficiency significantly lower



external voltage U and diffusion voltage V_D



Ge(Li) detectors - a revolution in γ spectroscopy in the mid 1960ies:
comparison of spectra obtained with NaI (state of the art technique until then) and Ge(Li)

comparative pulse height spectra recorded using a sodium iodide scintillator and a Ge(Li) detector source of γ radiation: decay of ^{108m}Ag and ^{110m}Ag, energies of peaks are labeled in keV from late 1970ies

similar to Li doped Ge or Si detectors, but dark current is kept low not by compensating impurities, but by making material very clean itself

by repeating the purification process (zone melting), extremely pure Ge can be obtained ($\leq 10^9$ impurity atoms per cm^3)
intrinsic layer like compensated zone in Ge(Li), similar sizes possible
advantage: cooling only needed during use to reduce noise

other applications

- low energy electrons
- strongly ionizing particles
- $\mathrm{d}E/\mathrm{d}x$ for particle identification

useful energy range determined by range of particle vs. size of detector

Bolometers

how to increase resolution further?
use even finer steps for energy absorption, e.g. break-up of Cooper pairs in a semiconductor
operate at cryo-temperatures

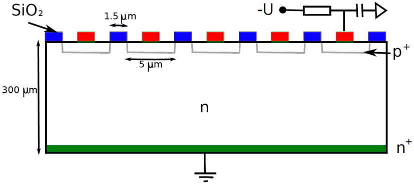
instead of current one can measure temperature rise due to absorption of e.g. an X-ray,
couple absorber with extremely low heat capacity (HgCdTe) with semiconductor thermistor
$\rightarrow$ excellent energy resolution: 17 eV for 5.9 keV X-ray, i.e. $\Delta E/E = 2.9\,10^{-3}$
but low rate capability

applications: dark matter searches, astrophysical neutrinos, magnetic monopole searches

Position Measurement

Position Measurement with Semiconductor Detectors

4.6.1 Principle

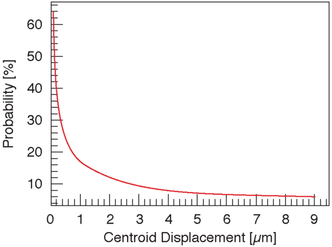


segmentation of readout electrodes into strips, pads, pixels
first usage in 1980ies
standard part of high energy experiments since LEP and Tevatron era

limitations of position resolution

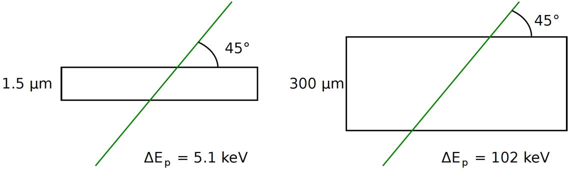
- δ-electrons can shift the center of gravity of the track estimate limit in Si for track incidence $\perp$ detector: r_δ range of δ-electron energy of δ-electron such that N_δ electron-hole pairs generated vs N_p for primary track: assume $\delta \perp$ to primary track

$$\Delta x = \frac{N_\delta (r_\delta/2)}{N_\delta + N_p}$$



example:
100 μm Si, 5 GeV pion $\rightarrow$ 240 eV/μm $\rightarrow N_p = 6700$
10% probability for δ with $T_\delta > 20$ keV and $r_\delta = 5\ \mu$m
$\rightarrow \Delta x \approx 1\ \mu m$
worse for thicker detector: see Fig for 300 μm Si

- energy loss (Landau) fluctuations have influence on position measurement



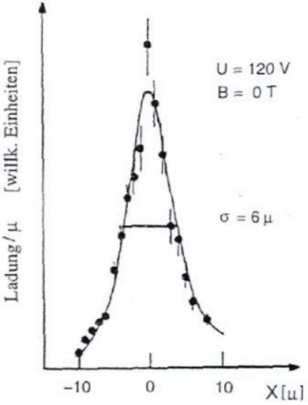
10 % probability for δ of 5 keV
→ Δx ≤ 4 µm but noise!

10 % probability for δ of 100 keV
→ Δx ≤ 87 µm but noise!

