Tracking particles at fluences 1E16 – 1E17 n/cm^2

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

Φ = 2-3E16 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 Φ = 1E17 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 Φ = 1E17 n/cm^2 ?

Why is it possible? (maybe)

The bottom line is:

Silicon irradiated at fluences 1E16 – 1E17 n/cm^2 does not behave as expected,

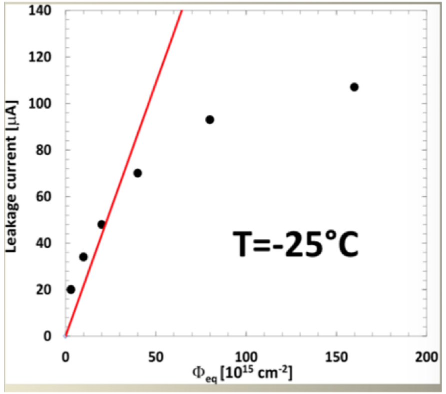
it behaves better

Extrapolations from Silicon sensors irradiated in the fluence range 1E14 – 1E15 n/cm^2 predict a hopeless situation

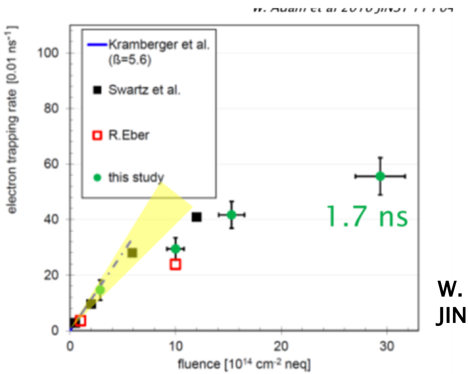
Examples:

