3. Détecteurs à semiconducteur

a) Silicium

Production of a FZ silicon ingot...
... at this stage almost all detectors look still the same

UE6
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I. INTRODUCTION

Semiconductor detectors have been used in experimental physics over more than 40 years. In the early days mainly Germanium, but also some Silicon and Lithium drifted Germanium detectors. A major effort has been put into the application of Ge detectors run at liquid nitrogen temperature, to perform high resolution spectroscopy measurements. This technology was the most commonly used over 20 to 30 years in Radiation Detection with semiconductor detectors.

Radiation here means all types of particles:

- Charged hadronic particles
- Charged leptons, electrons, muons,…
- Photons, X-rays and γ-rays
- Neutrons
- WIMPs (weakly Interacting Massive Particles)
- ….

Over the last 25 years however Silicon detectors have become more and more important, first in High Energy Physics (HEP), and recently increasingly in other fields.
What were the reasons for this evolution:

What are the advantages of solid state semiconductor detectors over e.g. solid state scintillator detectors?

Can overcome inherent limitation of energy resolution which can be obtained with scintillators:

This is due to the inherent mechanism of creating an electrical signal from a primary interaction of radiation in a scintillator. It involves a chain of relatively inefficient steps:

- Creation by incident radiation of (generally visible light) photons
- Transport and conversion of these primary photons into photo electrons
- Big fluctuations in the first dynode of a PMT adding further uncertainty to photon statistics and therefore additional error
- Thus the primary energy required to obtain one information carrier is 100eV or more

⇒ Limits e.g. the energy resolution of a 662 keV γ-ray from $^{137}\text{Cs}$ in a sodium iodide crystal to around 6%. This is a physical limit.
A specific example:

Signal Fluctuations in a Scintillation Detector

Example: Scintillation Detector - a typical NaI(Tl) system (from Derenzo)

511 keV gamma ray

25000 photons in scintillator

15000 photons at photocathode

3000 photoelectrons at first dynode

$3 \times 10^9$ electrons at anode

2 mA peak current

Resolution of energy measurement determined by statistical variance of produced signal quanta.

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

Resolution determined by smallest number of quanta in chain, i.e. number of photoelectrons arriving at first dynode.

In this example

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{3000}} = 2\% \text{ r.m.s.} = 5\% \text{ FWHM}$$

Typically 7–8% obtained, due to non-uniformity of light collection and gain.
Back to the advantage one could get from a solid state semiconductor detector:

• Only a few eV energy spent to create one information (charge) carrier
• Therefore much larger number charge carriers for the same incident radiation!
• Compact size
• Very small feature sizes possible \( \Rightarrow \) very high spatial resolution possible
• Very high number of channels possible since readout can be done by VLSI readout electronics relying on the same technologies as used for detector production.
The main reason (in my opinion):

About 25 years ago another “event” triggered a very fast and powerful development phase for semiconductor detectors: the discovery of new particles being made of very heavy constituents:

- charmed particles
- $\tau$ lepton
- beauty particles
- finally particles containing a top quark

Due to the finite but very short life times of these new particles high precision vertex measurements and tracking became a most important issue in instrumentation R&D for High Energy Physics.
HIGH PRECISION VERTEXING AS A PHYSICS TOOL

Search for D-hadrons and B-hadrons has driven the development of high spatial resolution Si sensors first in fixed target experiments attempting to discover and study hadro-production of charmed and beauty particles in the beginning of the 1980’s.

Weak decays of heavy particles with masses from 3 to 5 Gev and also the $\tau$-lepton happen to have decay times around $10^{-12}$ to $10^{-13}$ sec.

Transverse decay length: $ct \sim 150$ to $500 \, \mu m$

To measure decay vertices or tag these particles via their finite decay distances, a precision of $\sim 10 \, \mu m$ is needed.

Experiments using nuclear emulsions were originally made but need for fast electronic detectors was clear because of small hadronic production cross sections of CHARM and BEAUTY particles

$\Rightarrow$ powerful boost to the development of Si sensors
In experiments at present e⁺e⁻ colliders nearly all of physics results are based on information from VERTEX DETECTORS.

Similarly for future high luminosity hadron collider experiments big emphasis is put on b-flavour tagging and measurement of displaced vertices as a signature of interesting physics. All the interesting known (W⁺⁻, Z bosons) or new (Higgs) particles couple strongest to particles containing heavy quarks.

Particular cases are the LHCb experiment at LHC and BTEV experiment at the TEVATRON to study with ultimate precision CP VIOLATION in the B Sector.

B Meson decay channels with branching ratios of several times 10⁻⁵ to several times 10⁻⁷ have to be accumulated with high statistics to get a precise measurement of the 3 angles α, β and γ resulting from the unitarity conditions in the CKM matrix.

Similarly B-Factory experiments at SLAC and KEK are completely reliant on high performance vertex detectors to measure z coordinate- difference of decay vertices of a pair of B-mesons produced in energy asymmetric e⁺e⁻ collisions. Silicon detectors not working means NO EXPERIMENT.
Si Vertex Detectors were first developed for fixed target experiments using hybrid front-end electronics. Major limitations came from the inherent mismatch in size of front-end electronics and Si sensor granularity.

Quite astonishing: despite the availability of commercial VLSI electronics HEP did not develop suitable front-ends immediately for this instrumentation. Detectors came first (almost 10 years ahead of custom made read-out front-ends).

The first VLSI front-end chip - the MICROPLEX - was developed in 1983/1984 for the DELPHI and ALEPH experiments at LEP and for the MARKII experiment at SLC.

This new technology (in HEP) opened the door for construction of vertex detectors for collider experiments.

In the new generation of high luminosity $4\pi$ collider experiments, TRACKING inside the Calorimetry, necessary for precise determination of momenta of high $p_T$, high energy particles, will be done with Si TRACKERS covering large areas with millions of channels.

VERTEX DETECTORS  <==>  TRACKERS

In these systems Vertex Detection is performed by specific parts (layers) of the overall Tracker.
II. Some Fundamental Notions on Silicon

- Silicon is the most abundant, studied and understood material
- It is used extensively in IC industrial developments and production
- Si device planar technology is highly developed and state-of-art by the driving force of IC industry
- Even in today’s VLSI and ULSI with sub-micron technology, Si is still the material of choice, and will remain so for years to come
- It has very high radiation tolerance for HEP application
**Abundance of the semiconductor constituents in the Earth’s crust (weight fraction)**

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance</th>
<th>Element</th>
<th>Abundance</th>
<th>Element</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>0.283</td>
<td>Zinc</td>
<td>7x10^{-5}</td>
<td>Cadmium</td>
<td>2x10^{-7}</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.083</td>
<td>Gallium</td>
<td>1.5x10^{-5}</td>
<td>Indium</td>
<td>1x10^{-7}</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.001</td>
<td>Germanium</td>
<td>5x10^{-6}</td>
<td>Mercury</td>
<td>8x10^{-8}</td>
</tr>
<tr>
<td>Sulfur</td>
<td>2.6x10^{-4}</td>
<td>Arsenic</td>
<td>1.8x10^{-6}</td>
<td>Selenium</td>
<td>5x10^{-8}</td>
</tr>
<tr>
<td>Carbon</td>
<td>2x10^{-4}</td>
<td>Antimony</td>
<td>2x10^{-7}</td>
<td>Tellurium</td>
<td>1x10^{-9}</td>
</tr>
</tbody>
</table>
Silicon material as discussed in these lectures needs to be processed in order to be useful as radiation detection material, both for detectors and for electronics.

