Tracking particles at fluences $1 \times 10^{16} - 1 \times 10^{17} \text{ n/cm}^2$

At HL-LHC, in the inner layers of the tracker, fluences will be of the order of

$$\Phi = 2-3 \times 10^{16} \text{ n/cm}^2$$

- In the present plan, Silicon detectors are replaced once at HL-LHC.

- At FCC (?) fluences will be much higher, let’s suppose $\Phi = 1 \times 10^{17} \text{ n/cm}^2$:
  do we replace the Silicon sensors 10 times at FCC?

**Question:**

Can we design a Silicon tracker that can still work at

$$\Phi = 1 \times 10^{17} \text{ n/cm}^2$$?
Why is it possible? (maybe)

The bottom line is:
Silicon irradiated at fluences $1 \text{E}16 - 1 \text{E}17 \text{ n/cm}^2$ does not behave as expected.

It behaves better

Extrapolations from Silicon sensors irradiated in the fluence range $1 \text{E}14 - 1 \text{E}15 \text{ n/cm}^2$ predict a hopeless situation

Examples:
1) Leakage current saturates
2) Trapping slows down

G. Kramberger et al., *JINST* 8 P08004 (2013).

W. Adam et al 2016
*JINST* 11 P04023
Example: CCE in Silicon up to $2E16$ n/cm$^2$

Degradation of the CC(V) with fluence at 600 and 1000V

Note: regardless of the sensors thickness, the signal at $2E16$ n/cm$^2$ is almost a constant, 3-5k electrons.
Why are the sensors still working?

The depletion is ~ 30 micron for every sensor thickness

Consider the point at 2E16 n/cm²

According to low fluence models, the bulk should be doped N ~ 4E14 n/cm³ and the Efield should be way above breakdown

It should not work, however it does…

Less doped? Smaller mobility?
The plan: use very thin sensors and gain..

At high fluences, 1E16 – 1E17 n/cm², leakage current, bulk doping, and charge trapping are the enemies

➔ use thin sensors
➔ Signal too small

3D sensors decouple drift path and total charge deposition by collecting the charge carriers perpendicularly to the particle path.

Can we decouple drift path and total charge deposition using gain?

Why this can be possible?
• The acceptors creation by irradiation slows down at high fluence, so the bulk is not as doped as we forecast
• Using Vbias, we can still start multiplication if the mobility stays high enough
• The charge to be delivered is rather small: ~ 1-2 fC
How to obtain gain in silicon: $E \sim 300\text{kV/cm}$

1) Use external bias:

$E_{\text{critical}} = \sim 10 - 15 \text{ V/\mu m}$

Possible only in thin sensors:

50 microns need 500-750V

2) Use Gauss Theorem:

$$\sum q = 2\pi r \times E$$

$E = 300 \text{ kV/cm} \Rightarrow q \sim 10^{16} \text{ /cm}^3$

The doping of the bulk will generate the field
Gain and $E_{\text{field}}$ in Si detector: combination of Bias and doping

- **High-resistivity PiN**: Field due to $V_{\text{bias}}$; No contribution from bulk
- **Low-resistivity PiN**: Field due to $V_{\text{bias}}$ and contribution from bulk
- **LGAD**: Field due to $V_{\text{bias}}$ and gain layer doping

Critical field, gain near this line

Field due to $V_{\text{bias}}$ and contribution from bulk
Effect of radiation: increase bulk doping and gain layer removal

Let's start with an LGAD, n-in-p

Fluence $\sim 1E15$ n/cm$^2$ removes the gain layer and add p-doping to the bulk

High resistivity silicon has very flat field

Fluence $\sim 1E16$ n/cm$^2$ the bulk is so doped it cannot be depleted
Gain and $E_{\text{field}}$ in various sensors

**Controlled gain:** it happens when the $E_{\text{field}}$ is controllable by $V_{\text{bias}}$ and the contribution of the doping to the field accounts for a part ($\sim 50\%$) of the total $E_{\text{field}}$. 