1) Leakage current saturates

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



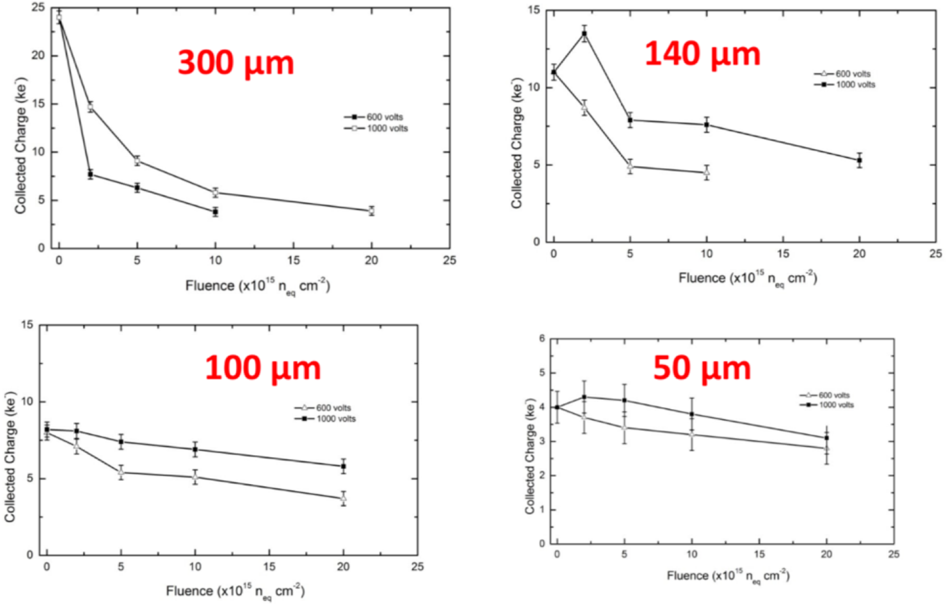
2) Trapping slows down



W. Adam et al 2016
JINST 11 P04023

Example: CCE in Silicon up to 2E16 n/cm2

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

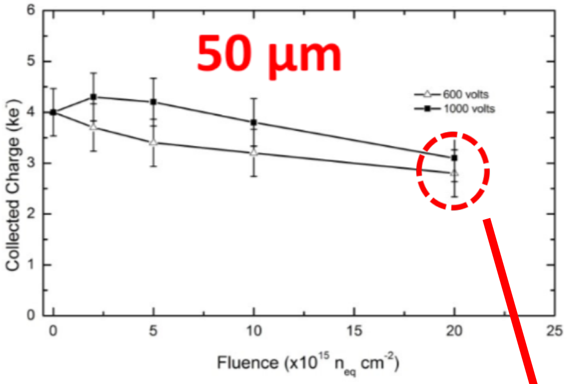


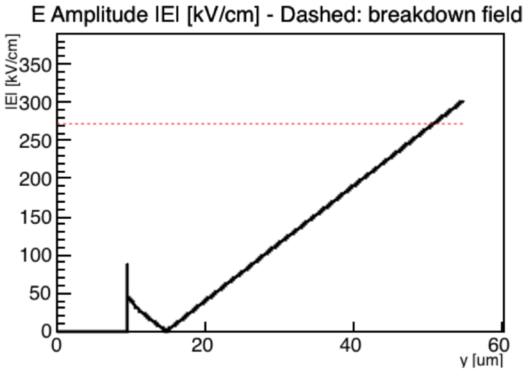
S. Wonsak, RD50, 02-04 Dez. 2015, CERN

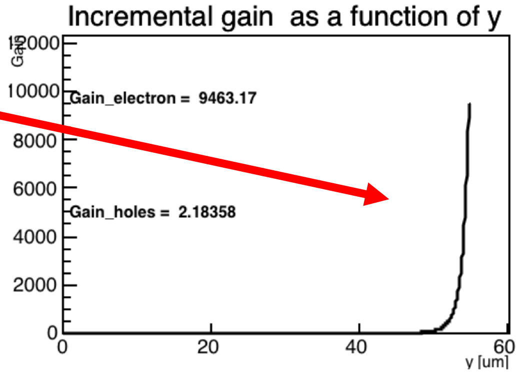
Note: regardless of the sensors thickness, the signal at 2E16 n/cm2 is almost a constant, 3-5k electrons.

Why are the sensors still working?

The depletion is ~ 30 micron for every sensor thickness







Consider the point at 2E16 n/cm^2

According to low fluence models, the bulk should be doped N ~ 4E14 n/cm^3 and the Efield should be way above breakdown

It should not work, however it does…

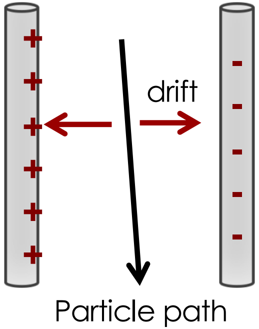
Less doped? Smaller mobility?

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

Use gain



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?

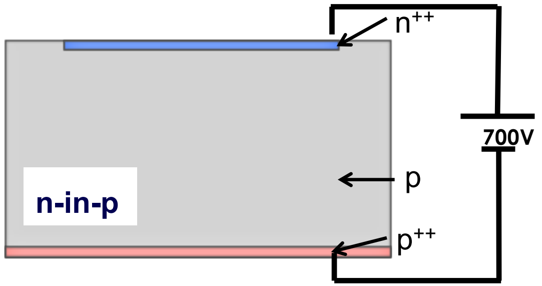
- The acceptors creation by irradiation slows down at high fluence, so the bulk is not as doped as we forecast
- Using Vbias, we can still start multiplication if the mobility stays high enough
- The charge to be delivered is rather small: ~ 1-2 fC

How to obtain gain in silicon: E ~ 300kV/cm

1) Use external bias:

E critical = ~ 10-15 V/µm

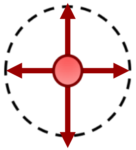
Possible only in thin sensors:
50 microns need 500-750V