It is its property to form a mono-crystalline lattice structure which allows it to be so dominant in our world.
Lattice constant a:  
- Diamond: 3.56 Å  
- Silicon: 5.43 Å  
- Germanium: 5.65 Å
All atoms in the diamond lattice are identical, while the two fcc sublattices are built of 2 different atoms in the case of III-V compounds.

Each atom is surrounded by four close neighbors belonging to the other fcc lattice. They are arranged in a tetrahedron and each atom shares its four outer (valence) electrons with those of the neighbors. Forming what is called covalent bonds.

Fig. 2.2a,b. Tetrahedron bond (a) and schematic two-dimensional representation (b). (After Sze 1985, p. 8 Fig. 6)
Silicon crystal growth
CZ Crystal Growth

- Silicon crystal ingots are pulled from molten silicon contained in a crucible.

- Seed crystal is lowered into the molten silicon, and is withdrawn at a controlled rate.

- Both the seed crystal and the crucible are rotated during the pulling process, but in opposite directions.

- Growth steps:
  - ✴ forming neck ⇒ dislocation free
  - ✴ shouldering out ⇒ desired diameter
  - ✴ tail off ⇒ growth completed
The Hollow of the Great Wave off Kanagawa (The Big Wave) by Katsushika Hokusai
Bandes d'énergie permises et interdites
Dans le métal une bande est seulement partiellement remplie.
Dans un semiconducteur, la bande de valence est (presque) pleine.
Effet Auger : un électron d'une couche externe saute dans un état électronique vacant et un électron d'une couche externe est éjecté.

\[
S(W) \propto \Delta W^{\frac{1}{2}} \quad P(W) \propto \exp\left[-\frac{W - W_F}{kT}\right] \quad W_F = \text{niveau Fermi} = \text{énergie ou } P(W)=1/2
\]
Some characteristics of Silicon crystals

- Small band gap \( E_g = 1.12 \text{ eV} \Rightarrow E(\text{e-h pair}) = 3.6 \text{ eV} \) \((\approx 30 \text{ eV} \text{ for gas detectors})\)
- High specific density \( 2.33 \text{ g/cm}^3 \); \( dE/dx \) (M.I.P.) \( \approx 3.8 \text{ MeV/cm} \approx 106 \text{ e-h/\mu m} \) (average)
- High carrier mobility \( \mu_e = 1450 \text{ cm}^2/\text{Vs}, \mu_h = 450 \text{ cm}^2/\text{Vs} \Rightarrow \text{fast charge collection (<10 ns)} \)
- Very pure <1 ppm impurities and <0.1ppb electrical active impurities
- Rigidity of silicon allows thin self supporting structures
- Detector production by microelectronic techniques \Rightarrow \text{well known industrial technology, relatively low price, small structures easily possible}

Alternative semiconductors

- Diamond
- GaAs
- Silicon Carbide
- Germanium

<table>
<thead>
<tr>
<th>Atomic number ( Z )</th>
<th>Diamond</th>
<th>SiC (4H)</th>
<th>GaAs</th>
<th>Si</th>
<th>Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap ( E_g ) [eV]</td>
<td>5.5</td>
<td>3.3</td>
<td>1.42</td>
<td>1.12</td>
<td>0.66</td>
</tr>
<tr>
<td>( E(\text{e-h pair}) ) [eV]</td>
<td>13</td>
<td>7.6-8.4</td>
<td>4.3</td>
<td>3.6</td>
<td>2.9</td>
</tr>
<tr>
<td>Density [g/cm(^3)]</td>
<td>3.515</td>
<td>3.22</td>
<td>5.32</td>
<td>2.33</td>
<td>5.32</td>
</tr>
<tr>
<td>e-mobility ( \mu_e ) [cm(^2)/Vs]</td>
<td>1800</td>
<td>800</td>
<td>8500</td>
<td>1450</td>
<td>3900</td>
</tr>
<tr>
<td>h-mobility ( \mu_h ) [cm(^2)/Vs]</td>
<td>1200</td>
<td>115</td>
<td>400</td>
<td>450</td>
<td>1900</td>
</tr>
</tbody>
</table>
How to obtain a signal?

In a pure intrinsic (undoped) semiconductor the electron density \( n \) and hole density \( p \) are equal.

\[
n = p = n_i \quad \text{For Silicon: } n_i \approx 1.45 \cdot 10^{10} \text{ cm}^{-3}
\]

4.5 \( \cdot \) 10^8 free charge carriers in this volume, but only 3.2 \( \cdot \) 10^4 e-h pairs produced by a M.I.P.

\( \Rightarrow \) Reduce number of free charge carriers, i.e. deplete the detector

\( \Rightarrow \) Most detectors make use of reverse biased p-n junctions
Configuration Electron pour Si:
\[
\begin{align*}
K & \quad 2 \\
L & \quad 8 \\
M & \quad 4 + 4 \text{ par liaison} \rightarrow 8 \text{ group} \\
E_g & \approx 1 \text{ eV}
\end{align*}
\]

Doper les semiconducteurs.

**n-Type**
P, As, Sb
5 électrons dans la couche M
\[ \rightarrow 1 \text{ électron avec énergie de liaison 10-50 meV} \]

**p-Type**
B, Al, Ga
3 électrons dans la couche M
\[ \rightarrow 1 \text{ électron manquant} \]
Doping, resistivity and p-n junction

- **Doping: n-type Silicon**
  - add elements from V\(^{th}\) group
  - electrons are majority carriers
  ⇔ donors (P, As,...)

- **Doping: p-type Silicon**
  - add elements from III\(^{rd}\) group
  - holes are the majority carriers
  ⇔ acceptors (B,..)

- **Resistivity**
  - carrier concentrations \( n, p \)
  - carrier mobility \( \mu_n, \mu_p \)

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

<table>
<thead>
<tr>
<th>detector grade</th>
<th>electronics grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>doping</td>
<td>( \approx 10^{12} \text{ cm}^{-3} )</td>
</tr>
<tr>
<td>resistivity ( \rho )</td>
<td>( \approx 5 \text{ k}\Omega \cdot \text{cm} )</td>
</tr>
</tbody>
</table>

- **p-n junction**
  - There must be a single Fermi level!
  - band structure deformation
  - potential difference
  - depleted zone
Une jonction p-n sans polarisation:

- Champ électrique maximum à la frontière entre p et n.
- Couche déplétée nette.
Depletion Region

Electron current

Electron

Positive ion from removal of electron in n-type impurity

Negative ion from filling in p-type vacancy

Hole

Equilibrium

Forward Bias

Reverse Bias

Capacitance

Depletion Layer

N:

#Donors

X:

Thickness of depletion Area

http://hyperphysics.phy-astr.gsu.edu/hbase/solids/diod.html

O. Ullaland/2006
The p⁺n Junction

p and n doped silicon regions “separate”

Intrinsic silicon  Few impurities  \( n=p=n_i \)

Donor impurities (Ph) all donor sites are contributing their \( \epsilon^- \) to the conduction band:  \( n = N_D \)

Acceptor impurities (B): missing \( \epsilon^- \) equivalent to moving holes in valence band:  \( p = N_A \)
The p+n Junction

Doped regions of Si brought into “contact”

“Fermi level” (level where probability of occupation of a energy state is \( \frac{1}{2} \)) must be constant across boundary: leads to “built in voltage: conduction band different in energy on both sides of the junction

In “reverse” bias condition one puts an external voltage \( V \) of the same polarity as the in-built junction voltage
Physically this is happening through the process of inter-diffusion of free positive and negative charge carriers on either side of the junction.

Holes move out of the region of high hole and low electron concentrations and vice versa across the junction.

