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Silicon Tracking Detectors in High Energy Particle Physics
Innermost part of most HEP Experiments are the tracking systems

- Outer parts for **momentum** measurement
- Inner parts for **vertexing**, and (if pixels are used) for track seeding

Most vertex detectors are based on **silicon**

- Suitable properties (signal, carrier life time, can be doped …)
- Low Z (material budget)
- Good availability in high quality, sufficiently cheap
- Well know processing technology (on principle)

**Competitors**

- Compound semi conductors: Not sufficiently radiation hard (high Z attractive for X-ray detection)
- Diamond: Expensive, not easily available (esp. single crystal) but very attractive features → R&D ongoing
**Principle of most tracking devices**

- A particle (or a photon) **ionizes** the detection medium
- The charge carriers are separated by an **E-field**
- Their drift induces charge on the collection electrodes
- If collection electrons are segmented, a spatial information is obtained
- Ionization energy needed for electron–ion separation
  - Argon: ~26 eV
  - Silicon: 3.6 eV

**“Ohmic” detector**

- Assume a piece of silicon: area 1cm² thickness 0.3mm
- Charge released from a m.i.p.: ~25000 e⁻ ~ 4fC
- Mobility (electrons): ~1400cm²/Vs, targeted collection time: 10ns
- **Signal** current I = 4 fC/10ns = **400 nA** (easy to detect)
- To achieve 10ns collection time an electric field of
  \[ E = \frac{v}{m} = 0.03 \text{cm}/10\text{ns}/1400\text{cm}^2/\text{Vs} \approx 2100 \text{ V/cm} \]
  or a **bias of 60V**

**But:**

- Silicon is a semiconductor
  - Highest practical resistivity: 10kΩcm → 300Ω (our piece)
  - Current at 60V: **200mA**
  - For very small cells (pixels) A~10⁻⁴cm⁻² good S/N possible but overall power consumption prohibitive (12W/cm²)
  - Large band gap materials (diamond) work in this regime
- For “high” temperature Silicon: **suppress leakage current → pn-junction**
A diode is formed by an interface between p- and n-doped silicon:

- Majority carriers diffuse to the other side
  \[ J_{\text{diff}} = -D_n \nabla n \quad \text{or} \quad J_{\text{diff}} = D_p \nabla p \]
  with \( D = kT \mu e \) (Einstein relation)
- Recombine with “local” majority carriers → zone with reduced concentration of free carriers (depletion zone)
- Remaining acceptor/donor ions cause electric field
  \[ J_{\text{drift}} = -e n \mu_n E \quad \text{or} \quad J_{\text{drift}} = e p \mu_p E \]
- Both currents cancel each other → relation field vs. position
- Forward bias → exponential IV curve
- Reverse bias
  - Depletion zone is increased
  - Current is suppressed (only thermal generation)
- In case one side of the junction is much heavier doped than the other and the junction is abrupt:
  - \( W = \sqrt{2\varepsilon_0 \varepsilon_{\text{Si}} V/eN_D} \) → depends only on bulk doping
  - Constant bulk doping → linear field
• Dark current by thermal generation of e-h-pairs in the space charge region (volume)
  • Effected by defects in the crystal
  • Heavily increased by radiation
  • Exponential Temperature dependence
    \[ J_{\text{vol}} \sim T^2 \exp(-E_g/2kT) \] or factor 2 every 8K

Other sources of leakage current
• Thermal generation at interfaces/surfaces
  • Segmentation
  • Process quality
  • Radiation
  • Charge multiplication (break down)
Strip detector (DC-coupled)

Simplest way to create diodes

- Implant Boron over a photoresist pattern into high resistive n-type silicon
- Electrodes typically have the shape of strips are connected to the read out electronics by wire bonding

Features:

- \( W = \sqrt{2\varepsilon_0\varepsilon_{Si}V/eN_D} \) \( \rightarrow \) depends only on bulk doping
- Full depletion for \( 300\mu m \) and \( n=10^{12}cm^{-2} \) \( \sim 70V \)
- Constant bulk doping \( \rightarrow \) linear field
- Strip implant forms junction \( \rightarrow \) peak at strip
- High dose implant on back side (ohmic contact, break down)
1st strip trackers

Left: 1st strip tracker at FNAL-E706 (around 1980)
- Signals were still routed to crates using flat band cables

Top: CERN WA82 (1986)
- Signal amplifiers built with discrete components

Due to the bulky readout electronics only used in fixed target experiments
ASIC readout → Collider experiments (LEP, HERA)
HERA - CST

