Detectors for Particle Physics

Semiconductor Detectors

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Tracking and Vertex Detectors

- Solid state detectors especially silicon offer high segmentation
- Determine position of primary interaction vertex and secondary decays

- Lifetime tags to identify B-hadrons (or tau leptons,...)
- Impact parameter (IP)
- Measurement of secondary vertex

This would have not been possible without semiconductor (pixel and strip) trackers
Silicon Detectors in HEP

(representative selection, approx. dates)

- Silicon detectors also continue to be improved
  - Size
  - Material
  - Radiation hardness

<table>
<thead>
<tr>
<th>Year</th>
<th>Silicon Area (m²)</th>
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<tr>
<td>1980</td>
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<td>L3</td>
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<td>2009</td>
<td>CMS</td>
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<td>2009</td>
<td>ATLAS</td>
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Tracking in pp collisions at the LHC

- ~1200 tracks every 25 ns or ~$10^{11}$ per second
- High radiation dose $10^{15} \text{n}_{eq}/\text{cm}^2/10 \text{ Yrs} @ \text{LHC}$ or 600 kGy (60 Mrad) through the ionisation of mips in 250 µm bulk silicon

$LHC \approx 10^6 \times LEP$ in track rate

HL–LHC = LHC x 10
Impact parameter resolution

Impact parameter

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Impact parameter resolution

\[ \sigma_b = \frac{r_2}{r_2 - r_1} \]

\[ \sigma^2 = \left( \frac{r_1}{r_2 - r_1} \sigma_2 \right)^2 + \left( \frac{r_2}{r_2 - r_1} \sigma_1 \right)^2 + \sigma_{MS}^2 \]

\[ \sigma_{MS} \sim \frac{1}{p} \sqrt{\frac{x}{X_0}} \]

Precision measurements at small radii
The LHC silicon detectors

- **ATLAS**
  - Strips: 61 m$^2$ of silicon, 4088 modules, 6x10$^6$ channels
  - Pixels: 1744 modules, 80 x 10$^6$ channels

- **CMS**
  - The world largest silicon tracker
  - 200 m$^2$ of strip sensors (single sided)
  - 11 x 10$^6$ readout channels
  - ~1m$^2$ of pixel sensors, 60x10$^6$ channels

- **ALICE**
  - Pixel sensors
  - Drift detectors
  - Double sided strip detectors

- **LHCb**
  - VELO: Si Strips

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The LHC detectors

- The ATLAS SCT strip
- The CMS TIB strip
- The LHCb-VELO strip
- The ATLAS pixel
- The CMS pixel
- ALICE pixel
A solid state detector is an ionization chamber

- Ionizing radiation creates electron/hole pairs
- Charge carriers move in applied E field
- Motion induces a current in an external circuit, which can be amplified and sensed.

<table>
<thead>
<tr>
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<th>Gas</th>
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<td>Density</td>
<td>Low</td>
<td>High</td>
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<tr>
<td>Atomic number (Z)</td>
<td>Low</td>
<td>Moderate ((Z=14))</td>
</tr>
<tr>
<td>Ionization Energy (\varepsilon_i)</td>
<td>Moderate (\approx 30,\text{eV})</td>
<td>Low (\approx 3.6,\text{eV})</td>
</tr>
<tr>
<td>Signal Speed</td>
<td>Moderate ((10,\text{ns}-10,\mu\text{s}))</td>
<td>Fast (&lt;20,\text{ns})</td>
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</table>
Why silicon?

• After Oxygen, Silicon is the 2nd most abundant element in Earth’s crust (>25% in mass)
• Leverages IC Technology
• Exponential improvements of silicon ICs
• WILL end someday… but when?

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Semiconductor

- Fermi level
  - Maximum electron energy at $T = 0$ K

- Semiconductor: at room temperature electrons can already occupy the conduction band and may recombine with holes.

- Thermal equilibrium is reached between excitation and recombination when the charge carrier concentration $n_e = n_h = n_i =$ intrinsic carrier concentration $\approx 1.5 \times 10^{10} \text{ cm}^{-3}$
**Principle of operation**

- $<l_0> = 3.62 \text{ eV}$, $<dE/dx>$ loss per flight path of a mip $dE/dx = 3.87 \text{ MeV/cm}$

- Consider a detector of thickness $d = 300 \mu m$ and area $A = 1 \text{ cm}^2$.