This would go on until everywhere in thermal equilibrium there is uniform concentrations of holes and electrons.

But when holes move out of the region with high acceptor atom concentration (fixed in the lattice), a fixed negative space charge is created. On the other side of the junction with high donor concentration for the same reason a fixed positive space charge region is created.

This leads to an electric field which builds up in a way that it stops the diffusion process. This field sweeps all movable charges out of the space charge region.

For devices one will in general have very high donor (acceptor) concentrations on one side of the junction and very low acceptor (donor) concentrations on the other side of the junction.

For silicon junction radiation detectors often a p^+n junction is used for practical reasons.
The external applied voltage (normally negative voltage on the ohmic contact side of the n-type depletion region of a detector) will naturally extend the depletion region deeper into the bulk.

Once the voltage is high enough the depletion region reaches all the way through the silicon bulk and come to a natural stop.

Voltage above this value $V_{\text{dep}}$ is called over-depletion voltage. It will add a constant electric field on top of the linear field.
The p+n Junction

For uniform space charge densities \(-eN_A\) and \(eN_D\) on both sides of the junction (oversimplified):

Poisson's equation:

\[
\frac{d^2 \phi}{dx^2} = -\frac{dE}{dx} = \frac{\rho(x)}{\varepsilon \varepsilon_0} = \begin{cases} 
0 & x \leq -W_p \\
-eN_A & -W_p < x \leq 0 \\
eN_D & 0 < x \leq W_n \\
0 & x > W_n 
\end{cases}
\]
The p+n Junction

Continuity and boundary conditions

Continuity at \( x=0 \):

\[
E(0^-) = E(0^+), \quad \phi(0^-) = \phi(0^+)
\]

Boundary conditions:

\[
E(-W_p) = E(W_n) = 0, \quad \phi(-W_p) = -(V_{bi} - V), \quad \phi(W_n) = 0
\]
The p+n Junction

Solutions

E-field:

\[
E(x) = \begin{cases} 
0 & \text{if } x \leq -W_p \\
-\frac{eN_A}{\varepsilon \varepsilon_0} (x + W_p) & \text{if } -W_p < x \leq 0 \\
-\frac{eN_D}{\varepsilon \varepsilon_0} (W_n - x) & \text{if } 0 < x \leq W_n \\
0 & \text{if } x > W_n 
\end{cases}
\]

Potential:

\[
\phi(x) = \begin{cases} 
-(V_{bi} - V) & \text{if } x \leq -W_p \\
\frac{eN_A}{2\varepsilon \varepsilon_0} (x + W_p)^2 - (V_{bi} - V) & \text{if } -W_p < x \leq 0 \\
\frac{eN_D}{2\varepsilon \varepsilon_0} (W_n - x)^2 & \text{if } 0 < x \leq W_n \\
0 & \text{if } x > W_n 
\end{cases}
\]

Build-in potential:

\[
V_{bi} = \frac{kT}{e} \ln \left( \frac{N_A N_D}{n_i^2} \right)
\]
From continuity conditions, we have:

\[ N_A W_p = N_D W_n \]
\[ N_A W_p^2 + N_D W_n^2 = 2 \varepsilon_0 (V_{bi} - V) \]

Define the depletion region width \( W \):

\[ W = W_p + W_n = \sqrt{\frac{2 \varepsilon_0 (V_{bi} - V)}{e}} \left( \frac{1}{N_A} + \frac{1}{N_D} \right) \]

If \( N_A \gg N_D \) (p+n junction): 

\[ W_p = \sqrt{\frac{2 \varepsilon_0 (V_{bi} - V)}{e N_D}} \left( 1 + \frac{N_D}{N_A} \right) \approx 0 \]
\[ W_n = \sqrt{\frac{2 \varepsilon_0 (V_{bi} - V)}{e N_D}} \left( \frac{N_D}{N_A} \right) \approx \sqrt{\frac{2 \varepsilon_0 (V_{bi} - V)}{e N_D}} \]
\[ W = W_n = \sqrt{\frac{2 \varepsilon_0 (V_{bi} - V)}{e N_D}} \]
Depletion region (or space charge region)

In the depletion region, the electric field is linear:

\[ E(x) = -\frac{eN_D}{\varepsilon \varepsilon_0} (W_n - x) \quad 0 < x \leq W_n \]

- Electron and hole pairs generated by light or particles will drift in this field to give a current or charge signal.
- For fully depleted detectors: \( W_n = d \)
- For a n-type detector with resistivity of 4kΩ-cm (or \( N_D = 1.08 \times 10^{12} / \text{cm}^3 \)) and 300 µm thickness, the full depletion voltage \( (V_d) \) is: 78 volts
Interaction of particles with Si

- **Photons**
  - Generation of secondary electrons with high energy
    - Photoelectric effect (<50 keV)
    - Compton scattering (50 k to 20 MeV)
    - Pair production (>20 MeV)
- **Charged particles (NP and HEP)**
  - e, p, α, π, heavy ions, etc.
    - Rutherford (Coulombic) scattering
    - Nuclear interaction (displacement damage)
- **Neutrons**
  - Nuclear interactions (displacement dam.)
    - Elastic scattering
    - Inelastic scattering
- **Transmutation**
Interactions of Radiation with Semiconductor Material
Radiation Interactions

An understanding of the response of a specific type of detector must be based on the understanding of the fundamental mechanism by which radiations interact and lose their energy in matter, in our case semiconductor material.

Charged hadrons and fast electrons interact directly by Coulomb interactions with the electrons present in any medium within the absorber material and create ionization. Neutrons have to first interact with the nuclei in the medium to produce charged radiation and photons will have interactions with electrons before they can leave a detectable trace. If there are no such interactions then these neutral radiation will pass through the detector without leaving any trace.

Photons can transfer either part or all of their energy to electrons in the medium. The resulting secondary electrons will have evidently the same interactions as primary electrons, like e.g. β – particles.

Neutrons may interact in such a way as to produce secondary heavy charged particles, sometimes splitting up the nucleus, which then serve as the basis of the detector signal.
Interaction of particles with Si

Photons

![Graph showing interaction of particles with Si focusing on photons.](image)

- **Photon Energy in MeV**
  - **Z of Target Atoms**
  - **Photoelectric Effect Dominates**
  - **Compton Scattering Dominates**
  - **Pair Production Dominates**
  - **Silicon**

**Graph Description:**
- The graph illustrates the interaction of particles with silicon, focusing on the effects of photons.
- It shows the energy range in MeV and the corresponding values for Z of target atoms.
- The transitions between the Photoelectric Effect, Compton Scattering, and Pair Production are indicated.
- Silicon is marked on the graph, indicating its specific properties or behavior in this context.
The Photo-electric Absorption

The photon undergoes an interaction with an absorber atom in which the photon completely disappears. An energetic photo-electron is ejected by the atom from one of its bound shells, mostly from the K-shell for energetic enough photons.

The energy of the photo-electron is:

\[ E_e = h\nu - E_b \]

With \( E_b \) the binding energy of the photo-electron in its original shell.