- Designed and built at PSI (1992-96)
- Read out with ASIC (apc128)
  - Readout electronics placed in small hybrids
  - 128 channels 50µm pitch
  - Digital controlled analogue signal processing
  - Very universal (e.g. now used for telescope)
Double sided read out
- N-side isolation
- Ground of electronics (one side on HV)
  - Readout via optical fibers
  - Control signals coupled in via capacitors
- Luminosity at HERA was small
  - 3 sensors daisy chained
  - 90 degree stereo angle
  - Double layer metal on n-side
    → Large capacitance → high noise

Insulation layer
Sensor bulk

via

p+ strip side
n+ strip side
n-bulk
p+
Al

p+ - strip readout

n+ - strip readout

particle hits
d fake combinations !
AC-coupled strip detector

- **Bias resistor and coupling capacitor** are difficult to implement on an ASIC
- Implementation on sensor is possible
  - **Capacitor: SiO2 layer**
    - Due to large strip size, a few 100nm thick layer possible
    - Can be very stable up to 100V
  - Long **poly resistor** (R > 1MΩ)
- **Yield of capacitor is cost driving**
  - Every capacitor/strip has to be tested
  - Yield can be improved by applying a sandwich layer of Si₃N₄
Pioneering in 2 respects

- 1st "large area" application: several m²
- 1st strip sensors which suffered substantial radiation induced degradation

Sensor choice: **Double sided AC coupled** sensors, both readout electronics on GND:

- Voltage drop over coupling capacitor
- Limit of max. bias to 170V

Solution: Insertion of "layer00":
- Single sided, stable > 600V
The requirements to CMS tracker

- **Intermediate and outer regions \((r>20\text{cm})\)**
  - “Moderate” radiation hardness required
  - Can be archived with “standard” sensors
- **Small stereo angle**
  - Less ambiguities
  - No double metal required to mount ASICs at “stave” end
- **Loss in z-resolution**
- **Very large area \((\sim 200\text{m}^2)\) → cost**
  - Single sided p-on-n sensors
  - Double sided → 2 sensors back-to-back
  - Large wafers (150mm instead of 100mm)
- **Inner region \((r<20\text{cm})\)**
  - High track density
  - No ambiguities
  - Zero suppression and local data storage
  - **Radiation induced degradation** (sensor and ROC)

→ Pixels
• **Surface damage**
  – Mainly by ionisation in the covering layers
  – Built up of positive surface charge
  – Danger of breakdown close to n-side electrodes
  → careful choice of n-side isolation

• **Crystal damage by displacement**
  • Leakage current increase proportional to $\Phi$
    $\Phi \sim ?? \ (\text{depending much on } T)$
    – power load (cooling), power
    – Preamplifier (if DC coupled)
  • Change of internal electric field
    $\Phi > \text{a few } 10^{14} \text{ Neq/cm}^2$ ($\int L > \sim 100/\text{fb}$)
    – Bias voltage has to be
    – Charge is focused $\rightarrow$ spatial resolution degrades
  • Reduced signal (trapping)
    $\Phi > \sim 10^{15} \text{ Neq/cm}^2$ ($\int L > \sim 250/\text{fb}$):
    – Possibly charge amplification $> 1\text{kV} \rightarrow \text{RD50}$
    – High voltage is presently limited by connectors, cables and power supplies

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36824 vacancies
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4145 vacancies
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8870 vacancies
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[Mika Huhtinen NIMA 491(2002) 194]
Leakage current

Leakage current was measured with a very large number of small diodes with the guard current separated

- **Volume current only**
- Segmented sensors might be different

**Result**

- Current density is proportional to the Fluence
- Damage constant $\alpha = \Delta I / (V \Phi_{eq})$ independent of
  - Kind of particle
  - Fluence
  - Growth method of the crystal
  - Impurities of the crystal
  $\rightarrow$ NIEL hypothesis correct for $I_{\text{leak}}$
- Leakage current of diodes is used for fluence calibration or as measurement of $\kappa$
- Annealing
Internal electric field

- Highest electric field moves from p-side to n-side ("type inversion")
- Double peak field builds up
- Total amount of space charge increases
  - **Minimum bias voltage increases**
- Depends on
  - material choice
  - kind of radiation (even compensating effects with proton/neutron irradiation)
- Effective doping ("average") described by Hamburg model (creation and anning)

![Graph showing electric field distribution and doping levels]

- [ROSE-Report]
Trapping

Charge trapping displays presently the absolute operational limit

- Not dependent on material properties (present status)
- Decreases anti proportional to fluence
- Presently measured only up to $10^{15}N_{eq}/cm^2$
- Holes and electron have about same inverse trapping time
- Annealing is different for electrons and holes
- Electrons are $3 \times$ more mobile, their collection is of advantage ($\rightarrow$ n-in-n/p sensors)
- Collection distance after $10^{15}N_{eq}/cm^2 \sim 200\mu m$