- **MIP signal is**

\[
\frac{(dE/dx)d}{l_0} = \frac{3.87 \cdot 10^6 \text{ eV/cm} \cdot 0.03 \text{ cm}}{3.63 \text{ eV}} 
\approx 3.2 \cdot 10^4 \text{ e-h pairs}
\]

- **Intrinsic charge carriers in the same volume ($T = 300 \text{ K}$):**

\[
n_idA = 1.45 \cdot 10^{10} \text{ cm}^{-3} \cdot 0.03 \text{ cm} \cdot 1 \text{ cm}^2 \approx 4.35 \cdot 10^8 \text{ e-h pairs}
\]

- Number of thermally created e–h-pairs (noise) is $x10^4$ than the signal
- We need to deplete the free charge carriers
Doped semiconductors

**DONOR (N)**
- Conduction band
- Valence band

**ACCEPTOR (P)**
- Conduction band
- Valence band
PN Junction

- PN junction without external voltage
  - Free charges move until the chemical potential is balanced by an electrical potential called the built-in potential

The space charge (depletion) region can be made bigger by applying a reverse bias voltage
Width of the depletion zone

- Solve Poisson eq. using conservation of charge $N_A d_p = N_D d_n$

- Effective doping concentration in typical silicon detector with $p^+$-n junction
  - $N_A = 10^{15} \text{ cm}^{-3}$ in $p^+$ region
  - $N_D = 10^{12} \text{ cm}^{-3}$ in $n$ bulk.

- Without external voltage:
  - $W_p = 0.02 \text{ } \mu\text{m}$ and $W_n = 23 \text{ } \mu\text{m}$

- Applying a reverse bias voltage of 100 V:
  - $W_p = 0.4 \text{ } \mu\text{m}$ and $W_n = 363 \text{ } \mu\text{m}$

\[ W_p = \sqrt{\frac{2\varepsilon|V|}{e} \frac{1}{N_A (1 + N_A / N_D)}} \]
\[ W_n = \sqrt{\frac{2\varepsilon|V|}{e} \frac{1}{N_D (1 + N_D / N_A)}} \]

- $p^+$
  - $N_a \approx 10^{15} \text{ cm}^{-3}$
- $n$
  - $N_d \approx 10^{12} \text{ cm}^{-3}$

Width of depletion zone

\[ W = \sqrt{\frac{2\varepsilon V}{e} \frac{1}{N_D}} \text{ if } N_A >> N_D \]

$e$=electron charge, $\varepsilon$=resistivity
$\mu$= majority carriers mobility
$N$= dopant density

The voltage $V$ needed to deplete a device of thickness $d$ is called the depletion voltage $V_d$.
Depletion Zone & Capacitance

- The depletion voltage can be determined by measuring the capacitance versus reverse bias voltage. The capacitance is simply the parallel plate capacity of the depletion zone.

\[ C = \varepsilon \frac{A}{d} = A \sqrt{\frac{\varepsilon}{2 \rho \mu V_b}} \]

\[ \frac{1}{C^2} \text{ vs voltage} \]

\[ V_d \]
Leakage current

Sensitive to process quality
Leakage current

- $I_{\text{leak}}$ sensitive to process quality

Diffusion current
- charge generated in the undepleted zone adjacent to the depletion zone which diffuse into the depletion zone

Generation current
- From thermal generation in the depletion region
- Reduced by using pure and defect free material with high carrier lifetime
- Keep temperature low & controlled

$$j_{\text{gen}} \propto T^{3/2} \exp\left(\frac{1}{2kT}\right)$$
Electron and hole pairs created in the depletion region move under the E field. The time required for a carrier to traverse the sensitive volume is the collection time. The collection time can be reduced by over-biasing the sensor.

\[ v_{e,h}(x) = \mu_{e,h} E(x) \]

\[ \mu_e = 1500 \text{ cm}^2 / \text{Vs} \]

\[ \mu_h = 450 \text{ cm}^2 / \text{Vs} \]
Silicon Strip Detectors (SSD)

- By segmenting the implant we can reconstruct the position of the traversing particle in one dimension
- DC-coupled strip detector – simplest position sensitive Silicon detector
- Standard configuration:
  - Strips p implants
  - Substrate n doped (~2-10 kΩcm) and ~300µm thick
  - $V_{dep} < 200$ V
  - Backside Phosphorous implant to establish ohmic contact and to prevent early breakdown
- Highest field close to the collecting electrodes (junction side) where most of the signal is induced
Strip Detector

- AC coupling blocks DC leakage current
- Integration of coupling capacitances in standard planar process.
  - Deposition of SiO$_2$ with a thickness of 100–200 nm between p+ and aluminum strip
  - Increase quality of dielectric by a second layer of Si$_3$N$_4$.
- Long poly silicon resistor with R>1MΩ to connect the bias voltage to the strips:
A typical strip module (CMS)

- silicon sensors
- ~20 cm strip length
- carbon fibre support
- pitch adapter
- hybrid front-end electronics with read-out chips
- kapton flat cables for power and data
Double Sided Silicon Detectors

- **Advantages:**
  - More elegant for measuring 2 coordinates than using stereo modules
  - Saves material