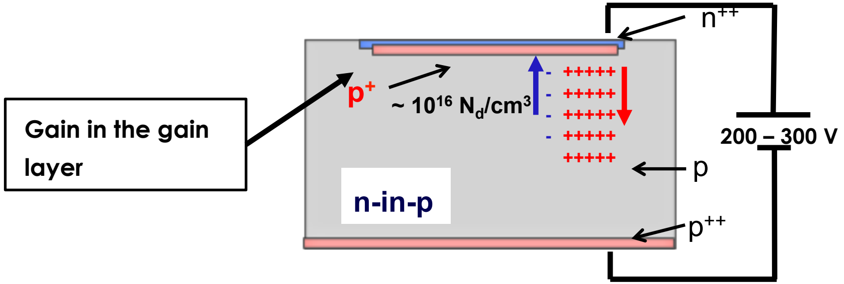


Traditional silicon detector

2) Use Gauss Theorem:

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



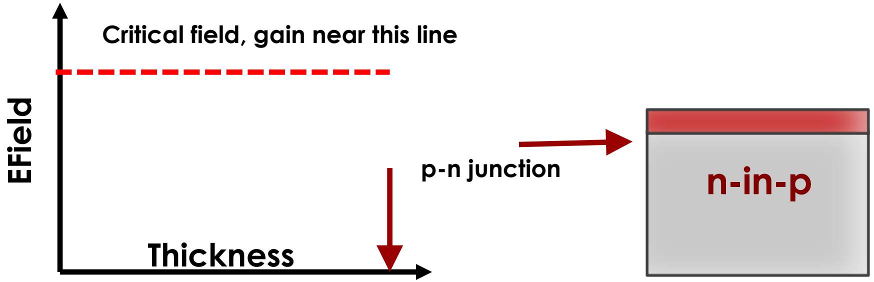


Low gain avalanche detectors

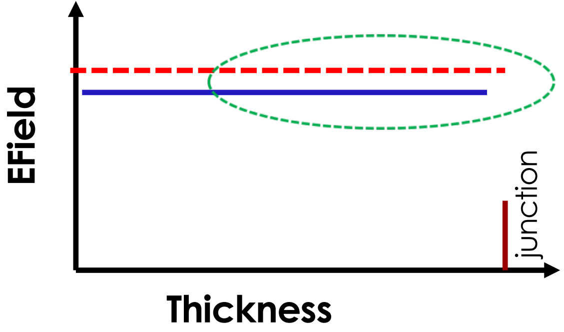
E = 300 kV/cm ➔ q ~ 10^{16} /cm^3

The doping of the bulk will generate the field

Gain and E_{field} in Si detector: combination of Bias and doping

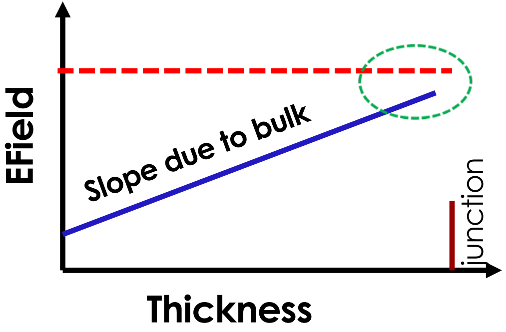


High-resistivity PiN



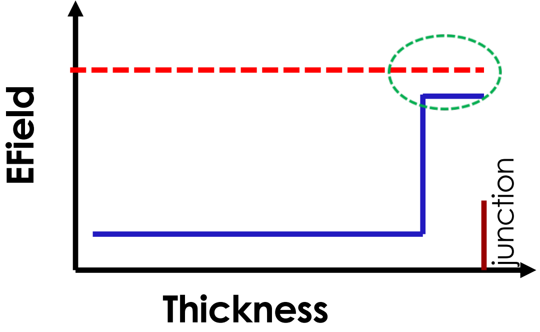
Field due to Vbias
No contribution from bulk