Data for holes
Data for electrons

Inverse trapping time $1/\tau$ [ns$^{-1}$]

Particle fluence $\Phi_{eq}$ [cm$^{-2}$]

Annealing time at 60°C [min]

24 GeV/c proton irradiation

$\Phi_{eq} = 4.5 \times 10^{14}$ cm$^{-2}$

[M.Moll; Data: O.Krasel, PhD thesis 2004, Uni Dortmund]

T. Rohe, PSI, 12.09.2013
CMS pixel sensor concept

Collect electrons (n-side readout)
- Less prone to trapping
- Larger Lorentz angle
- n-side isolation required

Avoid problems in module design
- N-Substrate
- Guard rings (and junction) on back side
- All sensor edges on ground potential
- Double sided processing

Pixel cell layout
- Moderated p-spray with bias grid
  - Reliable IV measurements prior to flip chip procedure
  - Only moderate over depletion necessary
  - Small partly insensitive area of the order of 2% (not effect on efficiency in CMS)
- Small gaps between implants
  - homogenous drift field
    - Minimize effect of field separation on charge sharing
    - Avoid flied peaks (high voltage capability in irradiated state)
  - higher C ~ 80fF (Not critical for performance)
Excursion: N-side isolation

**Fixed oxide charge**
- Creates a conducting channel between n-electrodes
- Determines the electrical field in the critical area close to the surface
- Technology parameters (dose of the isolation implant has to be adjusted)

**P-Stops (FPix)**
- High boron dose (adjustment uncritical)
- Alignment important
- (Breakdown after irradiation if dose is too high)

**P-Spray, mod. p-Spray (BPix)**
- HV-stability of un-irradiated device critical
- Boron dose to be adjusted
  - High enough to provide isolation
  - Low enough to enable HV operation of new devices (e.g. during module production)
- Narrow gaps possible (without moderation)
  - Punch through structures
  - Homogenous drift field at high voltages
Different pixel designs in 2003

<table>
<thead>
<tr>
<th>Design</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sintef (Ring)</td>
<td>- Only 1 un-irradiated (measured at 300V)</td>
</tr>
<tr>
<td>CiS (Ring)</td>
<td>- 1 un-irradiated (measured at 300V)</td>
</tr>
<tr>
<td></td>
<td>- Each 1 irradiated to 3 and $8 \times 10^{14}$ measured between 100 and 600V</td>
</tr>
<tr>
<td>CiS (Spray)</td>
<td>- 3 unirrad (Gap 20,15 &amp; 30)</td>
</tr>
<tr>
<td></td>
<td>- 2 (gap 20) irradiated to 8 and $11 \times 10^{14}$ measured between 100 and 600V</td>
</tr>
<tr>
<td>CiS (Cross)</td>
<td>- 1 un-irradiated</td>
</tr>
<tr>
<td></td>
<td>- 1 irradiated to $8 \times 10^{14}$ (bad bump-yield)</td>
</tr>
</tbody>
</table>

After many test beam and lab measurements we decided for the p-spray design.
• Use special test structure which “imitates” the biasing structure
• Applied 0.6V (~0.5 * $V_{ana}$)
• Measured the current as function of the back side voltage
  – Some over depletion needed to separate bias grid from pixels
  – No dramatic change with radiation
• Chosen gap of 7 µm
Collect electrons (n-side readout)
- Less prone to trapping
- Larger Lorentz angle
- n-side isolation required

Avoid problems in module design
- N-Substrate
- Guard rings (and junction) on back side
- All sensor edges on ground potential
- Double sided processing

Pixel cell layout
- Moderated p-spray with bias grid
  - Reliable IV measurements prior to flip chip procedure
  - Only moderate over depletion necessary
  - Small partly insensitive area of the order of 2% (not effect on efficiency in CMS)
- Small gaps between implants
  - Homogenous drift field
    - Minimize effect of field separation on charge sharing
    - Avoid flied peaks (high voltage capability in irradiated state)
  - Higher C ~ 80fF (Not critical for performance)
Excursion 2: guard rings

Prevent
- Edge breakdown by gently reducing the potential between diode and edge
- Current injection by preventing the space charge region from reaching the edge

![Diagram of guard rings showing depletion zones and charge injection](image-url)
Collect electrons (n-side readout)
- Less prone to trapping
- Larger Lorentz angle
- n-side isolation required

Avoid problems in module design
- N-Substrate
- Guard rings (and junction) on back side
- All sensor edges on ground potential
- Double sided processing