- **Disadvantages:**
  - Needs special strip insulation of n-side (p-stop, p-spray techniques)
  - Complicated manufacturing and handling procedures

- Expensive
- Ghost hits possible

![Diagram of a double sided strip detector](image)

Positive oxide charges cause electron accumulation layer.
Pixel detector

- Advantages
  - Pixel detectors provide space-point information
- Small pixel area
  - Low detector capacitance ($\approx 1$ fF/Pixel)
  - Large signal-to-noise ratio (e.g. 150:1)
- Small pixel volume
  - Low leakage current ($\approx 1$ pA/Pixel)
- n+-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

https://www.youtube.com/watch?v=ojEvwQxOrGo&feature=youtu.be
The signal generated in a silicon detector depends on the thickness of the depletion zone and on the $dE/dx$ of the particle.

- The distribution is given by the Landau distribution.
- Since the mean energy loss per cm is 3.87 MeV/cm.
- For 300 µm silicon the most probable charge is $\approx 23400$ e-/h pairs.

Most probable charge $\approx 0.7 \times$ mean

Mean charge
Noise in a pixel detector

- Noise is given as “equivalent noise charge” ENC.

\[
ENC_{tot}^2 = ENC_{shot}^2 + ENC_{therm}^2 + ENC_{1/f}^2
\]

\[
ENC_{shot} = \sqrt{\frac{I_{leak}}{2q} \tau_f} = 56 e^- \times \sqrt{\frac{I_{leak} \tau_f}{nA \ \mu s}}
\]

\[
ENC_{therm} = \frac{C_f}{q} \sqrt{\langle v_{therm}^2 \rangle} = \sqrt{\frac{kT}{q} \frac{2C_D}{3q} \frac{C_f}{C_{load}}} = 104 e^- \times \frac{C_D}{100 \text{ fF}} \frac{C_f}{C_{load}}
\]

\[
ENC_{1/f} \approx \frac{C_D}{q} \sqrt{\frac{K_f}{C_{ox}WL}} \sqrt{\ln \left( \frac{\tau_f}{C_{load}} \frac{g_m}{C_D} \frac{C_f}{C_{load}} \right)} = 9 e^- \times \frac{C_D}{100 \text{ fF}} \text{ (for NMOS trans.)}
\]

\[W, L = \text{width and length of trans. gate} \]
\[K_f = 1/f \text{ noise coefficient} \]
\[C_{ox} = \text{gate oxide capacitance} \]

Reference
Rossi, Fischer, Rohe, Wermes
Pixel Detectors
S/N optimization

• Silicon sensors have low occupancy ⇒ most channels have no signal. Good hits are select by requiring $N_{ADC} >$ noise tail. If cut is too high ⇒ efficiency loss

• Typical Values for strip detectors is $N/S > 10-15$. Radiation damage severely degrades the S/N. Thus S/N determines lifetime of the detector in a harsh radiation environment

• To achieve a high signal to noise ratio:
  – 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

• The optimal design depends on the application

• For pixel detectors the important parameter is the S/Threshold. The threshold in current detectors is of the order of $2500 \text{ e}^-$. 
Diffusion

- Diffusion is caused by random thermal motion
- Width of charge cloud after a time $t$ given by

\[
\sigma_D = \sqrt{2Dt} \quad \text{with} \quad D = \frac{kT}{e \mu}
\]

- Drift time for: $d=300 \mu m$, $E=2.5KV/cm$:

  $t_d(e) = 9$ ns, $t_d(h)=27$ ns

- Diffusion: Typical value: 8 $\mu m$ for 300 $\mu m$ drift.
- Can be exploited to improve position resolution

$\sigma_D$=width “root-mean-square” of the charge carrier distribution

$t$=drift time

$K$=Boltzman constant

$e$=electron charge

$D$=diffusion coefficient

$T$=temperature

$\mu$=mobility $\mu_e = 1350 \text{ cm}^2 / \text{V} \cdot \text{s}$, $\mu_h = 450 \text{ cm}^2 / \text{V} \cdot \text{s}$
Position resolution

- Resolution is the spread of the reconstructed position minus the true position

\[
\sigma = \frac{\text{pitch}}{\sqrt{12}}
\]

\[
\sigma \approx \frac{\text{pitch}}{1.5 \cdot \sqrt{12}}
\]

\[
\eta = \frac{PH_R}{PH_L + PH_R}
\]
Position resolution

- Position resolution is degraded by many factors
- Relationship of strip pitch and diffusion width (typically 25-150 µm and 5-10 µm)
- Statistical fluctuations on the energy deposition
- Typical position resolution is for a 300 µm thick sensor with S/N=20

![Graph showing position resolution vs pitch](image1)

- Single strip resolution dominates
- Low probability δ(E) release additional electrons drifting perpendicularly to the track and spoiling position resolution