The probability of this process is enhanced for low photon energies and for absorber materials with high atomic number \( Z \)

\[ P \sim \text{constant} \frac{Z^n}{E_\gamma^{3.5}} \]

With \( n \) varying from 4 to 5 depending on the energy range.
The Compton Effect

Compton Interaction of a photon with an electron in the medium:

we can show that

\[ h\nu' = \frac{h\nu - \frac{h\nu}{1 + \frac{m_0c^2}{h\nu}(1 - \cos \theta)}}{1 + \frac{m_0c^2}{h\nu}(1 - \cos \theta)} \]

(2.17)
Angular dependence of the Compton cross section as a function of the energy of the incident photon:

Klein-Nishina Formula for differential scattering cross section:

\[
\frac{d\sigma}{d\Omega} = Z r_0^2 \left( \frac{1}{1 + \alpha(1 - \cos \theta)} \right)^2 \left( \frac{1 + \cos^2 \theta}{2} \right) \left( 1 + \frac{\alpha^2(1 - \cos \theta)^2}{(1 + \cos^2 \theta)[1 + \alpha(1 - \cos \theta)]} \right)
\]

Figure 2.19 A polar plot of the number of photons (incident from the left) Compton scattered into a unit solid angle at the scattering angle \( \theta \). The curves are shown for the indicated initial energies.
Pair Production

Pair Production

If the $\gamma$ ray energy exceeds twice the rest mass of the electron the process of $e^+e^-$ pair production is energetically possible. It starts to become the dominant process above a photon energy of 10 MeV.
Interaction of Particles with Si

Charged particles

Rutherford cross-section:

\[
\frac{d\sigma}{dE} = \frac{2\pi^4}{mc^2} \cdot \frac{1}{E^2}
\]

Fig. 1 Passage of charged particle through matter. Close collisions (electrons with small impact parameter \(b\), shown by the inset) receive a powerful transverse impulse. Distant electrons receive a weak impulse.
Average differential energy loss of a charged particle with energy $E$ traversing the semiconductor detector is described by the Bethe-Bloch formula:

Energy loss from collisions

$$\left( \frac{dE}{dx} \right)_c = \frac{2\pi e^4 NZ}{m_0v^2} \left( \ln \frac{m_0v^2E}{2\left(1 - \beta^2\right)} - (\ln 2)(2\sqrt{1 - \beta^2} - 1 + \beta^2) \right. \left. + (1 - \beta^2) + \frac{1}{8} \left(1 - \sqrt{1 - \beta^2}\right)^2 \right)$$

Energy loss through radiation

$$\left( \frac{dE}{dx} \right)_r = \frac{NEZ(Z + 1)e^4}{137m_0^2c^4} \left( 4\ln \frac{2E}{m_0c^2} - \frac{4}{3} \right)$$

Only very fast electrons can have significant energy loss through radiation: for a 1 MeV electron in Si only about 2% of energy loss is through radiative processes. The bremsstrahlung photon energy is generally low and will be absorbed in the vicinity of its creation.
Interaction of particles with Si
Charged particles

For minimum ionizing particles (MIP)

- It takes about 3.6 eV of primary energy deposition to generate one e-h pair.

- On average, 80 e-h pairs will be generated per μm of Si: about \(2.4 \times 10^4\) for 300 μm thick Si.

- The signal is therefore limited by the energy deposited and the detector thickness.

- One attempts to have full depletion to obtain the highest possible signal. Only charge created in the depletion zone will contribute to the signal, since the electric field is zero outside the depletion region.
Charge Carrier Transport in Semiconductors

Mobile charge carriers (electrons in the conduction band and holes in the valence band) are essentially free particles. Their mean thermal kinetic energy is $\frac{3}{2}kT$, which means their mean velocity is $10^7\text{cm/s}$. They scatter mainly on imperfections in the lattice. Typical mean free path is $10^{-5}\text{cm}$ with mean free time between scatters of $\sim 10^{-12}\text{s}$.

If there is an electric field, like in the depleted space charge region of a p-n junction device, the charges will have a component of movement (drift) along the direction of the electric field with velocity

\[ v_n = -\mu_n E \]

\[ v_p = \mu_p E \]

If there is a inhomogeneous distribution of charges it will become homogeneous after a long time through diffusion.
Carrier drift velocities in several semiconductors

Low field mobility region is the region where the drift velocity is linear with electric field. For higher fields saturation sets in
Charge Collection in a Semiconductor Detector

Interaction of radiation in the semiconductor material creates electron hole pairs, either distributed along the track of a energetic charged particle uniformly, or nearly point like as in the absorption process of a $\gamma$ ray.

Electrons and holes will induce unequal charges in the electrodes of a detector.

If an external bias voltage $V$ is applied to the detector
Example: An electron hole pair is created in the middle of a Silicon detector with thickness d, with the hole drifting to the p+n junction

\[ V( \text{ positive}) \]

**Induced charge on top electrode:**

\[ Q_h = q \frac{(d-x_h)}{d} \]

\[ Q_e = -q \frac{(d-x_e)}{d} \]

The electric field as a function of depth \( x \) is given by:

\[
\mathcal{E}(x) = - \left[ 2 \frac{d-x}{d^2} \frac{V_{\text{dep}}}{d} + \frac{V - V_{\text{dep}}}{d} \right]
\]

\[
= - \left[ \frac{V + V_{\text{dep}}}{d} - 2 \frac{xV_{\text{dep}}}{d^2} \right]
\]
V is applied voltage, $V_{dep}$ is voltage needed for full depletion

What is the current induced in the top electrode due to the drift of the electron and the hole towards the respective electrodes. The drift velocity of the electron is:

$$\nu_n(x) = -\mu_n \mathcal{E}(x)$$

Similar for the hole. This leads to the differential equation which allows to calculate the electron [hole] position $x_e(t)$ [$(x_p(t)]$ as a function of time:

$$\frac{dx_e}{dt} = \mu_n \left[ \frac{V + V_{dep}}{d} - 2 \frac{V_{dep}}{d^2} x \right]$$

Integration gives

$$i(t) =$$
\[ = \frac{d}{2V_{dep}} \left( x_0 - \frac{d}{2V_{dep}} \right) e^{-2\mu_n \frac{V_{dep}}{d^2} t} \]

Boundary conditions are: \( x_e(t=0) = x_0 \), with \( x_0 \) being half the depth of the detector in this example.

The velocity is then:

\[ \frac{dx_e(t)}{dt} = \mu_n \frac{V + V_{dep}}{d} \left( 1 - \frac{x_0}{d} \frac{2V_{dep}}{V + V_{dep}} \right) e^{-2\mu_n \frac{V_{dep}}{d^2} t} \]

\[ = \mu_n \left[ \frac{2V_{dep}}{d^2} x_0 - \frac{V + V_{dep}}{d} \right] e^{-2\mu_n \frac{V_{dep}}{d^2} t} \]

The same equations can be written for the hole velocity by replacing \( \mu_n \) with \( \mu_p \)

The transit time of the charges, From the start of the drift until they reach the electrodes, is defined by \( x_e(t_e) = d \) and \( x_n(t_n) = 0 \).

\[ t_e = \frac{d^2}{2\mu_n V_{dep}} \ln \left[ \frac{V + V_{dep}}{V - V_{dep}} \left( 1 - \frac{x_0}{d} \frac{2V_{dep}}{V + V_{dep}} \right) \right] \]
The direct signal observed on the electrons is the time development of the induced charge, the signal current:

\[ t_h = -\frac{d^2}{2\mu_p V_{dep}} \ln \left( 1 - \frac{x_0}{d} \frac{2V_{dep}}{V + V_{dep}} \right) \]