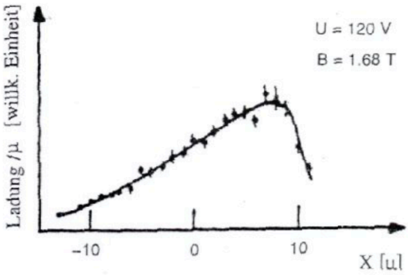
- noise: position measurement requires $S \gg N$
  if signal only on 1 strip (or pad), resolution $\sigma_x = \Delta s/\sqrt{12}$, independent of S/N
  if signal on several strips ⇒ more precise position by center-of-gravity method (see below), but influenced by S/N
- diffusion: smearing of charge cloud (see gaseous detectors, transverse diffusion)
  initially helps to distribute signal over more than one strip
  but 2-track resolution and S/N deteriorate with diffusion
- magnetic fields: Lorentz force on drifting electrons and holes: track signal is displaced if E not parallel B, increasing displacement with drift length

charge distribution registered for a semiconductor detector with or without magnetic field

no field



$B = 1.68\ T$



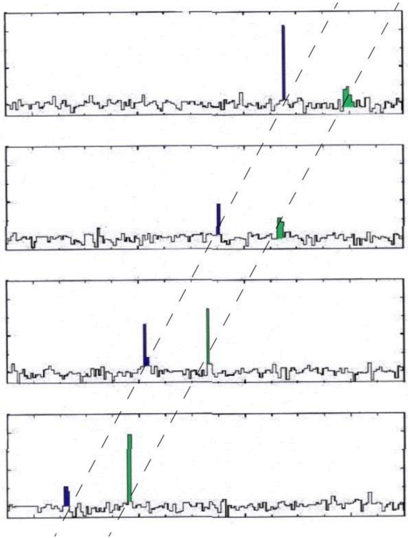
Si vertex detectors

main applications:

- tracking of particles close to primary vertex before multiple scattering
  $\Rightarrow$ good angular resolution
- identification of secondary vertices
  c, b, τ decays $\tau = 10^{-12} \ldots 10^{-13}$ s,
  $\gamma c\tau \cong \gamma \cdot 30\ \mu$m

'b-tagging' for top or Higgs decays

example: 4 layers microstrips of H1 experiment
$\Longrightarrow$

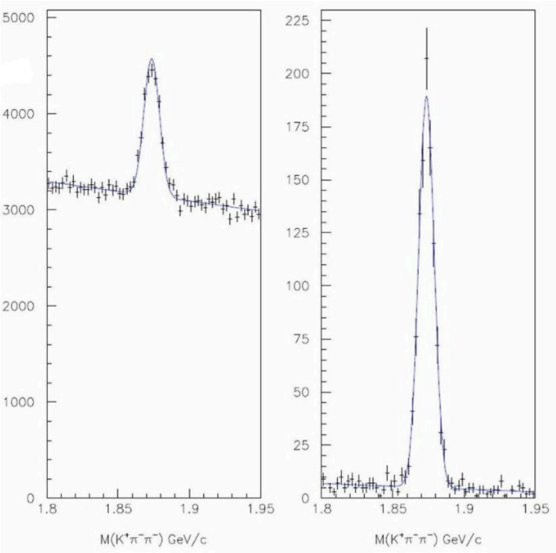


before and after vertex cuts

example: CDF

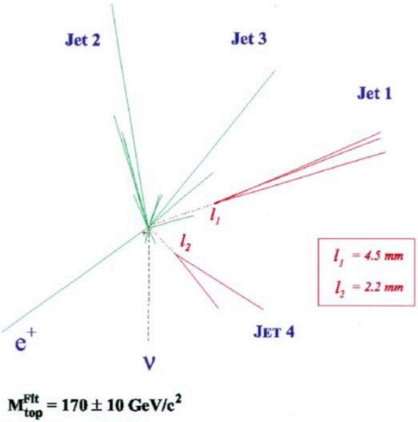
discovery top quark
3 Si-layers at
r = 1.5, 5-10, 20-29 cm
total active area approx. 10 m^2

$D^{\pm} \rightarrow K\pi\pi$ mass peaks
before and after 7σ vertex cut



example (CDF): detection of 2 b-jets from $t\bar{t}$-decay

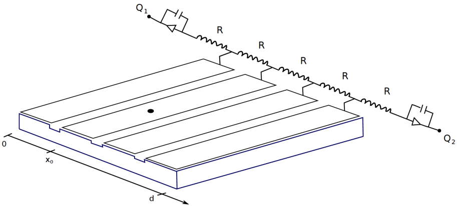
$$p + \bar{p} \rightarrow t\bar{t} + X$$
$$\hookrightarrow \bar{b} + W^+$$
$$\hookrightarrow e^+ + \nu_e$$
$$\hookrightarrow b + W^-$$
$$\hookrightarrow q\bar{q} \text{ (2 jets)}$$