![Graph showing centroid displacement](image2)
Material

- Reconstruction of photon conversions ($\gamma \rightarrow e^+e^-$) can provide precise map of the material
  - The number of photon conversion in a volume $\approx$ amount of material $\times$ reconstruction efficiency
  - The reconstructed vertices can be used to build detailed maps of the Tracker material

DATA

MC
Radiation damage

- Damage due to non ionizing energy loss (NIEL)
  - Atomic displacement caused by massive particles (p,n,π)

- Damage due to ionizing energy loss
  - Proportional to absorbed radiation dose
  - $1 \text{ Gy} = 1 \text{ J/kg} = 100 \text{ rad} = 10^4 \text{ erg/g}$ (energy loss per unit mass)
  - Trap of ionization induced holes by “dangling bond” at Si-SiO2 interface

- Affects mainly the sensors

- Affects both detector and electronics
Radiation damage due to NIEL

- Atomic displacement caused by massive particles ($p, n, \pi$)
  - Charge defects $\Rightarrow$ change of effective doping concentration $\Rightarrow$ increase $N_{\text{eff}} (= N_D - N_A)$ and depletion voltage
  - Shallow defect: Trapping centers created $\Rightarrow$ trapping of signal charge
  - Midgap defects: generation/recombination levels in band gap $\Rightarrow$ increase of leakage current

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![Diagram showing radiation-induced defects](image-url)
Radiation damage due to NIEL

- **INCREASE IN DARK CURRENT**
  - It can saturate a charge integrating amplifier
  - It can lead to thermal runaway

\[ \alpha = \frac{\Delta I}{V \cdot \Phi_{eq}} \approx 4 \times 10^{-17} \text{ A/cm} \]

- **TYPE INVERSION**
  - Increase of depletion voltage
  - Attention must be taken to avoid breakdown

- Even after heavy irradiation, both p and n sides work at low voltage (under depleted) and sensors act as if there were 2 diode junctions!
Annealing

- Shaking the lattice => beneficial annealing
- Too Long at a high temperature => defects that did not harm so far, become active => reverse annealing
- Solution: keep detectors cool @-5-10°C
Radiation damage due to NIEL

- Deterioration of Charge Collection Efficiency (CCE) by trapping
- Trapping is characterized by an effective trapping time $\tau_{\text{eff}}$ for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left( -\frac{1}{\tau_{\text{eff} e,h}} \cdot t \right)$$

where

$$\frac{1}{\tau_{\text{eff} e,h}} \propto N_{\text{defects}}$$

![Graph showing inverse trapping time vs. particle fluence](image-url)
Challenges for the future

• High Luminosity LHC
  – Radiation tolerance (~$10^{16}$/cm$^2$ for pixels, $10^{15}$/cm$^2$ for strips; ~20 x current)
  – High hit rate (up to 1.5 GHz/cm$^2$ in pixels)
  – High track density (200 or more spectator events)

• $e^+e^-$ colliders
  – Extremely low material (minimize multiple scattering)
  – Requires very low average power
  – Extremely good position resolution (ILC goal is ~3 microns)
Ultra radiation hard detectors: 3D

- P-N junction in the bulk by “drilling” electrodes using Deep Reactive Ion Etching (DRIE)
  - Maximum drift and depletion distance governed by electrode spacing
  - Lower depletion voltages
  - Radiation hardness
  - Fast response

Industrialization has been successful and 3D technology is used ATLAS IBL
Thin sensors

- Reduced material
- Reduced $I_{\text{leakage}}$
- Planar sensors: work at $2 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$
  - need high bias voltage
  - n in n (inner),
  - n in p (outer layers)
- Slim edges (both for 3D and planar)
Monolithic Pixels

- Sensors and ROC in the same wafer
- Signal is created in epitaxial layer (10-15 µm e.g. AMS 0.35 µm)
  - $Q \sim 80$ e-h / µm $\rightarrow$ signal $<1000$ e--
  - Q collection (thermally) to diode with help of reflection on boundaries with p-well and substrate (high doping)

- Advantages of CMOS sensors:
  - Signal processing circuits integrated on sensor substrate (system-on-chip)
  - Sensitive volume (epitaxial layer) is 10–15 µm thick
  - Standard production, fabrication technology $\rightarrow$ cheap, fast turn-around
  - small pixel sizes (pitch 20 –30 µm) $\rightarrow$ few µm resolution!