The current in this example then becomes:

\[ i(t) = \frac{q}{d} \frac{dx}{dt} \]

\[ i(t) = i_e(t) + i_h(t) = \frac{q}{d} \left( -\frac{dx_e}{dt} + \frac{dx_h}{dt} \right) \]

\[ = \frac{q(V + V_{dep})}{d^2} \left( 1 - \frac{x_0}{d} \frac{2V_{dep}}{V + V_{dep}} \right) \]

\[ \times \left[ \mu_n e^{-2\mu_n \frac{V_{dep}}{d^2} t} \Theta(t_e - t) \right. \]

\[ + \left. \mu_p e^{2\mu_p \frac{V_{dep}}{d^2} t} \Theta(t_h - t) \right] \]
\[
= \frac{q}{d^2} \left( 2V_{\text{dep}} \frac{x_0}{d} - (V + V_{\text{dep}}) \right) \\
\times \left[ \mu_n e^{-2\mu_n \frac{V_{\text{dep}}}{d^2} t} \Theta(t_e - t) + \mu_p e^{2\mu_p \frac{V_{\text{dep}}}{d^2} t} \Theta(t_h - t) \right]
\]

with \( \Theta(x) = \begin{cases} 1 & \text{for } x \geq 0 \\ 0 & \text{for } x < 0 \end{cases} \)

The total induced current is the superposition of an electron-induced current with falling exponential time behavior stopping at \( t = t_e \) and a hole-induced current with rising exponential time behavior stopping at \( t = t_h \).
**Transient current/charge technique**

**TCT/TChT**

- Laser (670 to 1030 nm, with absorption length of 5 µm to 300 µm in Si) to generate free carries.
- Free carrier generated: $10^5$ to $10^7$
- Temperature range: 77K to 320 K
- Bias range 0 to 1000 volts

---

Fig. 13. Block diagram of transient current technique experimental setup (a) and pulse shape of GaAs heterojunction laser (b).
Transport of free carriers in Si detectors and signal processing
TCT data (830 nm laser)

Fig. 9. A set of current pulses before and after depletion voltage for a deep level free detector: non-equilibrium carriers are generated (a) near the front p⁺-contact (drift of electrons); (b) near the back n⁻-contact (drift of holes).
TChT data (830 nm laser)

Fig. 12. Charge pulses at various bias for light illumination on the contact with minimum field of an irradiated \((3.61 \times 10^{13} \text{ cm}^{-2})\) Si-detector (a) and data processing of the pulse amplitude (b).
Various types of Si detectors in HEP and NP and for x-ray

Position sensing

- Si Strip detectors (SSD)
  - mm strips
  - micron strips (micro-strip det.)

- Si Pixel detectors (SPD)
  - mm pixels (pad detectors)
  - micron pixels (pixel det.)

- Si Drift detectors (SDD)
  - Linear SDD
  - Cylindrical SDD
  - Arbitrary shape SDD
Various types of Si detectors in HEP and NP and for x-ray

Strip detectors: Schematic
Various types of Si detectors in HEP and NP and for x-ray
Strip detectors

• Single-sided detector:
  – Easy to process
  – Fast transient time 10’s of ns
  – One dimensional sensing
    $\mu$m resolution
  – Modest number of read-out channels

• Double-sided detector
  – Two dimensional sensing
    – Difficult to process
    – Large number of read-out channels
    – Two-hit ambiguity
Various types of Si detectors in HEP and NP and for x-ray

Strip detectors (One example)

Single chip
Various types of Si detectors in HEP and NP and for x-ray

Strip detectors (One example)
Single chip
Various types of Si detectors in HEP and NP and for x-ray

Strip detectors (One example)

Single chip (fan-out)
Various types of Si detectors in HEP and NP and for x-ray

Strip detectors (One example)

Single chip (fan-out)
Various types of Si detectors in HEP and NP and for x-ray

Pixel detectors

Schematic
Various types of Si detectors in HEP and NP and for x-ray

Pixel detectors

• p on n pixel:
  – Easy to process
  – Fast transient time 10’s of ns
  – Two dimensional sensing
    μm resolution
  – Small leakage current
  – Maximum number of read-out channels
  – Bump-bonding needed

• n on n pixel
  – Maybe more rad-hard
  – Difficult to process
Various types of Si detectors in HEP and NP and for x-ray

Drift detectors

Schematic
Various types of Si detectors in HEP and NP and for x-ray

Drift detectors

Schematic

- Cathodes on both sides (Ref.[12])
Various types of Si detectors in HEP and NP and for x-ray
Drift detectors

- Small capacitance due to small anode (low noise) for large area detector
- Possible to separate bulk leakage current from surface current
- Smallest number of read-out channels
- Good multiplicity
- No two-hit ambiguity

- Difficult to process (two-sided)
- Long transient time ($\mu$s’s)
- Large biases (100’s to 1500 volts) needed
Various types of Si detectors in HEP and NP and for x-ray

Drift detectors

SVT for STAR at RHIC/BNL

- Detector schematic
Application of Si Devices as Detectors/Sensors

- Photodiodes
- Solar cells
- X-ray/Gamma/particle detectors
- Mechanical sensors
- Chemical sensors
- Bio-chemical sensors
- etc.
Silicon Vertex Detectors
THE INGREDIENTS

A. SENSORS

The majority of Vertex Detectors use Si sensors (example of another technique: scintillating fiber vertex detectors).

For high luminosity collider experiments other materials with more radiation resistance than Si have been and are investigated:

— GaAs
— Oxigenated Si
— CVD Diamond

GaAs seemed to be rad-hard for neutrons, but less resistant to pions compared with Si.

It has been demonstrated (RD42) that CVD Diamond is radiation hard for fluences beyond $10^{15}$ protons/cm$^2$.

Also oxigenated high resistive Si has in some aspects better radiation resistance than normal high resistive Si...
• Types of Sensors most commonly used in Vertex
• Detectors/Trackers:
  – **Microstrip Detectors**
    • single sided
    • double sided
  – **Pixel Detectors**
  – **Si Drift Chambers**
  – **Pad Detectors**
  – **Charge Coupled Devices (CCD)**
A Generic Si Detector: Principle of operation

Fig. 25 Sketch of cross-section of a generic double-sided microstrip detector. Exposed fixed charges are shown by open circles (positive) and filled circles (negative). Also shown is the electric field distribution in such a detector before and after radiation-induced displacement damage in the silicon.
Si $\mu$-Strip Detectors

- P$^+$ Strips on high resistive n-material most commonly used
- p$^+$n junction on structered side; n$^+$n ohmic contact on backplane
Some Standard Technologies

- **Coupling of p-n junction to read-out:**
  - \( dc \) with effective bias resistor as part of front-end electronics
  - \( dc \) with bias resistor (polysilicon) and ac coupling on separate bias chip (glass substrate)
  - ac coupling integrated on Si sensor: metal on top of \( \text{SiO}_2 \) or \( \text{SiO}_2-\text{Si}_3\text{N}_4 \); difficult to get yield above 99%

- **Integrated bias resistors:**
  - Polysilicon  Range 100k\( \Omega \) to 100M\( \Omega \); uniform; radhard
  - Punch-Through or Fox FET; Dynamic resistance very high, \( R \sim 1/I_{\text{leak}} \) simple technology
  - Implanted resistors: simple technology, radhard?, not suited for very high resistors
• **Guard Ring Structures:**

• New approach has been taken with the need of high operation voltage in the environment of high luminosity collider experiments
  
  – Increase of full depletion voltage after heavy irradiation and reverse annealing
  
  – Operation of detectors with sufficient overdepletion voltage to collect full charge at very short shaping times (ballistic deficit)
• $n^+$ strips on $n$-material:
  – most features are as with $p^+n$ strips

  However there are 2 additional technology steps needed:
  • Ohmic separation of $n^+$ strips which are shorted by electron accumulation layer has to be implemented
    – $p$-stops: $p^+$ implants all around the $n$ strips to break the accumulation layer
    – $p$-spray implant over the whole structured side
  • Guard Rings on the $p^+n$ junction side (backplane) of the detector
• The need for guard rings on both sides of the detector is the cause for
  – Higher cost
  – Basically full double sided processing required which also influences the yield

