Advanced Detector Technology

Luciano Musa - CERN
Lecture 1

• Tracking detectors in HEP experiments
• Silicon trackers – a brief historical excursus
• Silicon properties – a brief reminder
• Silicon detectors – basic principles

This lecture makes use of material from the following authors

• Mohsen Khakzad (St FX University, Canada)
• M. Krammer (CERN and IHEP Vienna, Austria), F. Hartmann (KIT, Germany)
• N. Wermes (Bonn University, Germany)
• P. Riedler (CERN), A. Kluge (CERN)
• D. Bortoletto (Oxford University, UK)
Introduction
Tracking Detectors in HEP Experiments
LHC pp collisions: a candidate Z boson event in the dimuon decay with 25 reconstructed vertices (ATLAS, April 2012)
Fixed Target Exp:

Collider Exp:

Interaction of particles in diff. detector components:

Traditional Particle Physics Experiment divided (simplified) in 4 main components

By the characteristic signatures particles leave in a detector

- particles can be either identified: e⁻, e⁺, μ⁻, μ⁺, γ
- or at least assigned to families: charged or neutral hadrons
**Tracking system** measures the traces left by charged particles

Tracking + Magnetic Field: magnetic spectrometer ➔ sign and momentum

Photons may convert into electron-positron pair, which can be detected in the tracking system

Charged kaon decays may be detected in a high-resolution tracking system through their characteristic “kink” topology:

\[
K^\pm \rightarrow \mu^\pm \nu_\mu \quad (64\%)
\]

\[
K^\pm \rightarrow \pi^\pm \pi^0 \quad (21\%)
\]

The kinematics of this kink topology allows separating $K$ decays from the main source of background kinks from charged pion decays
Almost all High Energy Physics (HEP) experiments with accelerators make use of magnetic spectrometers to determine the momentum of charged particles.

If a particle with mass $m_0$ and charge $q$ traverses a magnetic field $B$ with velocity $v$:

$$
\frac{dp}{dt} = F = qvB
$$

In case of homogeneous magnetic field the trajectory is given by an helix.

In experiments at hadronic colliders the emphasis is on the measurement of the transverse momentum $p_T$:

$$
p_T[GeV/c] = 0.3B[T] \cdot R[m]
$$

Use layers of position sensitive detectors before and after or inside a magnetic field to measure the trajectory and determine the bending radius $R$.

The relative error on the momentum is:
- proportional to $p$
- inversely proportional to $B$
- inversely proportional to $L^2$
- proportional to the detector spatial resolution $\sigma$

$$
\frac{\delta p}{p} = \frac{p}{0.3BL^2} \cdot 0.2 \cdot \frac{1}{\sqrt{C_N}}
$$

$$
BL^2 = \text{bending power}
$$
Assume N+1 detection layers, placed at $x_0, x_1, x_N$, measuring the $y$ coordinate all with the same resolution.

Good momentum resolution requires:
- Good spatial resolution
- Strong B field
- Long track path length (lever of arm)

Momentum resolution gets worse at large $p$!!

$$\frac{\delta p}{p} = \frac{p}{0.3BL^2} \sigma \cdot \sqrt{C_N}$$

true if multiple-scattering is neglected

$$C_N = \frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}$$

Weak dependence on $N$!!
Magnetic Spectrometers

Two main configurations

**Solenoidal field**
- Central Barrel Spectrometer
- Cylindrical symmetry
  - deflection in x-y ($r$-$\phi$) plane
  - Tracking detectors in cylindrical shells along $r$
  - Measurement of curved tracks in $r$-$\phi$ plane (bending plane) at fixed values of $r$

**Dipole field**
- Forward Spectrometers
- Rectangular symmetry
  - deflection in y-z plane
  - Tracking detectors arranged in parallel planes along $z$
  - Measurement of curved tracks in y-z plane at fixed values of $z$
  - Bending from difference of the slopes before and after B

**Solenoid:** CMS=4T, ATLAS=2T, ALICE=0.5T
**Dipole:** LHCb=4Tm
LHCb – A Forward Spectrometer

Dipole LHCb NI = 4Tm
Azimuthal symmetry

- deflection in (r-z) plane
- Tracking detectors in cylindrical shells along r
- Measurement of curved tracks in r-z plane at fixed values of r

TOROID ATLAS 0.5T
Azimuthal symmetry
Multiple Scattering

Particles moving through the detector material suffer innumerable EM collisions which alter the trajectory in a random fashion (stochastic process).

