Silicon Detectors in High Energy Physics

Thomas Bergauer (HEPHY Vienna)
Schedule

Sunday:
• Semiconductor Basics (45’)
• Detector concepts: Pixels and Strips (45’)

Coffee Break
• Strip Detector Performance (45’)
• Quality Control on strip detectors (45’)

Monday:
• Radiation Damage (45’)

22 May 2011
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Strip Detector Performance

• History of Silicon Detectors in HEP
• Signal-to-noise ratio
• Position Resolution
Silicon Detectors in High Energy Physics

HISTORY
Early Days till Now

- 1951: First detectors with Germanium pn-Diodes (McKay)
- 1960: working samples of p-i-n-Detectors for α- und β-spectroscopy (E.M. Pell)
- 1964: use of semiconductor detectors in experimental nuclear physics (G.T. Ewan, A.J. Tavendale)
- 1960ies: Semiconductor detectors made of germanium and silicon become more and more important for energy spectroscopy
- **1980**: Fixed target experiment with a planar diode (J. Kemmer)
- 1980-1986: NA11 and NA32 experiment at CERN to measure charm meson lifetimes with planar silicon detectors
- 1990ies (Europe): LEP Detectors (e.g. DELPHI)
- 1990ies and later (US): CDF and D0 at Tevatron
- Now: LHC Detectors with up to 200m² active detector area (CMS)
The Birth

- Fixed target experiment with a planar diode
- First use of planar process developed for chip industry

Fabrication of Low Noise Silicon Radiation Detectors by the Planar Process

J. Kemmer
Fachbereich Physik der Technischen Universität München, 8046 Garching, Germany

Received 30 July 1979 and in revised form 22 October 1979

Dedicated to Prof. Dr. H. J. Born on the occasion of his 70th birthday

By applying the well known techniques of the planar process—oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA cm$^{-2}$/100 μm at room temperature. Best values for the energy resolution were 100 keV for the 5.486 MeV alphas of $^{241}$Am at 22°C using $5 \times 5$ mm$^2$ detector chips.
First proof of principle to use a position sensitive silicon detector in HEP experiment

- Aim: measure lifetime of charm quarks (decay length 30 µm)
  ⇒ spatial resolution better 10µm required

NA11 Detector:
- 1200 diode strips on 2436mm² active area
- Resolution of 4.5 µm
- 250-500 µm thick bulk material
Vertex Detectors

Experiments:
• LEP Detectors at CERN
• SLAC Linear Collider (Mark II experiment)

• Minimize the mass inside tracking volume
• Readout chips at end of ladders
• Minimize the mass between interaction point and detectors
• Minimize the distance between interaction point and the detectors
DELPHI Microvertex detector

- 2 silicon layers, 40cm long, inner radius 7.8 cm, outer radius 12cm
- 300μm DSSDs with double metal readout
Collider Detector at Fermilab (CDF) is one of the two Experiments at the 2x1TeV Tevatron

- Discovery of top-quark (1995)

**Tracker:**

- Barrel only (no endcaps)
- Different Silicon Layers:
  - L00 (SSSD, r ~ 1.5 cm, l=94cm)
  - SVX (r = 5-10 cm)
  - ISL (DSSD, r = 20-29cm)
- Total active area: approx. 10 m²
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Tracking Paradigm

Tevatron and LHC Experiments:
• Emphasis shifted from vertexing to tracking
• Cover large area with many silicon layers

• Detector modules include readout chips and services inside the tracking volume
• Large number of layers (redundancy) because of limited access possibilities
DELPHI vs. CMS Tracker
Installation of CMS Tracker
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CMS Tracker layout

TOB
6 layers
5208 modules

Single sided

Double sided
(100 mrad stereo angle)

Interaction point

TIB
4 layers
2724 modules

Barrel: strips parallel to beam

End cap: strips in radial direction

TID
2x3 disks
816 modules

TEC
2x9 disks
6400 modules

200 m² of silicon sensors

Industry involvement + 25 institutes

Complex Logistic & Quality Assurance

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Silicon Sensors

- Two producers:
  - Hamamatsu Photonics (Japan)
  - ST Microelectronics (Italy)
- Four main Test centers
  - Supported by smaller tests in different locations
  - Irradiation
  - Bonding tests
  - Process Qualification & Longterm stability