- BUT:
  - Very thin sensitive volume impact on signal magnitude
  - Sensitive volume almost un-depleted impact on radiation tolerance & speed
HV and HR CMOS

- HV CMOS

- HR CMOS
  T. Hemperek et al., hOp://indico.cern.ch/getFile.py/ access?resId=1&materialId=slides&confId=273886
Alice Inner tracker

New, high-resolution, low-material Inner Tracking System (ITS)

- Monolithic Active Pixel Sensors (MAPS) with Tower Jazz 0.18 µm
- Chip size: 15 mm x 30 mm
- Pixel pitch ~ 30 µm
- Si thickness: 50 µm
- Spatial resolution ~ 5 µm
- Sensors not fully depleted, not a fast signal ~2 µs hit time resolution
- Integration time < 30 µs

Low-mass design:
- 0.3%X₀ (0.8%X₀) in inner (outer) layers

25 Gpixels, Area: ~10m²
Inner barrel: 3 layers;
Outer barrel: 2+2 layers;
|η| ≤ 1.22 for tracks from 90% most luminous region;
r coverage: 22 – 430 mm
Using monolithic pixels (MAPS)
HV/HR-CMOS: strip

- Amplifiers and comparators could be on sensor but the rest of digital processing, command I/O, trigger pipelines, etc will go into a readout ASIC.
- The active area is *pixelated*, with connections to the periphery that can yield 2D coordinates.
- Pixel size ~40 µm x 800 µm.
- Max reticle sizes are ~2x2 cm². Therefore rows of 4-5 chips could be the basic units (yield performance is critical here).

- Cost savings.
- Faster construction.
- Less material in the tracker.
AMS 180 nm HV process (p-bulk) 60-100V
Deep n-well to put pMOS and nMOS (in extra p-well)
Some CMOS circuitry possible (ampl. + discr.)
~10-20 µm depletion depth → 1-2 ke signal
Various pixel sizes (~20x20 – 50x125 µm²)
Replaces „sensor“ (amplified signal) in a „hybrid pixel“
Big advantage: industrial CMOS process
Electrical contacts through wire bonds
Indications of radiation hardness to >10^{15} n_{eq}/cm²
Silicon-on-Insulator

- Chemical bonding of low resistivity wafer electronics with high resistivity sensor wafer
  - Full CMOS capability
    - In-pixel processing, low power, high speed
  - Fully depleted sensor wafer
  - Back gating effect
    - $V_{\text{bias}}$ affects analog transistor functionality
References

- Sze, Physics of semiconductor devices
- Helmuth Speiler lecture notes (www-physics.kbl.gov/~spieler)
- Norbert Wermes (Infieri Lectures, Paris, 2014)
- Doris Eckstein (DESY lectures)
- Gino Bolla UTEV seminar: http://www.fnal.gov/orgs/utev/past_speakers.html
- R. Lipton Academic lectures: http://www-ppd.fnal.gov/eppoffice-w/Academic_Lectures/Past_Lectures.htm
- Steve Worm notes on Radiation Damage
- Pixel Detectors, Rossi, Fisher, Rohe, Wermes, Springer
- M. Moll thesis on Radiation Damage
• BACKUP
Radiation damage due to NIEL

- The conjecture that bulk damage is proportional to the total KE imparted to displaced silicon atoms is called “the NIEL hypothesis.”
- It is conventional to use 1 MeV neutrons as the benchmark

**KERMA = Kinetic Energy Released in Matter**

\[
\text{KERMA} (\text{MeV}) = D (\text{MeVmb}) \times \phi \left( \frac{\#}{\text{cm}^2} \right) \times (\# \text{Si}) \times \left( \frac{10^{-27} \text{ cm}^2}{\text{mb}} \right)
\]
Ionizing particle with $45^0$ angle
$t=7\text{ns}$

All charge is collected.
Silicon Properties

- Excellent detector material
  - Low ionization energy (good signal). The band gap is 1.12 eV, but it takes 3.6 eV to ionize an atom. The remaining energy goes to phonon excitations (heat).
  - Long mean free path (good charge collection efficiency)
  - High mobility (fast charge collection)
  - Low Z (Z=14 low multiple scattering)
- Oxide (SiO$_2$) has excellent electrical properties
- Good mechanical properties
  - Easily patterned to small dimensions
  - Can be operated in air and at room temperature (many SSD require cooling)
- Industrial experience and commercial applications
- Crystalline $\Rightarrow$ radiation damage
Hybrid Pixel Module for CMS

Sensor:
- Pixel Size: 150mm x 100mm
  - Resolution $\sigma_{r-\phi} \sim 15\mu m$
  - Resolution $\sigma_z \sim 20\mu m$
- n+-pixel on n-silicon design
  - Moderated p-spray $\rightarrow$ HV robustness

Readout Chip:
- Thinned to 175$\mu$m
- 250nm CMOS IBM Process
- 8” Wafer
Baseline CMS design: \( n^+ - n \) pixels for partial depletion operation and increased Lorentz angle in high B field.