(a) Low Gain Avalanche Detector

- Controlled Gain: high $E_{\text{bulk}}$ only in the gain layer
- $V_{\text{FD}}$ ~ $200 - 300$ V

(b) New PiN: $V_{\text{FD}} \ll V_{\text{Bias}}$

- Unstable gain: high $E_{\text{bulk}}$ everywhere in the bulk
- $V_{\text{FD}}$ ~ $700$ V

(c) Medium fluence: $V_{\text{FD}} \sim 0.5 V_{\text{Bias}}$

- Controlled Gain: high $E_{\text{bulk}}$ only near the junction
- $V_{\text{FD}}$ ~ $300$ V

(d) High fluence: $V_{\text{FD}} \gg V_{\text{Bias}}$

- Unstable gain: $E_{\text{bulk}}$ very steep
- $V_{\text{FD}}$ ~ $150$ V
E Fields vs irradiation

The field changes a lot, due to the appearance of the “double junction”, caused by high leakage current.
Look at the first 20-40 um: very uniform field
What type of Si detector can deliver 1fC from un-irradiated to a fluence $=1E17 \text{n/cm}^2$

We need to have a plan to deliver at least $1 \text{ fC}$ throughout the sensor lifetime. In thin sensors you need to have always gain.

Can we use a thin PiN diode?

In high resistivity silicon, the field is almost constant in the sensor,
- It reaches the critical value at the same voltage everywhere in the detector
- It burns the sensors

![Graph showing E Amplitude IEI (kV/cm) - Dashed: breakdown field.

No good: EField: high everywhere](image)
Is gain in high-resistivity PIN reliable?

Not really…. We cannot start with a thin PiN diode
The plan - I

- Select a thickness that can still be depleted after a fluence ~ 1E17 n/cm²
- Bias should be in control of the multiplication mechanism

Assuming standard rate of acceptor creation, a thickness of ~ 20 micron should be OK

Such thin detector will not provide enough charge

→ use an LGAD of ~ 20-30 micron (0.2 – 0.3 fC)
→ Gain ~ 5 – 10 is enough

Let’s start with an LGAD, n-in-p

Less gain layer and more p-doping to the bulk
The plan - II

2) In the $\sim 0.5 - 1 \times 10^{16}$ n/cm$^2$
   - The gain layer doping is removed
   - The gain from $V_{bias}$ and the bulk doping starts to be important

3) Above $5 - 10 \times 10^{15}$ n/cm$^2$: this is the fun part…

Condition to have gain:
1. High $E_{field}$
2. The width of a space charge region $>>$ the mean free path between two ionizing impacts

Irradiation decreases the mean free path, so even if the field is high, the sensors are not in breakdown, the gain is quenched, but maybe still reachable in thin sensors

Limiting fluence: Bias barely manages to deplete the sensors
Gain termination for 100% fill factor: trenches

**Trenches** (the same technique used in SiPM):
- No pstop,
- No JTE \(\Rightarrow\) no extra electrode bending the field lines

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**Trench isolation technology**

- Typical trench width < 1 um
- Max Aspect ratio: 1:20
- Trench filling with: \(\text{SiO}_2\), \(\text{Si}_3\text{N}_4\), PolySi

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Conclusions

**Goal: design a simple sensor that can deliver good signals for fluences $1E16 - 1E17 \text{n/cm}^2$**

In the sensor lifetime, there will be the interplay of 3 types of gain:

- Due to Gain Layer
- Due to $V_{bias}$
- Due to the bulk doping

**Below 2E15 n/cm$^2$**
- Start with thin LGAD sensors
- It looks possible to have a gain of ~ 5 without breakdown
- $V_{bias}$ and gain layer doping controls gain

**Range 5 - 10E15 n/cm$^2$**
- The initial gain layer is disactivated,
- gain comes from $V_{bias}$ and bulk doping

**above 1E16 n/cm$^2$**
- is the gain still there?
- Is the mobility decreasing to a point where no gain is possible?
- Damaged bulk acts as a quenching resistor?
- No holes multiplications?
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