Complex logistics

- Sensor Fabrication Center HPK
- Sensor Fabrication Center STM
- Control & Distribution Center CERN & Production Committee

- Quality Test Center Pisa
- Quality Test Center Perugia
- Quality Test Center Wien
- Quality Test Center Karlsruhe

- 25% sensors
- 1% sensors
- ~5% ts
- 5% sensors
- >5% ts

- Irradiation Qualification Centers Louvain, Karlsruhe
- Bonding Test Centers Pisa, Strasbourg
- Process Qualification & Stability Centers Strasbourg, Wien Florence

Module Assembly Centers

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SIGNAL-TO-NOISE RATIO
Signal to Noise Ratio

- **The signal** generated in a silicon detector depends essentially only on the thickness of the depletion zone and on the $\text{dE/dx}$ of the particle.

- **The noise** in a silicon detector system depends on various parameters: geometry of the detector, the biasing scheme, the readout electronics, etc.

Noise is typically given as “equivalent noise charge” ENC. This is the noise at the input of the amplifier in elementary charges.
Noise contributions

The most important noise contributions are:

1. Leakage current (ENC₁)
2. Detector capacity (ENCₖ)
3. Det. parallel resistor (ENCₚ)
4. Det. series resistor (ENCₛ)

The overall noise is the quadratic sum of all contributions:

\[ ENC = \sqrt{ENC₁^2 + ENCₖ^2 + ENCₚ^2 + ENCₛ^2} \]
Leakage current

- The detector leakage current comes from thermally generated electron holes pairs within the depletion region.
- These charges are separated by the electric field and generate the leakage current.
- The fluctuations of this current are the source of noise.
- In a typical detector system (good detector quality, no irradiation damage) the leakage current noise is usually negligible.
Leakage current (cont.)

Assuming an amplifier with an integration time (“peaking time”) $t_p$ followed by a CR-RC filter the noise contribution by the leakage current $I$ can be written as:

$$\text{ENC}_I = \frac{e^{-}}{2} \sqrt{\frac{lt_p}{e}}$$

Using the physical constants, the leakage current in units of nA and the integration time in µs the formula can be simplified to:

$$\text{ENC}_I \approx 107 \sqrt{lt_p} \quad [I \text{ in nA, } t_p \text{ in µs}]$$

To minimize this noise contribution the detector should be of high quality with small leakage current.
Detector Capacitance

The detector capacitance at the input of a charge sensitive amplifier is usually the **dominant noise source** in the detector system.

This noise term can be written as:

$$\text{ENC}_C = a + b \cdot C$$

The parameter $a$ and $b$ are given by the design of the (pre)-amplifier. $C$ is the detector capacitance at the input of the amplifier channel.

Integration time $t_p$ is crucial, short integration time leads usually to larger $a$ and $b$ values. Integration time is depending on the accelerator time structure.

Typical values are (amplifier with $\sim 1 \, \mu\text{s}$ integration time):

$$a \approx 160 \, \text{e und } b \approx 12 \, \text{e}/\text{pF}$$

To reduce this noise component segmented detectors with short strip or pixel structures are preferred.
Parallel resistor

The parallel resistor $R_p$ in the alternate circuit diagram is the bias resistor. The noise term can be written as:

$$\text{ENC}_{R_p} = \frac{e \sqrt{kT t_p}}{e e \sqrt{2R_p}}$$

Assuming a temperature of $T=300K$, $t_p$ in $\mu$s and $R_p$ in $M\Omega$ the formula can be simplified to:

$$\text{ENC}_{R_p} \approx 772 \sqrt{\frac{t_p}{R_p}}$$

To achieve low noise the parallel (bias) resistor should be large!

However the value is limited by the production process and the voltage drop across the resistor (high in irradiated detectors).
Series resistor

The series resistor $R_s$ in the alternate circuit diagram is given by the resistance of the connection between strips and amplifier input (e.g. aluminum readout lines, hybrid connections, etc.). It can be written as:

\[
ENC_{Rs} \approx 0.395 \frac{C \sqrt{R_s}}{t_p}
\]

Note that, in this noise contribution $t_p$ is inverse, hence a long $t_p$ reduces the noise. The detector capacitance is again responsible for larger noise.