Low-resistivity PiN



Field due to Vbias and
contribution from bulk

LGAD

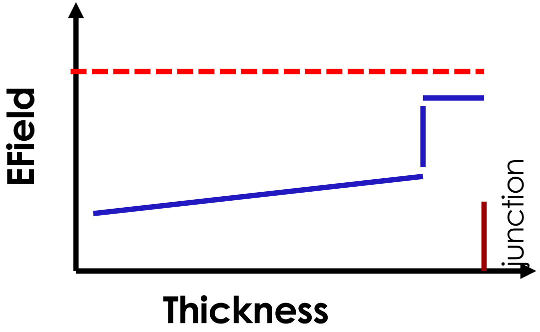


Field due to Vbias and
gain layer doping

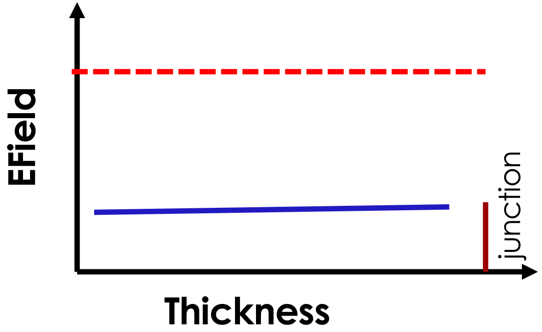
Effect of radiation: increase bulk doping and gain layer removal

Let’s start with an LGAD, n-in-p

irradiation

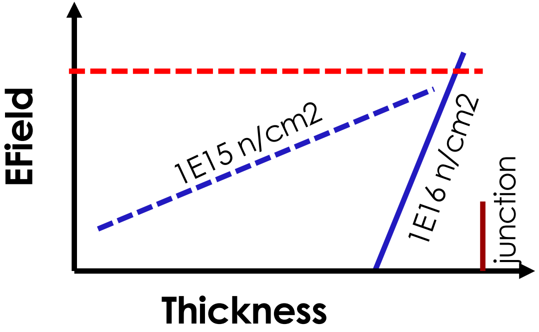


Fluence ~ 1E15 n/cm2 removes the gain layer and add p-doping to the bulk



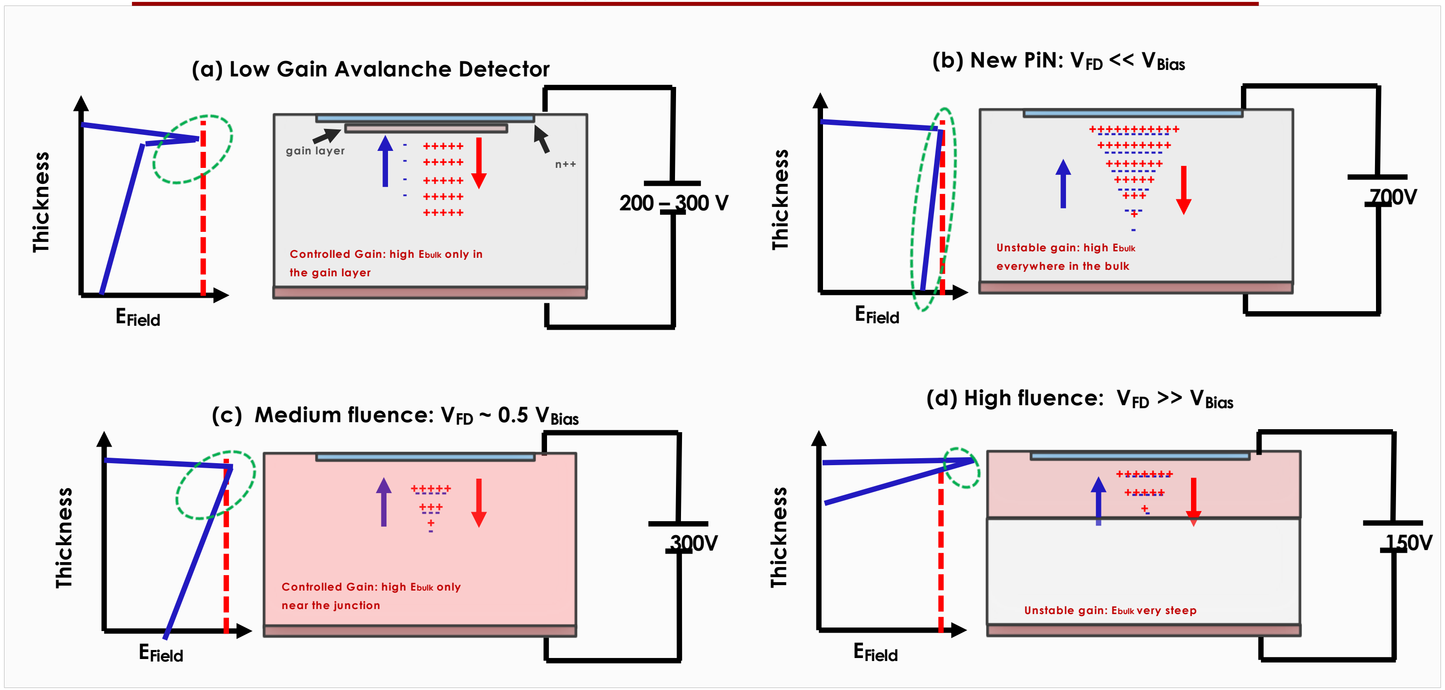
High resistivity silicon has very flat field