Statistical (quite complex) analysis of multiple coulomb collisions (Rutherford scattering at the nuclei of the detector material), gives:

\[
P(\theta) = \frac{1}{\sqrt{2\pi}\langle \theta^2 \rangle_p} \exp\left[ -\frac{1}{2\langle \theta^2 \rangle_p} \theta^2 \right]
\]

Probability that a particle is deflected by an angle \( \theta_p \) after travelling a distance \( x \) in the material is given by a (almost) Gaussian distribution with sigma of:

\[
\langle \theta_p \rangle = \frac{0.0136}{\beta_p c [\text{GeV}/c]}^{\frac{z_{\text{particle}}}{X_0}} \sqrt{\frac{x}{X_0}} \left( 1 + 0.038 \ln \frac{x}{X_0} \right)
\]

High tracking resolution \( \Rightarrow \text{less scattering} \)

- Small \( x \), i.e. very thin detectors
- Large radiation length \( X_0 \) – i.e. low Z and low density materials (Be, C, Al, ...)

Note: Lateral displacement \( \varepsilon_p \) displacement is proportional to the thickness of the detector: usually can be neglected for thin detectors (for 300 \( \mu \text{m} \) silicon \( \varepsilon_p \approx 0.01 \mu \text{m} \))
Central Trackers at the LHC Experiments

**ATLAS Tracker**

- **Si-pixel, Si strip, TRT (gas, transition radiation)**
- **Phase-I upgrade:** one more Si-pixel layer (IBL)
- **Phase-II upgrade:** **Si pixel + Si Strip** (entirely new)
  - $\approx 200 \text{ m}^2$ silicon strips
Central Trackers at the LHC Experiments

CMS TRACKER

Si-pixel, Si strip → All silicon

Phase-I upgrade: replacement of Si-pixel

Phase-II upgrade: Si pixel + Si Strip (entirely new)

≈ 200 m² silicon strips
Central Trackers at the LHC Experiments

ALICE Tracker

Si pixel, Si drift, Si strip, TPC (gas), TRD (gas, trans. rad.)

Phase-I upgrade: MAPS + TPC & TRD (new readout)

10 m² silicon pixels
Central Trackers at the LHC Experiments

Figure 9: Schematic view of the LHCb detector [18].

Silicon strips are used in the region close to the beam pipe, whereas strawtubes are employed in the outer regions. The VELO makes possible a reconstruction of primary vertices with 10 $\mu$m (60 $\mu$m) precision in the transverse (longitudinal) direction. In this way the displaced secondary vertices, which are a distinctive feature of beauty and charm hadron decays, may be identified. The overall performance of the tracking system enables the reconstruction of the invariant mass of beauty mesons with resolution $\Delta m \approx 15$ to $20$ MeV/c$^2$, depending on the channel.

2.3.3 Particle identification

LHCb in general looks like a slice out of a “traditional” experiment as described in Sect. 1.1, apart from the two RICH detectors providing hadron ID. The RICH detectors are described in more detail in Sect. 5.4. An EM calorimeter and a hadron calorimeter provide the identification of electrons, hadrons and neutral particles (photons and $\pi^0$) as well as the measurement of their energies and positions. The EM calorimeter is a rectangular wall constructed out of lead plates and scintillator tiles. The total thickness corresponds to $25 X_0$. In a beam test it was found that the relative energy resolution follows

$$\left(\frac{E}{E}\right)^2 = \left(0.094 / E(\text{GeV})\right)^2 + \left(0.145 / E(\text{GeV})\right)^2 + 0.0083.$$ 

The hadronic calorimeter consists of iron and scintillator tiles with a relative energy resolution of

$$\left(\frac{E}{E}\right)^2 = \left(0.69 / E(\text{GeV})\right)^2 + 0.09.$$ 

Finally, the muon system is designed to provide a fast trigger on high momentum muons as well as offline muon identification for the reconstruction of muonic final states and beauty flavor tagging. It consists of five stations (M1-M5) equipped mainly with Multi Wire Proportional Chambers (MWPCs). For the innermost region of station M1, which has
Silicon Trackers
A Brief Historical Excursus
The Rise of Silicon Detectors in HEP

Towards end of 1970’s: intensive R&D on devices which could measure short-lived particles (≤ ps)

R&D at CERN(A) and Pisa(B) demonstrated that strip detectors (100-200µm pitch):

