Introduction to Silicon Detectors

G. Villani
STFC Rutherford Appleton Laboratory
Particle Physics Department
Outlook

• Introduction to physics of Si and detection
• Examples of detectors
• Radiation effects and system issues
• Conclusions
Introduction

The Si detection chain

Detector physics:
- Silicon physical and electrical properties
- Detection principles
- Transport mechanisms
- Conversion

Detector examples:
- Strips, pixels
- MAPS
- ATLAS SCT

Detector system issues:
- Detection efficiency
- Power

all the boxes of the detection chain process based upon Silicon
After Oxygen, Silicon is the 2\textsuperscript{nd} most abundant element in Earth’s crust (>25\% in mass)

The crystalline structure is diamond cubic (FCC), with lattice spacing of 5.43 A
- Polysilicon consists of small Si crystals randomly oriented; in α-Si there is no long range order.

Apart from its abundance, that makes it also cheap, the key to success of Si is related to its oxide SiO\textsubscript{2}, an excellent insulator (BV \(\sim 10^7\) V/cm).
* Micro crystals but the flexible bond angles make SiO\textsubscript{2} effectively an amorphous: its conductivity varies considerably (charge transport in SiO\textsubscript{2} via polaron hopping between non-bonding oxygen 2p orbitals)
Silicon electrical properties

Silicon Band structure
The electronic band structure can be obtained by solving many-body SE in presence of periodic potential of the crystal lattice: (normally 1 electron SE in periodic potential neglecting electron interactions) : Bloch functions

\[(T+U)\psi = E\psi \Rightarrow \psi_{n,k}(r) = u_{n,k}(r)e^{ikr} \rightarrow E_n(k)\]

\(\approx\) a wave associated with free motion of electrons modulated by the periodic solution \(u_{n,k}\). The energy \(E\) is periodic in \(k\) so is specified just within the 1\(^{\text{st}}\) unit WS cell of the reciprocal lattice (the Brillouin zone).

➔ The appearance of Band Gap, separating CB and VB

➔ The 6 CB minima are not located at the center of 1\(^{\text{st}}\) Brillouin zone, INDIRECT GAP
Silicon electrical properties

The detailed band structure is complicated: usually quasi-equilibrium simplifications are sufficient to study the charge transport. Assuming that the carriers reside near an extremum, the dispersion relationship $E(k)$ is almost parabolic:

$$E(k) = \frac{\hbar^2 |k|^2}{2m^*_0} \to g(E) = \frac{(2m^*_0)^{3/2}}{2\pi^2 \hbar^3} \sqrt{E - E_o}$$

$$E(k) = \frac{\hbar^2 |k|^2}{2m^*_0} \to \langle v \rangle = \frac{1}{\hbar} \nabla_k E(k) = \frac{\hbar k}{m^*_0} = \frac{\langle p \rangle}{m^*_0}$$

$$\hbar \frac{dk(t)}{dt} = \hbar \frac{d\langle p \rangle}{dt} = \langle -\nabla V \rangle \equiv F$$

Under the assumptions of small variation of the electric field, the carrier dynamics resembles that one of a free particle, with appropriate simplifications.

The effective mass approximation takes into account the periodic potential of the crystal by introducing an effective carrier mass (averaged over different longitudinal and transverse masses). The lower the mass, the higher mobility ($\mu \propto 1/m^*$).

A similar approach is used to calculate the $E(k)$ for phonons.
Silicon electrical properties

The carrier density is calculated from:

- The density of states $g(E)$, which depends on dimension;
- The distribution function $F(E)$;

Only partly filled bands can contribute to conduction: carrier density in CB and VB.
At equilibrium the carrier density is obtained by integrating the product:

$$n_D = \int g_D(E)F(E)dE \equiv N_C e^{-\left(E_c - E_F\right)/kT} = n_i = p_i$$

$$F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

$$pn = n_i^2 = N_C^2 N_V e^{-(E_g)/kT} \approx 10^{20} \text{ at } T = 300K$$

In intrinsic Si a creation of e in CB leaves behind a hole in VB, that can be treated as an e with positive charge and mobility of the band where it resides.

The density of states $g_D(E)$ depends on the dimension.
Silicon electrical properties

- Conduction of Si intrinsic @ T = 300K:

\[ \sigma = q(\mu_n + \mu_p) n_i = 3.04 \times 10^{-6} \text{mho-cm} \rightarrow 329 \text{kOhm-cm} \]

- By adding atoms of **dopants**, which require little energy to ionize (~10’s mEV, so thermal energies @ ambient temperature are enough) we can change by many orders of magnitude the carrier concentration.