- 78 \( \mu m \) \( n^+ \)-implants.
- P-spay or open p-stops rings provide isolation.

\[ n^+ \]
Ultra-radiation hard: Diamond

- Poly crystalline and single crystal
- Competitive (to Si), used in several radiation monitor detectors
- Large band gap (x5 Si)
  - no leakage current
  - no shot noise
- Smaller $\varepsilon_r$ (x 0.5 Si)
  - lower input capacitance
  - lower thermal and 1/f noise
- Small $Z=6 \rightarrow$ large radiation length (x2 in g/cm$^2$)
- Narrower Landau distribution (by 10%)
- Excellent thermal conductivity (x15)
- Large $w_i$ (x 3.6) $\rightarrow$ smaller signal charge

- poly-CVD diamond wafers can be grown >12 cm diameter, >2 mm thickness.
- Wafer collection distance now typically 250µm (edge) to 310µm (center).
- 16 chip diamond ATLAS modules

- sc-CVD sensors of few cm$^2$ size used as pixel detectors
- High quality scCVD diamond can collect full charge for thickness 880µm
Summary of material properties

- Drift velocity for electrons: \( \vec{v}_n = -\mu_n \cdot \vec{E} \)
  for holes: \( \vec{v}_p = -\mu_p \cdot \vec{E} \)

- Mobility for electrons: \( \mu_n = \frac{e\tau_n}{m_n} \)
  for holes: \( \mu_p = \frac{e\tau_p}{m_p} \)

\( \mu_p(\text{Si, 300K}) \approx 450 \text{ cm}^2/\text{Vs} \)
\( \mu_n(\text{Si, 300K}) \approx 1450 \text{ cm}^2/\text{Vs} \)

- Resistance: \( \rho = \frac{1}{e(\mu_n n_e + \mu_p n_h)} \)

- e = electric charge
- E = external field
- \( m_n \) and \( m_p \) = effective mass of electrons and holes
- \( \tau_n \) and \( \tau_p \) = mean free path of electrons and holes
- \( n_n \) and \( n_p \) = density of electrons and holes
Wafer Fabrication

1) Start with very pure quartzite sand. Clean it and further purify by chemical processes. Melt it and add the tiny concentration of phosphorus (boron) dopant to make n(p) type silicon. Pour it in a mold to make a polycrystalline silicon cylinder.

2) Using a single silicon crystal seed, melt the vertically oriented polysilicon cylinder onto the seed using RF power to obtain single crystal ‘ingot’.

3) Slice ingot into wafers of thickness 300-500 µm with diamond encrusted wire or disc saws.

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Diode Processing

1) Start with n-doped silicon wafer, \( \rho \approx 1-10 \text{k}\Omega\text{cm} \). Silicon can be turned into n-type by neutron doping \((^{30}\text{Si}+n \rightarrow ^{31}\text{Si}, \quad ^{31}\text{Si} \rightarrow ^{31}\text{P}+\beta^-+\nu)\)

2) Oxidation at 800 - 1200°C

3) Photolithography (= mask align + photo-resist layer + developing) followed by etching to make windows in oxide
4) Doping by ion implantation (or by diffusion)

5) Annealing (healing of crystal lattice) at 600 °C

6) Photolithography followed by Al metallization over implanted strips and over backplane usually by evaporation.

⇒ Simple DC-coupled silicon strip detector
Oxide Charge

- Many defects can appear at the interface between Si and SiO$_2$.
  - Some of the interface atoms will miss oxygen atoms and create Si-O bonds
  - Impurities (H, OH, N)
- These will create levels that can trap mobile electrons and holes (Interface traps)
- The charge due to the trapped electrons and holes onto the oxide defects is the “oxide charge”
- The oxide charge is usually positive $\Rightarrow$ electron accumulation layer
- It can affect device characteristics: breakdown voltage, strip isolation, interstrip capacitance
Radiation Damage in Silicon

- Two general types of radiation damage
  - "Bulk" damage due to physical impact within the crystal
  - "Surface" damage in the oxide or Si/SiO$_2$ interface
- Cumulative effects
  - Increased leakage current (increased shot noise)
  - Silicon bulk type inversion (n-type to p-type)
  - Increased depletion voltage
  - Increased capacitance
- Sensors can fail from radiation damage
  - Noise too high to effectively operate
  - Depletion voltage too high to deplete
  - Loss of inter-strip isolation (charge spreading)
- Signal/noise ratio is the quantity to watch
Surface Damage

- Surface damage generation:
  - Ionizing radiation creates electron-hole pairs in the SiO$_2$
  - Many recombine, electrons migrate quickly
  - Holes slowly migrate to Si/SiO$_2$ interface since hole mobility is much lower than for electrons (20 cm$^2$/Vs vs. 2x10$^5$ cm$^2$/Vs)
  - Some holes ‘stick’ in the boundary layer

- Surface damage results in
  - Increased interface trapped charge
  - Increased fixed oxide charges
  - Surface generation centers