• exhibit high detection efficiency (>99%), good spatial resolution (~20µm) and good stability

• allow precise vertex reconstruction

However the technology for the fabrication of these devices was very tricky, thus limiting their availability

1980 – fabrication of silicon detectors using standard IC planar process (PIN diode ➔ μstrip detector)


First use of silicon strips detectors by NA11(CERN SPS) and E706 (FNAL)

(A) NA11 (1981): 6 planes (24 x 36mm²): resistivity 2-3 kΩcm, thickness 280µm, pitch 20µm

(B) E706 (1982): 4 planes (3x3 cm²) + 2 planes (5x5cm²)

Erik Heine, Joseph Kemmer and Gherard Lutz: 2017 EPS prize for “Outstanding Contributions to HEP” (pioneering the development of silicon μstrip)
The Rise of Silicon Detectors in HEP

The next step forward came with the advent of the VLSI technology that allowed coupling ASIC amplifier chips directly to the detectors

1990s - LEP, first silicon vertex detectors were installed in DELPHI and ALEPH experiments, then OPAL and L3

1989 - first DELPHI vertex detector, consisting of two layers of single-sided strip detectors

Projective geometry ➔ ambiguity at high multiplicities (high occupancy)

This started to become apparent already at DELPHI:

• High number of ambiguities ➔ reconstruction efficiency suffered a lot, especially in the forward direction

Not usable close to IP in hadron colliders (LHC) or HI experiments at SPS

Another problem at (very) high particle load ➔ degradation of the sensor by the high radiation dose

This implies starting with a very large signal-to-noise ratio, which can only be obtained with detector with small capacitance
The Inception of Silicon Pixel Detectors

“The silicon micropattern detector: a dream?”

“Development of silicon micropattern detectors”

1995 – First Hybrid Pixel detector installed in WA97 (CERN, Omega facility)

1996/97 – First Collider Hybrid Pixel Detector installed in DELPHI (CERN, LEP)

Work carried out by RD19 for WA97 and NA57/CERN

- 5 x 5 cm² area
- 7 detector planes
- ~0.5 M pixels
- Pixel size 75 x 500 µm²
- 1 kHz trigger rate
- Omega2 chip

CERN – WA97 Experiment (1995)

No-field, Pb-Pb, 153 reconstructed tracks
Pixel Detectors at the LHC Trackers

10 years after the first use in WA97... silicon detectors at the heart of the LHC Experiments
Beyond Hybrid Pixel Detectors …

Since the very beginning of pixel development (RD 19):

- dream to integrate sensor and readout electronics in one chip

Motivation to reduce: cost, power, material budget, assembly and integration complexity

Several major obstacles to overcome for CMOS MAPS:

- CMOS generally not available on high resistivity silicon (needed as bulk material for the sensor)
- Full CMOS circuitry not possible within the pixel area (only one type of transistor \(\rightarrow\) slow readout)
Owing to the industrial development of CMOS imaging sensors and the intensive R&D work (IPHC, RAL, CERN)

... several HI experiments have selected CMOS pixel sensors for their inner trackers and intensive R&D for ATLAS

STAR HFT
0.16 m² – 356 M pixels

CBM MVD
0.08 m² – 146 M pixel

ALICE ITS Upgrade (and MFT)
10 m² – 12 G pixel

sPHENIX
0.2 m² – 251 M pixel
Silicon Properties
A Brief Reminder
Silicon CMOS Industry

Monocrystalline silicon
main semiconductor used for the fabrication of Integrated Circuits

Monocrystalline, high purity single crystals (Czochralski)

Monocrystalline silicon is the main semiconductor used for the fabrication of Integrated Circuits. Monocrystalline, high purity single crystals (Czochralski) are used in the fabrication of Integrated Circuits (IC). Approximately 180 million wafers are produced annually, with a cost of approximately $3.5 per cm². The area of CMOS sub-micron fabs is approximately 9 x 10⁶ m².
Silicon Properties – Lattice Structure

Silicon Atom (Si)

- Z = 14 (2,8,4)
- Group IV
- 4 valence electrons

2D representation of Si crystal

Shared electrons of a covalent bond

Silicon lattice – diamond crystal structure

- Crystal structure
  - diamond cubic (tetrahedral)
  - lattice constant 5.43 Å

Each atom is surrounded by 4 equidistant nearest neighbors
In a crystal the discrete atomic levels form energy bands.