- Doping concentration: \(10^{12}\) to \(10^{18}\) cm\(^{-3}\)

In crystalline Si \(~5 \times 10^{22}\) atoms cm\(^{-3}\)

In equilibrium and for non degenerate case the relationship between carrier concentration and \(E\) is the same as in the intrinsic case:

\[ pn = n_i^2 = N_c N_v e^{-\frac{E_g}{kT}} \approx 10^{20} @ T = 300K \]

\(e.g.: N_D = 10^{17} \Rightarrow pn \approx pN_D \Rightarrow p \approx \frac{n_i^2}{N_D} = 10^3\)
Detection principles

**Detection principles:**

A: **Ionization**: by imparting energy to break a bond, electrons are lifted from VB to CB then made available to conduction. Most exploited concept (ionization chambers, microstrip, hybrid pixels, CCD, MAPS...)

B: **Excitation**: Charge or lattice (acoustic or optical phonons) some IR detectors, bolometer

\[
\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n \cdot z^2}{\beta^2} \cdot \left( \frac{e^2}{4\pi \epsilon_0} \right)^2 \cdot \ln \left( \frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2
\]

Bethe-Bloch formula for stopping power gives the rate of energy loss/unit length for charged particles through matter

\[
I(z) = I_0 e^{-\alpha(z) z}
\]

Photon interaction

**Bethe-Bloch formula** for stopping power gives the rate of energy loss/unit length for charged particles through matter.
The indirect BG semiconductors require higher energy than naively expected from their band gap for charge excitation, because energy and momentum must be conserved (Phonon-assisted pair creation/recombination)

In Si an average of 3.6 eV is required for pair creation
Detection

MIP charge density

\[ n = \frac{dE}{dx} \rho \frac{1}{\varepsilon_i \pi R^2} \approx 3 \cdot 10^{15} \text{cm}^{-3} \]

\[ R = \hbar \frac{v \cdot V}{\langle I \rangle} \approx 110 \text{nm} \]

A MIP forms an ionization trail of radius R when traversing Si, creating \( \sim 80e/\mu m \)

\[ \lambda \approx \frac{\hbar}{\sqrt{2mE}} \ll 10^{-15} \text{cm} \]

\[ L \approx 0.5 - 1 \cdot 10^{-7} \text{cm} \]

\[ \Rightarrow \text{High injection regime:} \]

The internal electric field can be affected by the generated charge

\[ I(z) = I_0 e^{-\alpha(E)z} \]

\[ n_\lambda(z) = \frac{P_{in}}{h \nu} \eta \alpha(\lambda) e^{-\alpha(\lambda)z} \approx 5.6 \cdot 10^6 e^-/\mu m \]

An optical power of -60dBm (= 1nW) of 1keV photons generates \( \sim 6 \cdot 10^6 e^-/\mu m \)

\[ \Rightarrow \text{Low injection regime:} \]

The associated wavelength is **much smaller** than mean free path:

Each charge is independent from each other;

Carrier dynamics does not need QM

The generated charge is too small to affect the internal electric field
Detection

The variance in signal charge $\sigma_i$ associated to the ionization process is related to the phonon excitation

$$\sigma_i = \sqrt{\frac{E}{E_i}} \sqrt{\frac{E_{pm}}{E_i} \left( \frac{\varepsilon_i}{E_i} - 1 \right)}$$

Fano factor $\sim 0.1$ in Si

High resolution requires smaller band gap ($\varepsilon_i$), direct or small phonon excitation energy

Intrinsic resolution of Si and Ge based detectors
Detection

B: Excitation:

Dispersion relation for phonons in Si

Phonon excitation energy ~ 10 meV: much lower threshold

Eigenvalues separation in quantized structures ~ 10’s meV
Charge transport

**Charge transport:**
Once the charge has been created in the material, the next step is its **collection**: The charge transport description relies on semi-classical **BTE** (continuity equation in 6D phase space)

\[
\frac{\partial f(\vec{r}, \vec{k}, t)}{\partial t} + \frac{1}{\hbar} \nabla_k E(\vec{k}) \cdot \nabla f(\vec{r}, \vec{k}, t) + \frac{F}{\hbar} \cdot \nabla f(\vec{r}, \vec{k}, t) = \frac{\partial f(\vec{r}, \vec{k}, t)}{\partial t} \bigg|_{\text{coll}} + S(\vec{r}, \vec{k}, t)
\]