To avoid excess noise the aluminum lines should have low resistance (e.g. thick aluminum layer) and all other connections as short as possible.
Signal to Noise Ratio Summary

To achieve a high signal to noise ratio in a silicon detector system the following conditions are important:

- Low detector capacitance (i.e. small pixel size or short strips)
- Low leakage current
- Large bias resistor
- Short and low resistance connection to the amplifier
- Long integration time

Obviously some of the conditions are contradictory. Detector and front end electronics have to be designed as one system. The optimal design depends on the application.
Example Signal-to-noise ratios

<table>
<thead>
<tr>
<th>DELPHI Microvertex:</th>
<th>CMS Tracker:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• readout chip (MX6): $a = 325 \text{ e}$, $b = 23 \text{ e/pF}$, $t_p = 1.8 \mu\text{s}$</td>
<td>• readout chip (APV25, deconvolution): $a = 400 \text{ e}$, $b = 60 \text{ e/pF}$, $t_p = 50 \text{ ns}$</td>
</tr>
</tbody>
</table>
| • 2 detectors in series each 6 cm long strips, $C = 9 \text{ pF}$  
  ➢ $\text{ENC}_C = 532 \text{ e}$ | • 2 detectors in series each 10 cm long strips, $C = 18 \text{ pF}$  
  ➢ $\text{ENC}_C = 1480 \text{ e}$ |
| • typ. leakage current/strip: $I \approx 0.3 \text{ nA}$  
  ➢ $\text{ENC}_I = 78 \text{ e}$ | • max. leakage current/strip: $I \approx 100 \text{ nA}$  
  ➢ $\text{ENC}_I = 103 \text{ e}$ |
| • bias resistor $R_p = 36 \text{ M}\Omega$  
  ➢ $\text{ENC}_{R_p} = 169 \text{ e}$ | • bias resistor $R_p = 1.5 \text{ M}\Omega$  
  ➢ $\text{ENC}_{R_p} = 60 \text{ e}$ |
| • series resistor = 25 $\Omega$  
  ➢ $\text{ENC}_{R_s} = 13 \text{ e}$ | • series resistor = 50 $\Omega$  
  ➢ $\text{ENC}_{R_s} = 345 \text{ e}$ |
| ➢ Total noise: $\text{ENC} = 564 \text{ e}$ (SNR 40:1) | ➢ Total noise: $\text{ENC} = 1524 \text{ e}$ (SNR 15:1) |

Calculated for the signal of a minimum ionizing particle (mip) of 22500 e.
POSITION RESOLUTION
Position Resolution Introduction

The position resolution – the main parameter of a position detector – depends on various factors, some due to physics constraints and some due to the design of the system (external parameters).

- **Physics processes:**
  - Statistical fluctuations of the energy loss
  - Diffusion of charge carriers

- **External parameter:**
  - Binary readout (threshold counter) or analogue signal value read out (CMS case)
  - Distance between strips (strip pitch)
  - Signal to noise ratio
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Statistical fluctuation of the energy loss

• Silicon position detectors are thin (300–500 µm) and absorb only a small fraction of the total energy of through going particles.

• The energy loss $dE/dx$ follows a Landau distribution, an asymmetric probability function with a long “tail” to large energy deposits.

• Example of a mip measured in a 300 µm thick silicon detector:

  o Most probable energy loss (Maximum of the distribution):
    78 keV in 300 µm $\Rightarrow \approx 72 \ e^-h^+$ pairs per µm

  o Mean of the energy loss:
    116 keV in 300 µm $\Rightarrow \approx 108 \ e^-h^+$ pairs per µm

Statistical fluctuation of the energy loss – 2

Long tail in energy loss distribution is due to $\delta$-electrons. $\delta$-electrons have a high energy (keV) and are produced by rare, hard collisions between incident particle and electrons from the detector material.