For a single atom the electrons can only occupy certain energy levels.

When $N$ atoms are moved closer, until they reach the equilibrium inter-atomic distance $d$, the energy levels split into $N$ levels ($N$-fold degenerate) very close to each other. If $N$ is large (which is the case in a crystal) they eventually form a continuous energy band.
Material Basic Properties

Solid state materials classification

**isolators** (large band gap)

**semiconductors** (small band gap)

**metals** (conduction band partially filled or overlaps with valance band)

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**Note:** in reality the band structure is more complex, depending on crystal momentum, crystal orientation, etc.

**Band gap at 300K:** $\text{Si} = 1.12\text{eV}$, $\text{Ge} = 0.67\text{eV}$, $\text{GaAs} = 1.42\text{eV}$, $\text{Diamond} = 5.5\text{eV}$

**Band gap Si at 0K:** $1.17\text{eV}$
At absolute zero (-273.15°C)

Conduction band

All states empty

Valence band

All states filled

$E_f$ ... Fermi Energy

If an electrical field is applied to the crystal no current can flow as this would require an electron to acquire energy. This is not possible because no higher energy states in the valence band are available.

At higher temperatures

Electrons can gain energy due to thermal excitation

Probability that an electronic state is occupied by an electron follows the Fermi-Dirac statistics

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

$k$ ... Boltzmann constant

$E_F$ is the energy at which the probability of occupation is 1/2.

$$\epsilon = E, \mu = E_F,$$

Fermi-Dirac distribution. States with energy $\epsilon$ below the Fermi energy ($\mu$) have higher probability $n$ to be occupied, and those above are less likely to be occupied.
How much energy is required to generate an electron-hole pair in silicon?

Due to phonon scattering the average energy required to generate an electron-hole pair is 3.62 eV at room temperature.

An electron moving to a state in the conduction band leaves an unoccupied state in the valence band = hole
The creation of an electron-hole pair can also be seen in respect with chemical bonding: an electron is broken free from the covalent bond between two Si-atoms.

Example of column IV elemental semiconductor

- Each atom has 4 closest neighbors, the 4 electron in the outer shell are shared and form covalent bonds.
- At low temperature all electrons are bound (no conductivity).
- At higher temperature thermal vibrations of the reticle break some of the bonds ⇔ free e− cause conductivity (electron conduction).
- The remaining open bonds attract other e− creating a vacancy (hole) ⇔ The holes change position creating conductivity (hole conduction).
Silicon Basic Properties

Intrinsic semiconductor: contains only small amounts of impurities compared to the thermally generated electrons and holes

\[ E_F = E_i = \frac{E_C + E_V}{2} + \frac{kT}{2} \ln \left( \frac{N_V}{N_C} \right) \]

\( E_F \) lies very close to the mid band gap at RT

\( N_V, N_C : \text{effective densities of states in the valence band and conduction band} \)

- Due to the small band gap electrons already occupy the conduction band at room temperature
- Electrons from the conduction band may recombine with holes
- A thermal equilibrium is reached between excitation and recombination: charge carrier concentration \( n_e = n_p = n_i \)

\[ n_i = \sqrt{N_C N_V \cdot e^{-\frac{E_g}{2kT}}} \propto T^\frac{3}{2} \exp \left( -\frac{E_g}{2kT} \right) \]

\( N_V, N_C : \text{effective densities of states in the valence band and conduction band} \)

At RT: \( N_V=1.04 \times 10^{19} \text{ cm}^{-3}, N_C=2.8 \times 10^{19} \text{ cm}^{-3} \)

\( \Rightarrow n_i \) (Si at RT) = \( 1.45 \times 10^{10} \text{ cm}^{-3} \)

Compared to \( \approx 1 \times 10^{22} \text{ cm}^{-3} \) atoms in a silicon crystal only every \( \approx 10^{12} \text{th} \) atom is ionized at RT
Free charge carriers can be seen as free particles - they are not associated with a lattice site
- Mean kinetic energy: $3/2 \ kT$
- Mean velocity at RT: $\sim 10^{11} \ \mu\text{m/s}$

The charge carriers scatter on lattice imperfections due to thermal vibrations, impurity atoms and lattice defects.

If no electric field is applied, the average displacement due to random motion is zero.

Applying an electric field $E$:

Charge carriers will be accelerated in between random collisions in the direction determined by the electric field.