irradiation



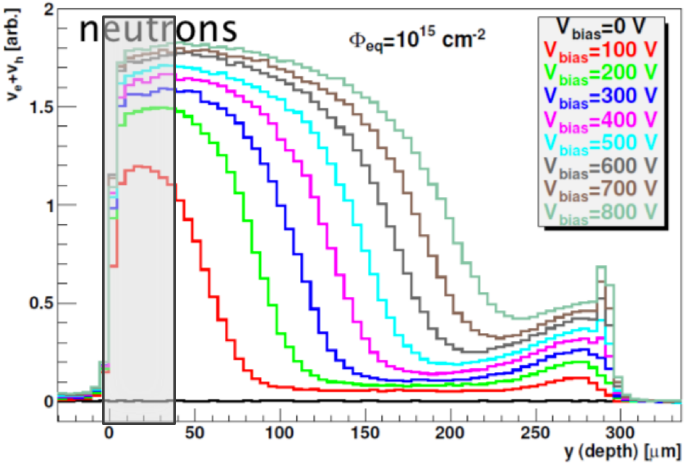
Fluence ~ 1E16 n/cm2 the bulk is so doped it cannot be depleted

Gain and E_{field} in various sensors

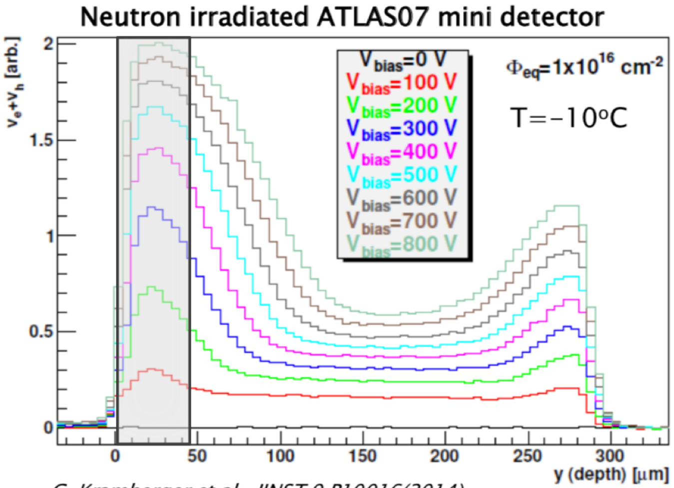


Controlled gain: it happens when the E_{field} is controllable by V_{bias} and the contribution of the doping to the field accounts for a part (~ 50%) of the total E_{field}