\[
n(\vec{r}, t) = \frac{1}{V} \int_k f(\vec{r}, \vec{k}, t) \quad \text{Q conservation}
\]

\[
J(\vec{r}, t) = -\frac{q}{V} \int_k v(\vec{k}) f(\vec{r}, \vec{k}, t) \quad \text{P conservation}
\]

\[
W(\vec{r}, t) = \frac{1}{V} \int_k E(\vec{k}) f(\vec{r}, \vec{k}, t) \quad \text{E conservation}
\]
Under (many) simplifying assumptions the 1\textsuperscript{st} moment of BTE gives the DD model (The ‘semiconductor equations’):

\begin{align*}
J_n &= qn\mu_n E(r) + qD_n \nabla n \\
J_p &= q\mu_p E(r) - qD_p \nabla p \\
\frac{\partial n}{\partial t} &= \frac{1}{q} \nabla \cdot J_n + U_n \\
\frac{\partial p}{\partial t} &= -\frac{1}{q} \nabla \cdot J_p + U_p \\
\nabla \cdot \varepsilon \nabla V &= -(p - n + N_D^+ - N_A^-)
\end{align*}

⇒ DD expresses momentum conservation: it becomes invalid when sharp variation in energy of carriers occur (due to F for example: deep submicron devices). When feature size is 0.\textmu m the DD model becomes invalid: higher moments required.
Half summary

Under a number of assumptions, the description of the detection processes in semiconductor detectors can be hugely simplified:

**Physical characteristics:**
- Quasi equilibrium;
- Homogeneity;
- ‘Room’ temperature;
- Non degenerate Si;

**Charge generation:**
- Ionization: Small injection, QM not needed;
- Stopping power, average ionization energy

**Charge transport:**
- Big devices, DD adequate;
- Small injection, electric field as static;

Under conditions of
- quasi stationary conditions
- non degenerate semiconductor
- not small feature size
- low injection
- …
Detectors examples

- **Strip / pixel detectors**
  - HEP, Scientific applications
  - Monolithic Active Pixel Sensors (MAPS)
  - Consumer and scientific applications

- **Charge Coupled Devices (CCD)**
  - Imaging, scientific and consumer applications

RAL PPD has (is) actively involved with all these detector technologies.
Almost all HEP experiments use Si detectors:
The high density track region usually covered by pixel detectors; by strip
at larger radius (cost reason)
Signal conversion: The PN junction

Homojunction: two pieces of **same** semiconductor materials with **different** doping levels:

- In equilibrium, the Fermi level equalizes throughout the structure
- thermal diffusion of charge across the junction leaves a depleted region, with the ionized dopants: an electric potential $\Phi$, and a field $F$, develops across
- the charge concentration depends exponentially on energy, or $\Phi$:

$$0 = qn\mu_n E(r) + qD_n \nabla n \rightarrow n = n_0 e^{\frac{\Delta \Phi}{kT}}$$

$$0 = qp\mu_p E(r) - qD_p \nabla p \rightarrow p = p_0 e^{\frac{\Delta \Phi}{kT}}$$

- by applying a small voltage to decrease the barrier, the charge increases exponentially
- by applying a voltage to increase the barrier, the depleted region increases

**Unidirectionality** of current characteristics
Signal conversion: The PN junction

- when charge is generated in the depleted region is swept across by the electric field sustained by the ionized dopants and the biasing.

⇒ PN junction as signal converter: capacitor with a $F$ across

⇒ A PN junction with a large depleted region can be used to efficiently collect radiation generated charge (Solid state ionization chamber)

Depletion width

$$W = \sqrt{\frac{2\varepsilon V_b N_a + N_d}{q N_a \cdot N_d}}$$

To achieve large $W$ high field region:
- Low doping (high resistivity), $N_a$ or $N_d$
- Large voltages $V_b$
Array of **long silicon diodes on a high resistivity silicon substrate**
A strong F in the high resistivity Si region helps collect charge efficiently.