Average drift velocity (*): $\nu_e = -\mu_e E$  \hspace{1cm} $\nu_h = -\mu_h E$

$\mu_e$ electron mobility \hspace{1cm} $\mu_h$ hole mobility

$\mu_e = \frac{e\tau_e}{m_e}$ \hspace{1cm} $\mu_h = \frac{e\tau_h}{m_h}$

$m_e, m_h$ ... effective mass \hspace{1cm} $\tau_e, \tau_h$: mean free time between collisions for $e$ and $h$

(*) Holds for small fields $E$ (“acceleration” is small compared to the thermal velocity).

If the electric field is high enough so that the carrier energies are larger than the thermal energies, the drift velocities become independent of the electric field.
In the linear region of $v(E)$ the charge carrier mobilities are

$$\mu_e = 1350 \text{ cm}^2/\text{Vs} \quad \mu_h = 480 \text{ cm}^2/\text{Vs}$$

$2V$ is applied over $20\mu m$

$$v_e \sim 10^{10} \mu m/s$$

$$v_h \sim 0.5 \times 10^{10} \mu m/s$$

Charge collection time ($e$)

$$T_e = 2 \text{ns}$$
Adding Impurities to Intrinsic Silicon – n-doping

Silicon n-type

Doping with an element of the V group (e.g. P, As, Sb). The 5\(^{th}\) valence electron is weakly bound

- The doping atom is called donor
- The released electron can contribute to electrical conduction and leaves a positively charged ion

![Diagrams showing silicon lattice with dopant atoms and their valence electrons]
• The energy level of the donor is just below the edge of the conduction band
• At RT most electrons are raised to the conduction band
• The Fermi level $E_F$ moves up
Adding Impurities to Intrinsic Silicon – p-doping

Silicon p-type

Doping with an element of the group III (e.g. B, Al, Ga, In). One valence bond remains open. This open bond attracts electrons from their neighbor atoms:

- The doping atom is called acceptor.
- The acceptor atom in the lattice is negatively charged. The hole acts as a free mobile charge.
• The energy level of the acceptor is just above the edge of the valence band
• At RT most levels are occupied by electrons leaving holes in the valence band
• The Fermi level $E_F$ moves down
Silicon Properties – Resistivity

Depends on concentration of free charge carriers and their mobility

\[ \rho = \frac{1}{q(\mu_e n + \mu_h p)} \]

- Resistivity of intrinsic silicon \( \sim \) 235 kΩ cm
- A silicon for pixel detectors \( \sim \) 1-6 kΩ cm
- Silicon substrate for CMOS IC \( \sim \) 0.1 – 10 Ω cm

Fig. 7 Resistivity versus impurity concentration for Si and GaAs.

From Sze, Semiconductor Devices 1985
Semiconductor Detectors
Basic Principles
The Ideal Semiconductor Detector

One of the most important parameters of a detector is the signal to noise ratio (SNR).

A good detector should have a large SNR. However, this leads to two contradictory requirements:

- **Large Signal**
  - Low ionization energy $\Rightarrow$ small band gap
- **Low noise**
  - Very few intrinsic charge carriers $\Rightarrow$ large band gap

An optimal material should have $E_g \approx 6\text{eV}$

In this case the conduction band is almost empty at room temperature and the band gap is small enough to create a large number of $e^-h^+$ pairs by ionization.

A material with such characteristic is the **diamond**. However even artificial diamond (e.g. CVD diamonds) are too expensive for large area detectors.

\[
\begin{align*}
\text{Diamond band gap} & \approx 5.5\text{eV (RT)} \\
\text{Intrinsic charge carrier density} & \approx 10^{-27} \text{ cm}^{-3} \text{ (T=300K)}
\end{align*}
\]
Intrinsic Silicon – A Very Poor Detector

How does Silicon perform as detection medium?

• Mean ionization energy $I_0 = 3.62 \text{ eV}$
• Mean energy loss for a MIP in intrinsic silicon at $T = 300 K$: $dE/dx = 3.87 \text{ MeV/cm}$
• $n_i = 1.45 \times 10^{10} \text{ cm}^{-3}$

Assuming a detector with a thickness of 300 μm

⇒ Signal of a MIP in such a detector

Assuming a detector with a surface $A = 1 \text{ cm}^{-2}$

⇒ Intrinsic charge carrier density ($T = 300 K$)

Number of $\text{e}^-\text{h}^+$ pair generated by ionization (signal) is four orders of magnitude smaller than the number of electrons generated thermally (noise) at room temperature!!!