Microstrip Detectors

principle and segmentation see above

- typical pitch $20 - 50\ \mu$m
- width of charge distribution (for $\perp$ incidence) $\cong 10\ \mu$m
- signal in $300\ \mu$m Si: $\cong 25\,000\, e$ for minimum ionizing particles
- order 100 channels/cm^2



read-out:

- resistor network for charge division

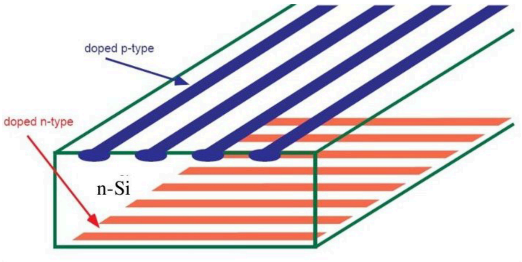
$$\langle x \rangle = \frac{Q_2}{Q_1 + Q_2} d$$

charge sensitive preamplifier

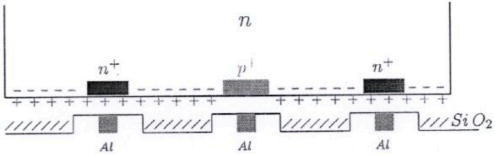
disadvantages:

- only 1 hit per event and detector
- R has to be large enough for good S/N
- slow due to RC of resistor chain

Double-sided Microstrip Detectors



between n^+ side strips, additional strips are needed for insulation:
SiO_2 surface layer: positive space charge $\Rightarrow$ e^- layer in n-material
p^+ blocking electrodes for separation of n^+ strips

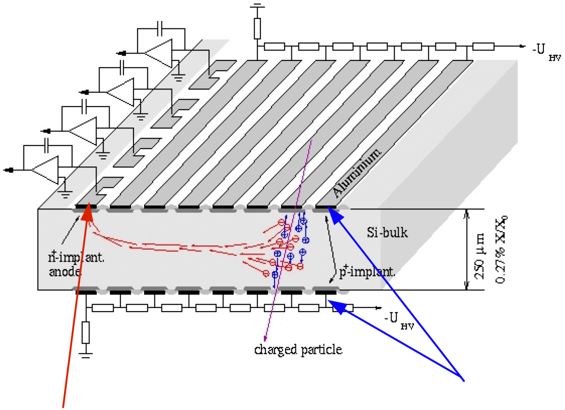


used in:
DELPHI, ALEPH, H1, ZEUS, HERA-B, CDF, D0

Silicon drift Detectors

proposed by Gatti and Rehak in 1984, first realized in 1990ies

potential inside wafer has parabolic shape (see next page), superimpose linear electric field

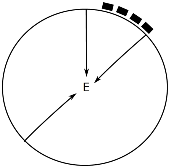


wafer can be fully depleted by reverse bias voltage on a small n+ anode implanted on wafer edge

n-type bulk Si with p+ electrodes on both flat sides analog to gaseous drift chambers: charge carriers drifting in well-defined E-field

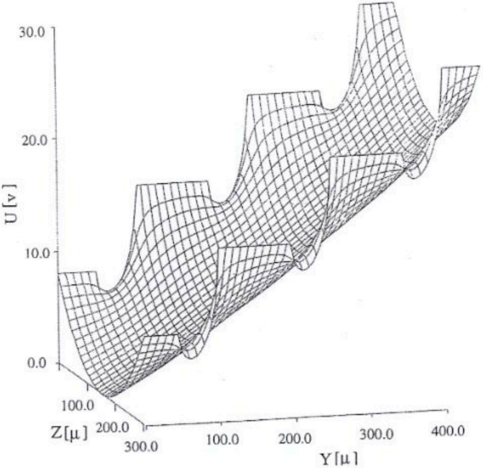
measurement of drift time
$\Rightarrow$ position of ionizing track

typical drift time: a few μs for $5 - 10$ cm



first example CERES at SPS:
radial Si drift-chamber

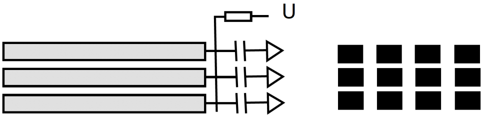
readout: 1° sectors in φ, 256 time samples (flash ADC) for determination of r, equivalent of 1 plane in a TPC



potential shape in Si drift-chamber:
trough-like shape due to positive space charge in depletion area, slope from external voltage divider