- The probability to produce a $\delta$-electrons is small.
- $\delta$-electrons have a long track length in the detector material and may produce $e^+h^-$ pairs along the track.
- Dislocate the measured track
- Measurement errors in the order of $\mu$m unavoidable

Displacement probability (calculation) of the charge center of gravity due to $\delta$-electrons:
Diffusion

- After the ionizing particle has passed the detector the e⁺h⁻ pairs are close to the original track.
- While the cloud of e⁺ and h⁻ drift to the electrodes, diffusion widens the charge carrier distribution. After the drift time \( t \) the width (rms) of the distribution is given as:

\[
\sigma_D = \sqrt{2Dt}
\]

with:

\[
D = \frac{kT}{e\mu}
\]

\( \sigma_D \) ... width “root-mean-square” of the charge carrier distribution
\( t \) ... drift time
\( D \) ... diffusion coefficient
\( k \) ... Boltzmann constant
\( T \) ... temperature
\( e \) ... electron charge
\( \mu \) ... charge carrier mobility

Note: \( D \propto \mu \) and \( t \propto 1/\mu \), hence \( \sigma_D \) is equal for e⁻ and h⁺.
Diffusion (cont.)

- $h^+$ created close to the anode (i.e. the $n^+$ backplane) and $e^-$ created close to the cathode (i.e. the $p^+$ strips or pixels) have the longest drift path. As a consequence the diffusion acts much longer on them compared to $e^- h^+$ with short track paths.

- The signal measured comes from many overlapping Gaussian distributions.

Drift and diffusion acts on charge carriers:

Charge density distribution for 5 equidistant time intervals:
Diffusion (cont.)

- Diffusion widens the charge cloud. However, this may have a positive effect on the position resolution!
  
  ⇒ charge is distributed over more than one strip, with interpolation (calculation of the charge center of gravity) a better position measurement is achievable.

- This is only possible if analogue read out of the signal is implemented.

- Interpolation is more precise the larger the signal to noise ratio is.
  
  ⇒ Strip pitch and signal to noise ratio determine the position resolution.

- Larger charge sharing can also be achieved by tilting the detector.
Digital readout

- Position of hit strip
- Resolution proportional to strip pitch
  - ATLAS Tracker is working in this way
- What happens when more than one strip is hit → Cluster

\[ \sigma_x \approx \frac{p}{\sqrt{12}} \]

- \( p \) … distance between strips (readout pitch)
- \( x \) … position of particle track
Analogue readout

- Analogue readout allows a much better position resolution than with the simple position of the strip
  - Proportional to signal-to-noise ratio

- Different methods to calculate
  - center-of-gravity interpolation (signal on two strips)

\[
\begin{align*}
x &= x_1 + \frac{h_1^2}{h_1 + h_2} (x_2 - x_1) = \frac{h_1 x_1 + h_2 x_2}{h_1 + h_2} \\
\sigma_x &\propto \frac{P}{SNR}
\end{align*}
\]

- Position of 1\textsuperscript{st} and 2\textsuperscript{nd} strip
- Signal on 1\textsuperscript{st} and 2\textsuperscript{nd} strip
- Signal to noise ratio

22 May 2011

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Intermediate strips

- **The strip pitch determines the position resolution.** With small strip pitch a better position resolution is achievable. Small pitch requires
  - large number of electronic channels
  - cost increase
  - power dissipation increase

- A possible solution is the implementation of intermediate strips. These are **strips not connected to the readout electronics** located between readout strips.

  The signal from these intermediate strips is transferred by capacitive coupling to the readout strips.
  - more hits with signals on more than one strip
  - Improved resolution with smaller number of readout channels.
Intermediate strips (cont.)

Scheme of a detector with two intermediate strips. Only every 3rd strip is connected to an electronics channel. The charge from the intermediate strips is capacitive coupled to the neighbor strips.
Example – influence of readout pitch and SNR

Two examples of a detectors with analogue readout.

**Example 1**: strip pitch of 25 µm
Binary readout: 7 µm resolution

**Example 2**: strip pitch of 50 µm
Binary readout: 14 µm resolution

- Bottom curve: no intermediate strips
- Top curve: one intermediate strip
Part 3: Strip Detector Performance

END