How to suppress the charge carriers?  Depleted zone in reverse biased pn junctions
2.5 The p-n Junction

Creating a p-n junction

At the interface of an n-type and p-type semiconductor the difference in the Fermi levels (carriers concentration) cause diffusion of the majority carriers to the other type until thermal equilibrium is reached. The Fermi levels are equal.

Opposite carriers recombine

Space charges remain in the junction region

Generate an electric field, which counteract the diffusion

Depleted region, the stable charge region free of charge carriers

The corresponding potential is called built-in-voltage $V_{bi}$

$$V_{bi} = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

$kT \sim 26$ mV (at RT)
A More Realistic Detector – The p⁺n Reversed Biased Junction

Build a more Realistic Detector

Thin highly doped (p⁺) and n-well doped bulk, and apply an external voltage to deplete the bulk volume of free charge carriers

Applying a negative potential difference V between the side p and the side n (reverse bias voltage) the depleted region becomes larger

The potential barrier becomes higher by eV and diffusion across the junction is suppressed.

The current across the junction is very small ("leakage current")

Depletion width W

\[ W = \sqrt{\frac{2\varepsilon_s (V_{ext} - V_{bi})}{qN_D}} \]

\[ \varepsilon_s = \text{product of rel. permittivity of silicon and of vacuum} \]

This is a reverse biased junction (diode)
A More Realistic Detector – The p⁺n Reversed Biased Junction

p⁺n diode detector
• Reverse bias (positive voltage on n-bulk wrt p⁺ side)
• Increase reverse voltage to fully deplete the entire bulk of free charge carriers

⇒ Full volume is sensitive to a passing particle (ionization chamber)
• Highly n-doped layer to provide ohmic contact (n⁺)

Effective doping concentrations
• \( N_a = 10^{15} \text{ cm}^{-3} \) in p⁺ region
• \( N_d = 10^{12} \text{ cm}^{-3} \) in n bulk

Without applying any external voltage
• \( W_p = 20 \text{ nm}, \ W_n = 23 \mu\text{m} \)

Applying an external voltage of 100V
• \( W_p = 400 \text{ nm}, \ W_n = 363 \mu\text{m} \)

Voltage at which full thickness of the diode is depleted

\[
V_{fd} = \frac{e}{2\varepsilon_s} (N_D - N_A) d^2
\]

d ..thickness
\( N_D-N_A=N_{\text{eff}} \) ...effective doping concentration

e.g. \( N_D = 10^{12}/\text{cm}^3, \ N_a = 10^{15}/\text{cm}^3, \ d = 300\mu\text{m} \)
\( (\varepsilon_s = 11.7 \times 8.8 \times 10^{-12} \text{ F/m}) \)

\( V_{fd} \sim 80 \text{ V} \)
Detector characteristics – Current-voltage (I-V)

The current-voltage characteristic curve of a p-n junction (diode): exponential increase in forward bias, small saturation in reverse bias.

**Ideal diode equation**

\[ I = I_0 \cdot \left( e^{\frac{eV_{bd}}{kT}} - 1 \right) \]

- \( I_0 \) = reverse saturation current

- **A silicon detector is operated in reverse biased mode**
- **Reverse saturation current** is relevant (leakage current)
- **This current is dominated by e^-h^+ pairs generated thermally**
- **Due to the applied electric field they cannot recombine drift to the electrodes causing the leakage current**

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Room temperature leakage current measured on a CMS strip detector (from M. Krammer and F. Hartmann)
Depletion voltage = minimum voltage at which bulk is fully depleted
The operating voltage is usually chosen to be slightly higher (over depletion)
High resistivity material (i.e. low doping) requires low depletion voltage

\[ V_{fd} = \frac{e}{2\varepsilon_s} (N_D - N_A) d^2 \]

For a Typical Si p-n junction (\(N_a >> N_d >> n_i\)) with planar geometry, the detector capacitance is

\[ C = \sqrt{\frac{\varepsilon_0 \varepsilon_r}{2\mu \rho V}} \cdot A \]

\(\rho\): resistivity of the bulk
\(\mu\): mobility of majority carrier
\(V\): bias voltage
\(A\): detector surface

Measured detector capacitance as function of bias voltage, CMS strip detector
M. Krammer, F. Hartmann
A charged particle traversing the detector generates by ionization a trail of e⁻h⁺ pairs ($\approx 100 \text{ e}^-\text{h}^+/\mu\text{m}$).