- The high resistivity Si is not usually used in mainstream semiconductor industry:
  **Hybrid solution**: sensor (high resistivity Si) connected (wire/bump-bonded) to the readout electronic (low resistivity Si)
Detectors examples

**ATLAS SCT**

- 4 single-sided p-on-n sensors
- 2x2 sensors daisy chained
- Stereo angle 40 mrad
- Strip pitch 80 µm
- 768 channels/side
- Binary RO
- Bias Voltage up to 500 V
- Operating temperature -2 C
- Space point resolution: rPhi 17µm / z 50 µm
- Power consumption: 5.6 W (initially) to 10 W (after 10y)
- Rad hard up to $2 \times 10^{14}$ 1-MeV n eqv/cm²

**ATLAS SCT RO ASIC (ABCD3TA)**

- 128 channels/ASIC
- RAD-HARD DMILL technology
- ASICS glued to hybrid
- 40 MHz Ck
Detectors examples

ATLAS SCT
- 61 m² of Si
- $6.3 \times 10^6$ channels
- 50 kW total power consumption
  - 1 barrel
    - 4 layers
    - 2100 modules
  - 2 endcaps
    - 9 disks/each
    - 988 modules
- 2 T solenoidal field
Detectors examples

ATLAS Tracker overview

Pixel: (n+ on n) 1.8m², 80M channels
SCT: 61 m², 6.3M channels
TRT: 0.4M channels
Detectors examples

Barrel insertion in the ATLAS Cavern

ATLAS SCT - Red cables: power cables
Detectors examples
Detectors in operation

An ATLAS event with 4 muons. The four muons are picked out as long blue tracks.
Detectors in operation

- 4088 modules with 6.3 million readout channels

99% are operational

<table>
<thead>
<tr>
<th>Disabled Readout Components</th>
<th>Endcap A</th>
<th>Barrel</th>
<th>Endcap C</th>
<th>SCT</th>
<th>Fraction (%)</th>
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<td>Disabled Modules</td>
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<td>15</td>
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<td>Total Disabled Detector Region</td>
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<table>
<thead>
<tr>
<th>Total Fraction (%)</th>
<th>Endcap A</th>
<th>Barrel</th>
<th>Endcap C</th>
<th>SCT</th>
<th>Fraction (%)</th>
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<td>1</td>
<td>7</td>
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<tr>
<td>HV</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>0.15</td>
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<tr>
<td>Readout</td>
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<td>3</td>
<td>0</td>
<td>4</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Detectors examples

MAPS detectors

≈1’s µm

2 D array of pixels

3T (3MOS) MAPS structure

- Monolithic solution: detector and readout integrated onto the same substrate
Detectors examples

MAPS detectors

- The charge generated in the thin active region moves mainly by diffusion:
  - ‘Long’ collection time
  - Small signal
  - Low radiation hardness

- However, complex circuit topologies allow DSP on pixels for low noise performances ($\approx$ some e$^{-}$ noise)
Detectors examples

Example of MAPS detectors:

\[ \frac{\partial n}{\partial t} = D_n \nabla^2 n + U_n \Rightarrow t_{\text{coll}} \approx \frac{l^2}{D_n} \]

Charge collection time (s) in MAPS vs. perpendicular MIP hit

TPAC 1 pixel size 50x50 µm²
Chip size ~1cm²
Total pixels 28k
>8Meg Transistors
Detectors examples

Example of charge collection in MAPS: simulated MIP vs. 1064nm laser 2x2 µm² 5ns pulse
Detectors example

Proposed use of MAPS (50x50 µm²) sensors in SuperB Vertex Tracker

- Striplets option: mature technology, not so robust against background occupancy.
  - Marginal with background rate higher than ~ 5 MHz/cm²
  - Moderate R&D needed on module interconnection/mechanics/FE chip (FSSR2)

- Hybrid Pixel option: viable, although marginal.
  - Reduction of total material needed!
  - Reduction in the front-end pitch to 50x50 µm² with data push readout (developed for DNW MAPS)
  - FE prototype chip (4k pixel, ST 130 nm) now under test.

- CMOS MAPS option: new & challenging technology.
  - Sensor & readout in 50 µm thick chip!
  - Extensive R&D (SLIM5-Collaboration) on
    - Deep N-well devices 50x50µm² with in-pixel sparsification.
    - Fast readout architecture implemented
  - CMOS MAPS (4k pixels) successfully tested with beams

Thin pixels with Vertical Integration: reduction of material and improved performance.
- Two options are being pursued
  - DNW MAPS with 2 tiers
  - Hybrid Pixel: FE chip with 2 tiers + high resistivity sensor
Radiation damage