• Double sided detectors are just combining both single sided technologies
• In general double sided detectors would give the best physics performance but are more delicate to operate
  • High voltage at least on one side for readout
  • Front End electronics in sensitive volume or rerouting of readout on one side (double metal) in case of $90^\circ$ stereo
  • ..................
Si PIXEL DETECTORS

- Technology is identical to strip detector technology.
- Pixel detectors are usually installed very close to the interaction region in an extremely severe radiation environment. Most presently developed systems need sensor material with very high radiation hardness.
- For this reason a widely pursued option is Si $n^+n$ pixels with $p$-spray isolation between adjacent pixels.
- Reasons: after space charge inversion (also “Type Inversion”) the space charge region develops from the n-side into the bulk when voltage is applied. The charge carriers move close to the read-out electrodes also when not fully depleted.
- Multi guard ring structures to assure high breakdown voltage, in excess of 500V.
Si PIXEL DETECTORS

• GEOMETRY:

• Minimum pixel size needed for accommodating all the necessary functions on the front-end chip is about 20000 $\mu m^2$.
  – 150 x 150 $\mu m^2$
  – 50 x 400 $\mu m^2$

• point resolution: $\sigma_{r\phi} = 12 \mu m$, $\sigma_z = 60 \mu m$
Si PIXEL DETECTORS

Layout of CMS pixel. Floating double p-stop around each pixel
Si PIXEL DETECTORS

ATLAS Pixel Layout

Resolution obtained with ATLAS pixel in test beam
Charge Coupled Devices

• Most precise 2 dimensional electronic sensor for vertex detection.
• Big devices commercially available: 80 x 16 mm$^2$ with 4 output nodes
• Pixel size: 20 x 20 µm$^2$ $\Rightarrow$ 3.2 x 10$^6$ pixels
• Radiation length small: 0.4% per layer
• Read-out time long: 210 ms
• Spatial resolution: $\sigma \sim 4$ µm
• Missed distance for $\mu$–pairs: $\delta = 8 - 10$ µm
• Smallest multiple scattering contribution: $33/\text{psin}\theta^{3/2}$

• Alignment very important
Charge Coupled Devices

Very powerful, fully commercial device
Supported by Multi-Billion dollar industry
(Videa Cameras, HDTV,…….)

- The principle of a Charged Coupled Device

- First time used in experiment in 1983/1984 in NA11/NA32

$\Lambda_C$ in hadronic production
Charge Coupled Devices

The VXD3 CCD

- Pixel size 20\(\mu\)m \(\times\) 20\(\mu\)m, epitaxial layer=20\(\mu\)m
- Active area 80X16\(\text{mm}^2\)
  4,000X800 pixels
  (x96CCD=307M pixels!)
- Small radiation length
  0.4%/Layer
- 4 readout nodes
- Readout time=210ms
  However intrinsically
deadtimeless operation
Charge Coupled Devices
Charge Coupled Devices

drz distributions

Doublet

σ=3.83μm

Triplet

σ=3.76μm

Shingle

σ=3.80μm

Pairs

σ=4.05μm
Fig. 44. (Top) Raw data (mostly SR X-ray hits) in the SLD vertex detector. (Bottom) The same event, with background filtered out by a drift chamber/vertex detector track linking algorithm. This proved to be a $Z^0 \rightarrow \mu^+\mu^-$ event.
Reverse biased abrupt p⁺ n junction

Poisson’s equation
\[- \frac{d^2 \phi(x)}{dx^2} = \frac{q_0}{\varepsilon \varepsilon_0} \cdot N_{\text{eff}}\]

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

Neutral bulk (no electric field)

Electrical charge density

Electrical field strength

Electron potential energy

Depletion voltage
\[ V_{\text{dep}} = \frac{q_0}{\varepsilon \varepsilon_0} \cdot |N_{\text{eff}}| \cdot d^2 \]

effective space charge density

Full charge collection only for \( V_B > V_{\text{dep}} \)!
Calculation of depletion voltage (diode)

Poisson’s equation

\[ -\frac{d^2}{dx^2} \phi(x) = \frac{q_0}{\varepsilon \varepsilon_0} \cdot N_{\text{eff}} \]

with

\[ \frac{d}{dx} \phi(x = w) = 0 \]
\[ \phi(x = w) = 0 \]

\[ -\frac{d}{dx} \phi(x) = \frac{q_0}{\varepsilon \varepsilon_0} \cdot N_{\text{eff}} \cdot (x - w) \]

\[ \phi(x) = \frac{1}{2} \cdot \frac{q_0}{\varepsilon \varepsilon_0} \cdot N_{\text{eff}} \cdot (x - w)^2 \]

w = depletion depth

d = detector thickness

U = voltage

\( N_{\text{eff}} \) = effective doping concentration

\[ C = \frac{dQ}{dU} = \frac{dQ}{dw} \cdot \frac{dw}{dU} \]

\[ dQ = q_0 \cdot \left| N_{\text{eff}} \right| \cdot A \cdot dw \]
\[ dw = \sqrt{\frac{\varepsilon \varepsilon_0}{q_0 \left| N_{\text{eff}} \right| 2U}} \cdot dU \]

\[ V_{\text{dep}} = \frac{q_0}{2 \varepsilon \varepsilon_0} \cdot \left| N_{\text{eff}} \right| \cdot d^2 \]

\[ w(V) = \sqrt{\frac{2\varepsilon \varepsilon_0}{q_0 \left| N_{\text{eff}} \right|}} \cdot V \]

\[ C(U) = A \cdot \sqrt{\frac{\varepsilon \varepsilon_0 q_0 \left| N_{\text{eff}} \right|}{2U}} \]

\[ C(w) = \frac{\varepsilon \varepsilon_0 A}{w} \]
How to make a Float Zone Silicon wafer?

- **Produce a polysilicon rod**
  - Melt very pure sand ($SiO_2$) together with coke (~1800°C)
    \[ SiO_2 + 2C \rightarrow Si + 2CO \]
  - Grind the “metallurgical grade silicon” (98% Si) and expose it to hydrochloric gas
    \[ Si + 3HCl \ (gas) \rightarrow SiHCl_3 + H_2 \]
  - **Trichlorosilane** boils at 31.7°C and can thus be distilled and purified

- **Float Zone process**
  - Using a single Si crystal seed, melt the vertically oriented rod onto the seed using RF power and “pull” the monocrystalline ingot

- **Monocrystalline Ingot**
  - Grind into round shape
  - Make the flat or a notch

- **Wafer production**
  - Slice the ingot into wafers of 300-500 μm (diamond saw)
  - Lapping of wafers
  - Etching of wafers
  - Polishing of wafers
Silicon Sensor Production

- A "simple" production sequence (schematic)

- Polished n-type silicon wafer (typical $\rho \sim 1-10 \text{ K}\Omega \text{cm}$)

- Oxidation (800-1200°C)

- Photolithography (coat with photo resist; align mask, expose to UV light, develop photoresist)

  Etching of oxide

  ![Etching of oxide diagram]

- Doping with boron and phosphorus by implantation (or by diffusion)
  Annealing to cure radiation damage and activate dopants
  - $p^+$ n junction on front side
  - n n$^+$ ohmic contact on back side

- Aluminize surface (e.g. by evaporation)

- Pattern metal for diode contacts
Single Sided Strip Detector

- Segmentation of the p⁺ layer into strips (Diode Strip Detector) and connection of strips to individual read-out channels gives spatial information

- Typical thickness: 300µm (150µm - 500µm used)