Pixel Detectors

- principle: like micro-strips, but 2-dimensional segmentation of p^+ contacts: 'pixel' each pixel connected to bias voltage and readout electronics



- advantage: 2-dim information like double-sided micro-strip, but more simultaneous hits per detector allowed low capacity and thus low noise $\Rightarrow$ good S/N
- disadvantage: large number of read-out channels $\Rightarrow$ expensive, large data volume pixel contacts are complicated ('bump bonding' or 'flip chip' technologies)
- typical pixel areas $\sim 2000\ \mu\text{m}^2 \rightarrow$ order 5000 channels/cm^2 square ($150 \times 150\ \mu\text{m}^2$) rectangular ($50 \times 300\ \mu\text{m}^2$)
- hit resolution: $\Delta x/\sqrt{12}$ and $\Delta y/\sqrt{12}$

examples: all LHC experiments

Putting all together: pixel, strips and drift

the challenge at LHC:

high rate, high hit density, radiation damage

$\sim$ 1000 tracks every 25 ns or 10^{11}/s

$\Rightarrow$ high radiation dose

$10^{15} \frac{n_{eq}}{\text{cm}^2 \cdot 10\text{a}}$ @ LHC

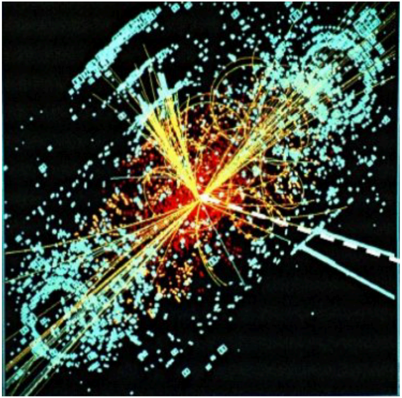
or

600 kGy (60 Mrad)
1 kGy = 1 J/g

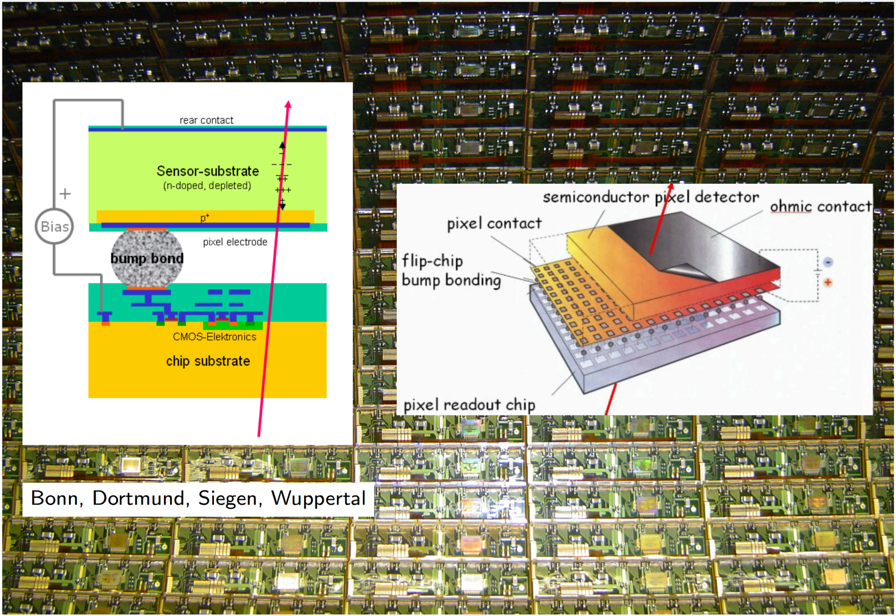
through the ionization of mips
in bulk silicon

LHC $\cong 10^6\times$ LEP in track rate!
detectors in ATLAS and CMS need to be replaced by 2018

14 TeV pp-collisions seen with the ATLAS pixel detector



ATLAS pixel detector: 5 cm from collision point



Lecture Summary