MOS devices are sensitive to surface damage

- Electron accumulation under the oxide interface can alter the depletion voltage (depends on oxide quality and sensor geometry)
- In silicon strip sensors, surface damage effects (oxide charge) saturate at a few hundred kRad
Surface Damage Effects

- Charges in the oxide layer can cause:
  - Risk to readout electronics
    - threshold shifts
    - noise and gain deterioration
  - Increase in the sensors capacitances
  - Single event upset in small feature size devices

- Problems can be minimized by:
  - Silicon crystal orientation (<100> rather than <111>) can minimize interface traps at boundary
  - Reducing oxide thickness
    - Voltage shifts are proportional to the square of the thickness (0.25 µm CMOS more rad hard)
  - Processing

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*Figure 4-14* Silicon/silicon dioxide structure with mobile, fixed charge, and interface states (©1980).

*Figure 4-15* High frequency C-V traces showing the effects of interface states and fixed charge.
Surface Damage

- Oxide charges in the silicon strip sensors depend on vendor
  - Oxide charge starts out high before irradiation
  - Adversely influences operation in certain biasing configurations
  - Could set a limit to max bias voltage
Process Defects and Scratches
Bulk Damage

- Bulk damage is mainly from hadrons displacing primary lattice atoms (for \( E > 25 \text{ eV} \))
  - Results in silicon interstitial, vacancy, and large disordered region
  - 1 MeV neutron transfers 60-70 keV to recoiling silicon atom, which in turn displaces \(~1000\) additional atoms

- Defects can recombine or migrate through the lattice to form more complex and stable defects
  - Annealing can be beneficial
  - Defects can be stable or unstable
  - Displacement damage is directly related to the non-ionizing energy loss (NIEL) of the interaction
  - Varies by incident particle type and energy
Bulk Damage

Displacement damage occurs for all particles – pions and neutrons are typically the most numerous.

Particle flux in a collider environment – experience from CDF Run I suggests $\Phi = \Phi_0/r^{1.7}$. Neutron flux falls less rapidly; it eventually becomes significant.

NIEL Radiation damage studies typically normalized to 1 MeV neutron damage equivalent.
Bulk Damage Effects

• Leakage Current:
  \[ \Delta I = \alpha(t) \Phi V \]
  - \( \alpha(t) \) (damage constant), \( V \) (volume), and \( \Phi \) (fluence).
  - Annealing reduces the current
  - Independent of particle type

• Depletion Voltage:
  \[ V_{\text{dep}} = q|N_{\text{eff}}|d^2/2\varepsilon\varepsilon_0 \]
  - Effective dopant concentration \( (N_{\text{eff}} = N_{\text{donors}} - N_{\text{acceptors}}) \), sensor thickness \( (d) \), permittivity \( (\varepsilon\varepsilon_0) \).
  - Depletion voltage is parameterized in three parts:
    - Short term annealing \( (N_a) \)
    - A stable component \( (N_c) \)
    - Long term reverse annealing \( (N_Y) \)
Leakage Current

• Defects create intermediate states within the band gap
  - intermediate states act as ‘stepping stones’ of thermal generation of electron/hole pairs
  - Some of these states anneal away; the bulk current reduces with time (and temperature after irradiation)

• Annealing function $\alpha(t)$
  - Parameterized by the sum of several exponentials $\alpha_i \exp(-t/\tau_i)$
  - Full annealing (for the example below) reached after ~1 year at 20°C
  - At low temperatures, annealing effectively stops
  - Dependant on incident particle type (?)

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D. Bortoletto Lecture 4
Leakage Current

- Measured values of $\alpha(t)$
  - One quotes measured values of $\alpha(t)$ after complete annealing at $T=20^\circ C$: $\alpha_\infty = \alpha(t=\infty)$
  - 'World averages' for $\alpha_\infty$ are:
    - $2.2 \times 10^{-17} \text{ A/cm}^3$ for protons, pions
    - $2.9 \times 10^{-17} \text{ A/cm}^3$ for neutrons
  - Measurement show $\alpha(t=80\text{min}, T=60^\circ C) = 4.0 \times 10^{-17} \text{ A/cm}^3$ for all types of silicon, levels of impurities, and incident particle types (NIM A426, 86, 1999).
Depletion Voltage

Depletion voltage is often parameterized in three parts (Hamburg model):
\[ \Delta N_{\text{eff}}(T,t,\Phi) = N_A + N_C + N_Y \]

- **Short term annealing** \(N_A\)
  \[ N_A = \Phi_{\text{eq}} \sum_i g_{a,i} \exp(-k_{a,i}(T)t) \]
  - Reduces \(N_Y\) (beneficial)
  - Time constant is a few days at 20 C

- **Stable component** \(N_C\)
  \[ N_C = N_{c0}(1-\exp(-c\Phi_{\text{eq}})) + g_c\Phi_{\text{eq}} \]
  - Does not anneal
  - Partial donor removal (exponential)
  - Creation of acceptor sites (linear)