- Using n-type silicon with a resistivity of
  \[ \rho = 2 \text{ K} \Omega \text{cm} \ (N_D \sim 2.2 \cdot 10^{12} \text{cm}^{-3}) \]
  results in a depletion voltage \( \sim 150 \text{ V} \)

- Resolution \( \sigma \) depends on the pitch \( p \) (distance from strip to strip)

  - E.g. detection of charge in binary way (threshold discrimination) and using center of strip as measured coordinate results in

  \[ \sigma = \frac{p}{\sqrt{12}} \]

  - Typical pitch values are 20 µm - 150 µm \( \Rightarrow \) 50 µm pitch results in 14.4 µm resolution
**Bias resistor**
- Need to isolate strips from each other to collect/measure charge on each strip
  \[ \Rightarrow \text{high impedance bias connection (} \approx 1 \text{M} \Omega \text{ resistor)} \]

**Coupling capacitor**
- Couple input amplifier through a capacitor (AC coupling) to avoid large DC input from leakage current

**Integration of capacitors and resistors on sensor**
- Bias resistors via deposition of doped polysilicon
- Capacitors via metal readout lines over the implants but separated by an insulating dielectric layer (SiO₂, Si₃N₄).

\[ \Rightarrow \text{nice integration} \]
\[ \Rightarrow \text{more masks, processing steps} \]
\[ \Rightarrow \text{pin holes} \]
Collected Charge for a Minimum Ionizing Particle (MIP)

- Mean energy loss
  \[ \frac{dE}{dx} (\text{Si}) = 3.88 \text{ MeV/cm} \]
  \[ \Rightarrow 116 \text{ keV for 300} \mu\text{m thickness} \]

- Most probable energy loss
  \[ \approx 0.7 \times \text{mean} \]
  \[ \Rightarrow 81 \text{ keV} \]

- 3.6 eV to create an e-h pair
  \[ \Rightarrow 72 \text{ e-h/} \mu\text{m (mean)} \]
  \[ \Rightarrow 108 \text{ e-h/} \mu\text{m (most probable)} \]

- Most probable charge (300 \mu m)
  \[ \approx 22500 \text{ e} \approx 3.6 \text{ fC} \]
Signal to noise ratio (S/N)

- **Landau distribution** has a low energy tail - becomes even lower by noise broadening

**Noise sources**: (ENC = Equivalent Noise Charge)

- Capacitance \( ENC \propto C_d \)
- Leakage Current \( ENC \propto \sqrt{I} \)
- Thermal Noise (bias resistor) \( ENC \propto \sqrt{k_B T / R} \)

- Good hits selected by requiring \( N_{ADC} > \) noise tail
  - If cut too high ⇒ efficiency loss
  - If cut too low ⇒ noise occupancy

- **Figure of Merit**: Signal-to-Noise Ratio \( S/N \)

- Typical values >10-15, people get nervous below 10.
  Radiation damage severely degrades the S/N.
**Charge Collection time**
- Drift velocity of charge carriers $v \approx \mu E$, so drift time, $t_d = \frac{d}{v} = \frac{d}{\mu E}$

Typical values: $d = 300 \mu m$, $E = 2.5 \text{ kV/cm}$, with $\mu_e = 1350 \text{ cm}^2/\text{V} \cdot \text{s}$ and $\mu_h = 450 \text{ cm}^2/\text{V} \cdot \text{s}$

$\Rightarrow t_d(e) = 9 \text{ ns}$, $t_d(h) = 27 \text{ ns}$

**Diffusion**
- Diffusion of charge "cloud" caused by scattering of drifting charge carriers, radius of distribution after time $t_d$:

$$\sigma = \sqrt{2Dt_d} \quad \text{with diffusion constant} \quad D = \mu \frac{kT}{q}$$

- Same radius for $e$ and $h$ since $t_d \propto 1/\mu$

Typical charge radius: $\sigma \approx 6 \mu m$, could exploit this to get better position resolution due to charge sharing between adjacent strips (using centroid finding), but need to keep drift times long (low field).
**Double sided silicon detectors**

- **Get a 2nd coordinate**
  Put n⁺ and p⁺ strips on opposite sides and read them both.

- **Problem: Electron accumulation layer**
  n⁺-strips are not isolated because of an electron accumulation layer at the Si-SiO₂ interface. This effect is due to the presence of positive charge in SiO₂ layer which attracts electrons.

- **Solution: “Break” accumulation layer**
  - p-strips in between the n-strips ("p-stop")
  - moderate p⁺-implantation over all surface ("p-spray")
  - "field plates" (metal over oxide) over the n⁺-strips and apply negative potential with respect to n⁺-strips to repel electrons.
Detector Modules - “Basic building block of tracking detectors”
- Silicon Sensors
- Mechanical support (cooling)
- Front end electronics and signal routing (connectivity)

Example: ATLAS SCT Barrel Module

- Silicon sensors (x4)
  - 64 x 64 mm²
  - p-in-n, single sided
  - AC-coupled
  - 768 strips
  - 80μm pitch/12μm width

- Mechanical support
  - TPG baseboard
  - BeO facings

- Hybrid (x1)
  - flexible 4 layer copper/kapton hybrid
  - mounted directly over two of the four silicon sensors
  - carrying front end electronics, pitch adapter, signal routing, connector

SCT = SemiConductor Tracker
ASICS = Application Specific Integrated CircuitS
TPG = Thermal Pyrolytic Graphite

- ASICS (x12)
  - ABCD chip (binary readout)
  - DMILL technology
  - 128 channels

- Wire bonds (~3500)
  - 25 μm Al wires

ATLAS – SCT
- 15.552 microstrip sensors
- 2.112 barrel modules
- 1.976 forward modules
- 61 m² silicon, 6.3·10⁶ strips
Détecteurs Si-pad développés à IPN Orsay
300 μm/1500 μm d’épaisseur avec 60/30 pads de 4x4 mm²
Wire bonding

- Uses ultrasonic power to vibrate needle-like tool on top of wire. Friction welds wire to metallized substrate underneath.
- Can easily handle 80μm pitch in a single row and 40μm in two staggered rows (typical FE chip input pitch is 44μm).
- Generally use 25μm diameter aluminum wire and bond to aluminum pads (chips) or gold pads (hybrid substrates).
- Heavily used in industry (PC processors) but not with such thin wire or small pitch.

Microscope: connect sensor to fan-out circuit

Electron microscope: bond “foot”
Silicon Drift Detectors

- Principle of sideways depletion (as for DEPFET sensors)
- \( p^+ \) segmentation on both sides of sensor
- Complete depletion of wafer from segmented \( n^+ \) anodes located at one side of sensor
- Electrons drift parallel to substrate surface to \( n^+ \) anodes
- Voltage divider network (resistors) for p-strips to provide uniform drift field

- Need to ensure good material uniformity, low defect rates, good drift field homogeneity, precise voltage dividing on p-strips and good temperature control.
- HEP: Implemented for STAR at RHIC and for ALICE at LHC
Hybrid Pixel Detectors

- **HAPS – Hybrid Active Pixel Sensors**
  - segment silicon to diode matrix with high granularity (⇒ true 2D, no reconstruction ambiguity)
  - readout electronic with same geometry (every cell connected to its own processing electronics)
  - connection by “bump bonding”
  - requires sophisticated readout architecture
  - Hybrid pixel detectors will be used in LHC experiments: ATLAS, ALICE, CMS and LHCb

Solder Bump: Pb-Sn

Flip-chip technique
CCD – Charged Coupled Devices

(1) MOS structure with segmented metal layer; Charge is captured in a potential well.