Pixel cell layout
- Moderated p-spray with bias grid
  - Reliable IV measurements prior to flip chip procedure
  - Only moderate over depletion necessary
  - Small partly insensitive area of the order of 2% (not effect on efficiency in CMS)
- Small gaps between implants
  - Homogenous drift field
    - Minimize effect of field separation on charge sharing
    - Avoid field peaks (high voltage capability in irradiated state)
  - Higher $C \sim 80\text{fF}$ (Not critical for performance)
Bare module

Pixel Sensor with UBM & Indium balls

16 tested CMOS ROC chips with UBM & Indium

Bump bonded “raw module”
Half shell of the detector
Insertion in CMS

Barrel Pixel Detector

Pixel Installation
CMS
- Performance fully satisfactory
- Radiation level is still low but above the point of space charge sign ("type") inversion

Radiation hardness studies
- Up to $\sim 1.2 \times 10^{15} N_{eq}/cm^2$:
  - Several test beam studies in the years 2002-06
  - Including tilt angle, B-field, and threshold
  - Summarized in NIM A 583 (2008) 25-41
- Higher fluences up to $\sim 3 \times 10^{15} N_{eq}/cm^2$
  - Source tests. Dac settings and trimming procedure not 100% settled
- Fluences up to $\sim 5 \times 10^{15} N_{eq}/cm^2$
  - ATLAS IBL (same sensor concept and vendor)

Signal height and detection efficiency fully sufficient for the targeted radiation level of $1.5 \times 10^{15} N_{eq}/cm^2$ ($\sim 250fb^{-1}$ in layer 1 at 3cm)

Increase of bias voltage increase the live time
Value in $r\phi$: ~9 $\mu$m

- Cluster size in $r\phi$-direction ~ 2
  - Lorentz angle presently about 22°
  - High mobility of electrons
  - “Small-gap” implant geometry
Perpendicular to the beam axis

- Lorentz angle is reduced by higher bias voltage
- Process is slow and steady
- Well understood and measured since many years
- No way to prevent this
- Better focusing of charge onto one channel leads to better detection efficiency
**New detector:**
- Very low $\eta$ (cluster length: 1): $\sim 150\mu$m $\times$ $\sqrt{12}$ $\sim 40\mu$m
- “optimum” (cluster length 2): best interpolation possible $\sim 15$-$20\mu$m
- Larger $\eta$ (cluster length $>2$): Interpolation more difficult. Fluctuations in the centre of the cluster do not contain information.
- Reach in average $\sim 28\mu$m (overlap studies)

**In irradiated sensor:**
- Shape of cluster has to be taken into account “template algorithm”)
- If fluence is too high/signal too low:
  - level is low (pitch is smaller than thickness)
  - fluctuations might lead to “hole” in the clusters
  - present software cannot “glue” to clusters together
  - large errors in position determination
- Smaller pitch makes things worse

**Need**
- lower threshold (digital ROC will reach below 2000e)
- powerful software tools to “reconnect” broken cluster, which is difficult in multi track environment inside jets
Outlook

Needs of LHC-experiments are fulfilled by sensors presently available:

- Large areas: p-in-n strips
- Vertexing: n-in-n pixel

Future projects (e.g. LHC upgrade 2) require

- “Outer” layers: improved radiation hardness at same price level → n-in-p sensors
  - High resistive p-material available
  - Same level of radiation hardness as present pixels
  - Might profit from mixed radiation environment ($\pi/n$) in the outer tracker regions
- Pixel layers
  - Level of $\sim 5 \times 10^{15} N_{eq}/cm^2$ or above achieved with present technologies
  - Should consider radiation hardness of read out electronics
  - Easily exchangeable “standard” detector might be the cheapest solution

Other candidate technologies

- 3D sensors
  - Reduce drift distance
  - Proven to deliver high signal at $10^{16} N_{eq}/cm^2$
  - Not attractive for small pixel size (dead area, capacitance)
- Diamond
  - Used in beam monitors at ATLAS, CMS, GSI
  - Polarization effects to be understood
  - Availability of single crystals
Linear Colliders

Here an extremely thin tracker is required
- Very thin
- Little power (air cooling)

One prototype: BELLE II Vertex Detector
- 2 layers at radii = 1.4, 2.2 cm
- Based on DEPFET principle
  - Sensor can store charge
  - 1st amplification on sensor
  - Also used for X-ray astronomy
- Monolithic sensor thickness 75μm
- Pixel size ~50 x 50 μm²
- Rolling shutter mode, 100nsec → S/N=17/1

Final device 75μm thick → X/X₀ = 0.18% !!
(self supporting, no extra mechanics in sensitive region)
Silicon sensors are an interesting and active field

- Requirements to sensors are very different depending on the experiment
- Up to now all requirements were met
- Development is ongoing with high speed