- **Long term reverse annealing** \(N_Y\)
  \[ N_Y = N_{Y,\infty}[1-1/(1+ N_{Y,\infty}k_Y(T)t)], \quad N_{Y,\infty} = g_Y\Phi_{\text{eq}} \]
  - Strong temperature dependence
  - 1 year at \(T=20\) C or \(~100\) years at \(T=-7\) C (LHC)
  - Must cool Si at the LHC
Most common semiconductors

- **Germanium:**
  - Used in nuclear physics
  - Needs cooling due to small band gap of 0.66 eV (usually done with liquid nitrogen at 77 K)

- **Silicon:**
  - Can be operated at room temperature (but electronics requires cooling)
  - Synergies with micro electronics industry
  - Standard material for vertex and tracking detectors in high energy physics

- **Diamond (CVD or single crystal):**
  - Large band gap (requires no depletion zone)
  - Very radiation hard
  - Disadvantages: low signal and high cost
Compound semiconductors

- Compound semiconductors consist of
  - two (binary semiconductors) or
  - more than two atomic elements of the periodic table.
    - IV-IV- (e.g. SiGe, SiC),
    - II-V- (e.g. GaAs)
    - II-VI compounds (CdTe, ZnSe)
- Important III-V compounds:
  - GaAs: Faster and probably more radiation resistant than Si. Drawback is less experience in industry and higher costs.
  - GaP, GaSb, InP, InAs, InSb, InAlP
- Important II-VI compounds:
  - CdTe: High atomic numbers (48+52) hence very efficient to detect photons.
  - ZnS, ZnSe, ZnTe, CdS, CdSe, Cd1-xZnxTe, Cd1-xZnxSe
A brief history of solid state detectors

J. Kemmer 1979

• NA11 at CERN
  – First use of a position-sensitive silicon detector in HEP experiment
  – Measurement of charm quark lifetimes
  – 1200 diode strips on 24x 36 mm²
  – 250-500 µm thick bulk material
  – 4.5 µm resolution
LEP and SLAC SLC Experiments

- LEP and SLC
  - Readout ASICs at end of ladders
  - Minimize mass inside tracking volume
  - Minimize mass between interaction point and detectors
  - Minimize the distance between interaction point and the detectors
- Enabled measurement of b-quark lifetimes and b-tagging

ALEPH
- 2 silicon layers, 40cm long, inner radius 6.3cm, outer radius 11cm
- 300 μm silicon wafers giving thickness of only 0.015$X_0$
- $S/N(r-\phi) = 28:1$
- $S/N(z) = 17:1$
- $r-\phi = 12 \, \mu m; \, z = 14 \, \mu m$
CDF & D0 at the Tevatron

- CDF pioneered the silicon vertex detector in the hadron collider environment and pioneered the silicon vertex trigger separating $b$-hadrons
- Emphasis shifted to tracking and vertexing allowing precision measurements in very complex environment
- Cover large area with many silicon layers
- Detector modules including ASIC’s and services INSIDE the tracking volume

CDF’s first Silicon Vertex Detector at the Smithsonian Museum, Washington
From LEP to the LHC
Comparison solid state versus gas

Ionization chamber medium could be gas, liquid, or solid
- Gas $\Rightarrow$ electron and ion pairs; Semiconductor $\Rightarrow$ electron and hole pairs

<table>
<thead>
<tr>
<th></th>
<th>Gas</th>
<th>Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Atomic number (Z)</td>
<td>Low</td>
<td>Moderate (Z=14)</td>
</tr>
<tr>
<td>Ionization Energy ($\varepsilon_i$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Moderate ($\approx 30$ eV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low ($\approx 3.6$ eV)</td>
<td></td>
</tr>
<tr>
<td>Signal Speed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Moderate (10ns-10$\mu$s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fast (&lt;20 ns)</td>
<td></td>
</tr>
</tbody>
</table>

Solid State Detectors

- Energy ($E$) to create e-h pairs 10 times smaller than gas ionization $\Rightarrow$ increase charge $\Rightarrow$ good E resolution

$$\Delta E \propto \frac{1}{\sqrt{N}} \times \frac{1}{\sqrt{E / \varepsilon_i}} \propto \sqrt{\varepsilon_i}$$

- Greater density:
  - Reduced range of secondary electrons $\Rightarrow$ excellent spatial resolution
  - Average $E_{loss} \approx 390$eV/ $\mu$m $\approx 108$ e-h/ $\mu$m (charge collected is a function of thickness $d$. Up-to-now no multiplication)

- To minimize multiple scattering $d$ is small
  - $300 \mu$m $\approx 32,000$ e-h pairs $\Rightarrow$ good S/N