(2) Readout: Shift electrons towards anode by periodic variation of 3 potentials

(3) Create an array of pixel for a 2D detector

Pixel CCD
- needs only few readout channels
- small charge (∼2000 e) ⇒ needs cooling
- long readout time, active during readout
- sensitive to radiation damage

⇒ applicable for low rate experiment without high intensity radiation field
Monolithic detectors
- readout electronics directly within sensor material (same epi layer)

- charge collected at n-well / p-epi diode
- thermal diffusion of free charge
- reflection at potential barriers between areas with different doping concentration
- no depletion voltage applied ⇒ potential formed by different doping concentrations only

- no connections needed to electronics (e.g. no bumps)
- very small sizes achievable
DEPFET - DEP(leted)F(ield)E(ffect)T(ransistor)

- FET integrated on high resistivity bulk, bulk sideward depleted
- electrons collected in potential minimum at internal gate
  - transistor current modulated by collected charge
  - charge removed by reset mechanism (clear)
- switch on/off by (external) top gate to read out

- amplification of charge at the position of collection ⇒ no transfer loss
- full bulk sensitivity, bulk can be thinned down to 50 μm if needed
- non structured entrance window (backside)
- very low input capacitance ⇒ very low noise
CMS - Currently the Most Silicon

Micro Strip:
- ~ 214 m² of silicon strip sensors
- 11.4 million strips

Pixel:
- Inner 3 layers: silicon pixels (~ 1m²)
- 66 million pixels (100x150μm)
- Precision: σ(ρφ) ~ σ(z) ~ 15μm
- Most challenging operating environments (LHC)
Radiation Levels at LHC and SLHC

- Example: ATLAS
  - Fluences per year at full Luminosity

![Graph showing fluences per year at full Luminosity]

- LHC silicon detectors:
  - All detectors have been extensively tested and developed for radiation tolerance and are expected to survive the LHC radiation environment.
  - Some experiments have already foreseen upgrades (e.g. LHCb Velo after 3 years).

- Super LHC
  - Upgrade of LHC to 10 x higher Luminosity
  - 10 x higher radiation levels
  - Radiation damage will become a critical issue!
  - New, radiation tolerant detectors needed!

- Pixel detector: up to $\Phi_{eq} \approx 3.5 \cdot 10^{14}$ cm$^{-2}$/year
- Dominating type of particle is different for pixel (pions) and strip detectors (neutrons)

- What is radiation damage?
- How to cope with it?

CERN – PH/DT2
Particle Detectors – Principles and Techniques
Radiation Damage: Microscopic defects

- **Damage to the silicon crystal:** Displacement of lattice atoms

  particle → $Si_S$ → $E_K > 25 \text{ eV}$

  $E_K > 5 \text{ keV}$

  point defects and clusters of defects

  "point defects", mobile in silicon, can react with impurities (O, C, ...)

  Distribution of vacancies created by a 50 keV Si-ion in silicon (typical recoil energy for 1 MeV neutrons):

  - Schematic [Van Lint 1980]
  - Simulation [M.Huhtinen 2001]

- **Defects can be electrically active (levels in the band gap)**
  - capture and release electrons and holes from conduction and valence band
  - can be charged - can be generation/recombination centers - can be trapping centers
Radiation Damage: Particle dependence

- particle → $S_i_S$ → $E_K > 25$ eV
  - $E_K > 5$ keV → point defects and clusters of defects
  - Vacancy + Interstitial → point defects (V-O, C-O, ...)

$^{60}$Co-gammas
- Compton Electrons with max. $E_y \approx$ MeV (no cluster production)

Electrons
- $E_e > 255$ keV for displacement
- $E_e > 8$ MeV for cluster

Neutrons (elastic scattering)
- $E_n > 185$ eV for displacement
- $E_n > 35$ keV for cluster

only point defects ↔ point defects & clusters ↔ mainly clusters

Simulation:
Initial distribution of vacancies in $(1 \mu m)^3$
after $10^{14}$ particles/cm²

- 10 MeV protons: 36,824 vacancies
- 24 GeV/c protons: 4,145 vacancies
- 1 MeV neutrons: 8,870 vacancies

[Mika Huhtinen NIMA 491(2002) 194]
Radiation Damage in Silicon Sensors

Two general types of radiation damage:

- **Bulk (Crystal) damage** due to **Non Ionizing Energy Loss (NIEL)**
  - Displacement Damage –
    
    I. Change of **depletion voltage** (higher operation voltage, underdepletion)
    \[\Rightarrow\] constant cooling needed to avoid reverse annealing

    II. Increase of **leakage current** (increase of shot noise, thermal runaway)
    \[\Rightarrow\] needs cooling of sensors during operation

    III. Decrease of **charge collection efficiency**
         due to underdepletion and increased trapping

- **Surface damage** due to **Ionizing Energy Loss (IEL)**
  - accumulation of positive in the oxide (SiO$_2$) and the Si/SiO$_2$ interface –
    
    affects: interstrip capacitance (noise factor), breakdown behavior
    and other structures depending on near-surface effects

- **Signal/noise ratio is the quantity to watch**

  \[\Rightarrow\] **Sensors can fail from radiation damage**!
R&D: Radiation tolerant tracking detectors

Scientific Strategies:

I. Material engineering
II. Device engineering
III. Variation of detector operational conditions

Defect Engineering of Silicon

- Needs: profound understanding of radiation damage (microscopic defects, macroscopic parameters, dependence on particle type and energy, defect formation kinetics and annealing processes)
- Examples: Oxygen enriched silicon, Hydrogen enriched silicon, Pre-irradiated silicon

New Materials (other semiconductors than Si)
- Diamond, Silicon Carbide (SiC), ...

New detector designs
- Examples: p-type silicon detectors (n-in-p), thin detectors, epitaxial detectors, 3D and Semi 3D detectors

Cryogenic operation of detectors

Operate detectors at 100-200K to reduce the charge loss ("Lazarus effect")

Active CERN R&D collaborations:
- RD50 "Radiation hard semiconductor devices for very high luminosity colliders"
- RD42 "CVD Diamond Radiation Detectors"
- RD39 "Cryogenic Tracking Detectors"
New Material: Oxygen enriched silicon – DOFZ

**DOFZ (Diffusion Oxygenated Float Zone Silicon)**
- 1999 Introduced to the HEP community by CERN - RD48 (ROSE-Collaboration)

Very long oxidation (e.g. 48h at 1150°C) increases the oxygen content in silicon

![Graph showing O-concentration versus depth](image1)

Strong improvement after charged hadron irradiation observed

![Graph showing N_eff versus Φ_{24 GeV/c protons}}](image2)

- 2005: DOFZ silicon used for the ATLAS and CMS Pixel detectors
- 2005: Other types of oxygen rich silicon under investigation: Czochralski Si, epitaxial Si
New detector concepts: 3D detectors

- **Electrodes:**
  - narrow columns along detector thickness—"3D"
  - diameter: \( \approx 10 \mu m \); distance: 50 - 100\( \mu m \)

- **Lateral depletion:**
  - lower depletion voltage needed \( (V_{dep} \approx d^2) \)
  - radiation tolerant or thick detectors possible
  - fast signal \( (\approx 3.5 \text{ ns measured}) \)

- **Processing of detectors:**
  - complex fabrication: Holes have to be made and filled with electrodes (DRIE etching, Laser drilling, Photo Electro Chemical etching);
  - present aspect ratio (depth to diameter) \( \approx 30:1 \)
  - possibility to implement narrow dead regions at edges "edgeless detectors"

- **Application:**
  - detectors still under development!
  - option for LHC experiments upgrade?