These charges drift to the electrodes (strips) inducing a current (charge moving in an electric field).

The (drift) current is amplified by an electronic circuit connected to each strip.

From the signals on the individual strips the position of the particle can be reconstructed.

A typical n-type Si strip detector:

- p⁺n junction: $N_a \approx 10^{15} \text{ cm}^{-3}$, $N_d \approx 1-5 \times 10^{12} \text{ cm}^{-3}$
- n-type bulk: $\rho > 2 \text{k}\Omega\text{cm}$
- thickness $300\,\mu\text{m}$
- Operating voltage < 200V
- n⁺ layer on backplane to improve ohmic contact
- Aluminum metallization

From M. Krammer and F. Hartmann (EDIT 2011)
AC coupling blocks leakage current from the amplifier

- Integration of coupling in standard planar process
- Deposition of SiO₂ with a thickness of 100-200nm between p⁺ and aluminum strip

- Depending on oxide thickness and strip width the capacitance are in the range 8-32pF/cm
- Problems are shorts through the dielectric (pinholes) usually avoided by a second layer of Si₃N₄
- Several methods to connect the bias voltage: polysilicon resistor, punch trough bias, FOXFET bias

From M. Krammer and F. Hartmann (EDIT 2011)
Microstrip Detector – Polysilicon Bias Resistor

- Deposition of polycrystalline silicon between \( p^+ \) implants and a common bias line
- Depending on width and length a resistor of up to \( R \approx 20 \, \text{M}\Omega \) is achieved \( (R = R_s \times \text{length/width}) \)
- To achieve high resistor values winding poly structures are deposited
- Drawback: additional production steps and photo lithographic masks required

Cut through an AC coupled strip detector with integrated poly resistors

Close view of area with polysilicon resistors, probe pads, stip ends. (CMS microstrip detector)
Hybrid Pixel Detector

- Sensor based on silicon junction detectors produced in a planar process
- High resistivity wafers (few kΩcm) with diameters of 4” – 6” (8” now becoming available)
- Specialized producers (~10 world wide)
- **Readout Chip**: ASIC - CMOS sub-micron technology
- Interconnect technology based on **flip-chip bonding**

⇒ currently installed at the LHC experiments

Monolithic Pixel Detector

- Charge generation volume integrated into the ASIC
- Exist in many different flavours: **CMOS**, HV/HR CMOS, DEPFET, SOI, ...
- The following will cover only CMOS Monolithic Active Pixel Sensors (CMOS MAPS) = **CMOS Pixel Sensors (CPS)**
Hybrid Pixel Detectors

Each pixel cell in the sensor is connected to a pixel cell in the readout chip via a bump bond

Advantages

- Pixel detector provides truly space-point information (3D coordinates) removing hit ambiguities
- Small pixel area
  - Low detector capacitance (~fF)
  - Large signal-to-noise ratio (e.g. 150:1)
- Small pixel volume
  - Low leakage current (~1 pA/pixel)
- p+ on n for the LHC
  - Electron have faster collection time

Disadvantages

- Large number of readout channels
- Large bandwidth
- Large power consumption
- Bump bonding is costly and complex
Each pixel cell in the sensor is connected to a pixel cell in the readout chip via a bump bond.

Usually several readout chips are connected to a single sensor.
Hybrid Pixel Detectors

How to efficiently cover large surfaces? **Ladders (modules)**

- sensor size limited by wafer size and bump bonding requirements (flatness!),
  - \( \Rightarrow \) LHC experiments: \( \sim 7 \text{ cm} \times 2 \text{ cm} \)
- chip size limited by CMOS lithography
- larger chip \( \rightarrow \) lower yield in production

To avoid dead areas between chips: long boundary pixels

To avoid dead areas between ladders: turbine configuration \( \Rightarrow \) higher material budget in some regions

ATLAS, CMS

ALICE

L. Musa – HCP 2017 - CERN
• Charge from the detector is integrated on the feedback capacitor
• The output voltage is proportional to the input charge
• \( V_{out} \) remains constant for times >t

To avoid pile-up a feed-back resistor is added in parallel to \( C_f \) to discharge \( C_f \)

\[
V_{out} = \frac{1}{C_f} \int_0^t i_{in}(t) dt = \frac{Q(t)}{C_f}
\]
References

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