In HEP and space applications the detectors are exposed to high level of dose of radiation:
LHC: 10’s Mrad (100kGy) over 10 years of operation
N.B.: 1 rad/cm³ Si ~10¹³ e/h pairs
Lethal dose: 5 Gy Total Body Irradiation

Main damage in strip layers due to neutrons
## Radiation damage

Radiation environment in LHC experiment

<table>
<thead>
<tr>
<th></th>
<th><strong>TID</strong></th>
<th><strong>Fluence</strong></th>
<th>1MeV n eq. [cm⁻²] @ 10 years</th>
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<tbody>
<tr>
<td>ATLAS Pixels</td>
<td>50 Mrad</td>
<td>1.5 x 10¹⁵</td>
<td></td>
</tr>
<tr>
<td>ATLAS Strips</td>
<td>7.9 Mrad</td>
<td>2 x 10¹⁴</td>
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<tr>
<td>CMS Pixels</td>
<td>~24 Mrad</td>
<td>~6 x 10¹⁴ *</td>
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</tr>
<tr>
<td>CMS Strips</td>
<td>7.5 Mrad</td>
<td>1.6 x 10¹⁴</td>
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<tr>
<td>ALICE Pixel</td>
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<tr>
<td>LHCb VELO</td>
<td>-</td>
<td>1.3 x 10¹⁴/year **</td>
<td></td>
</tr>
</tbody>
</table>

All values including safety factors.
Radiation damage

**Microscopic effects:** Bulk damage to Silicon:
Displacement of lattice atoms

- Atoms scattered by incoming energetic particles leave behind vacancies or atoms in interstitial positions (Frenkel pairs).
- Low energy particle ~ point defects
- High energy particles ~ cluster defects

\[ V + \text{Interstitial} \to E_k \geq 25 \text{ eV} \]

![Displacement Damage Processes in Si](image)

- 50 keV silicon recoil atom
- Cluster
- Location of initial collision
- Clusters
- Free defects, Coulomb, Nuclear Elastic
- Single cascade, Nuclear elastic
- Many subcascades, Nuclear reactions
- Proton energy
- Recoil energy
- 1-2 keV
- 12-20 keV
- 6-10 MeV
- > 20 MeV
Radiation damage

The appearance of spurious band gap states affects the electro/optical characteristics of the device:

- Thermal generation of carriers (increased leakage current)
- Reduced recombination time (quicker charge loss, reduced signal)
- Charge trapping
- Scattering
- Type conversion
Radiation damage

**Macroscopic effects:**
Charge Collection Efficiency (CCE) is reduced by decreased recombination time and trapping
Noise increases because of increased leakage current
Depletion voltage increases because of type inversion

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

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

\[
\Phi_{\text{eq}} \propto \frac{1}{\tau_{\text{eff} e,h}}
\]

10^{15} 1MeV n-eq.
Radiation damage

To increase the Radiation Hardness of Sensors:

• Operating conditions (cooler – lower leakage)
• Material engineering (OFZ - Diamond detectors)
• Device engineering (n in n/p – 3D detectors):
  • Electrodes in the bulk – lateral collection reduces the drift distance
  • Lower depletion voltage – less power consumption
  • Difficult to manufacture

• 3D DDTC similar to 3D but easier to manufacture; also Better mechanical strength.
Detector systems

HEP experiments: large detector systems
Challenging engineering issues

The ATLAS SCT (semiconductor tracker) detector. The thick red cables on show feed the detector with half of its power.

Low power solutions are crucial for future HEP (and others) experiments:

Estimated lowest power consumption for simple generic pixel: \( \approx 10 \, \mu W \)

10\(\mu W\) continuous \(\rightarrow\) 10\(\mu J\) energy

Energy deposited by a MIP particle: 0.2 – 10\(fJ\)

Required energy/deposited energy \(\gg\) 10\(^{10}\) !!!

‘Huge’ energy inefficiency

Alternative powering schemes:

A serial powering (SP) or DC2DC approach can increase efficiency in power distribution compared to a parallel approach.
The field of semiconductor detectors encompasses different scientific and technology fields: solid state physics, nuclear and particle physics, electrical engineering, …

Some of the issues relevant to particle and radiation detectors:

• Development of new detection techniques based on novel and well established semiconductor material: (phonon-based detectors, quantum detectors, compounds, low dimensional)
• Integration with electronics (monolithic solution to achieve more compactness and reduce cost), 3D structures
• Topologies optimization (power reduction, noise reduction)
• Simulation and modelling;
• Radiation hardness