E Fields vs irradiation



G. Kramberger et al., JINST 9 P10016(2014).



G. Kramberger et al., JINST 9 P10016(2014).

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 =1E17n/cm2

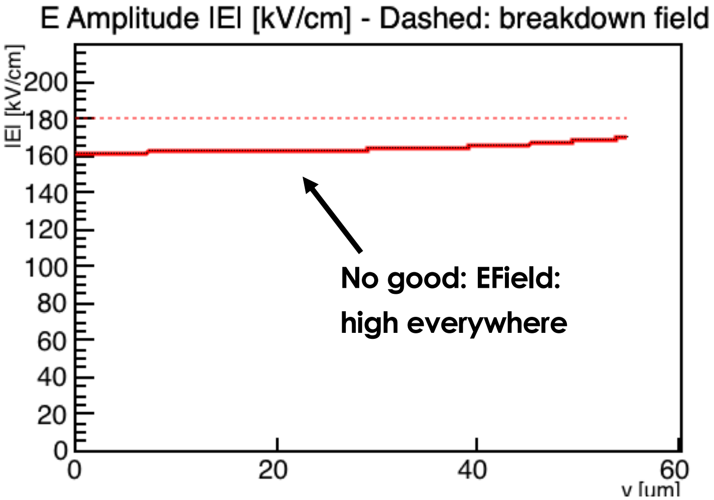
We need to have a plan to deliver **at least1 fC** throughout the sensor lifetime. In thin sensors you need to have always gain

Can we use a thin PiN diode?

In high resistivity silicon, the field is almost constant in the sensor,

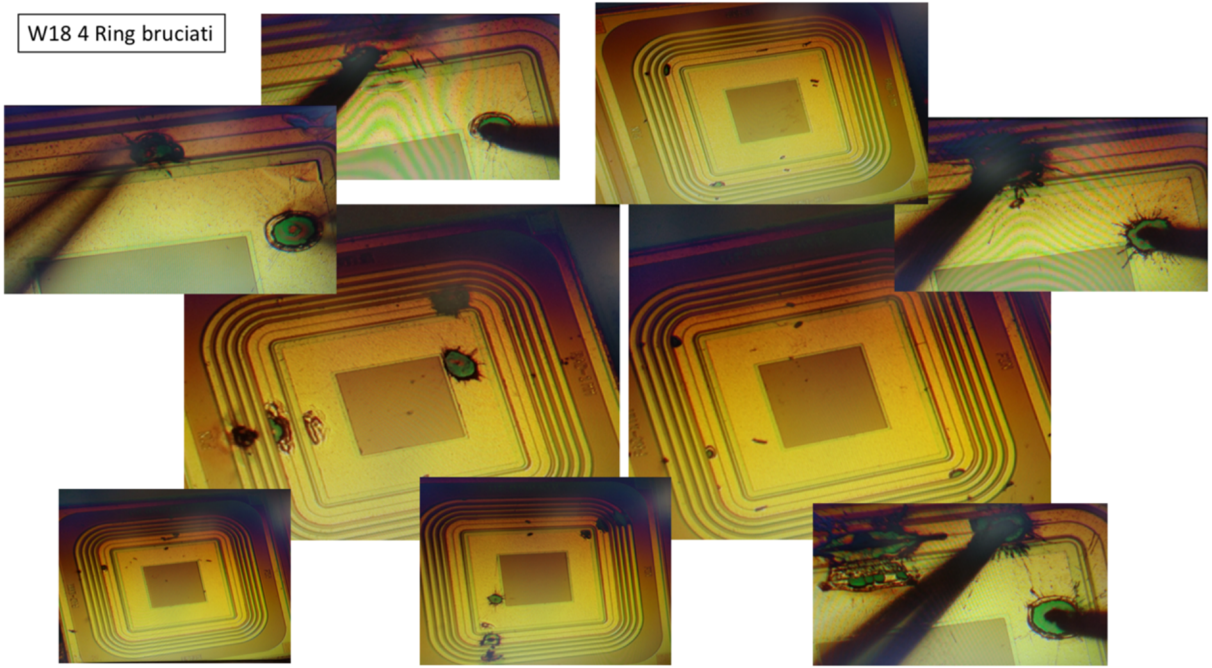
➔ It reaches the critical value at the same voltage everywhere in the detector

➔ It burns the sensors



No good: EField: high everywhere

Is gain in high-resistivity PIN reliable?

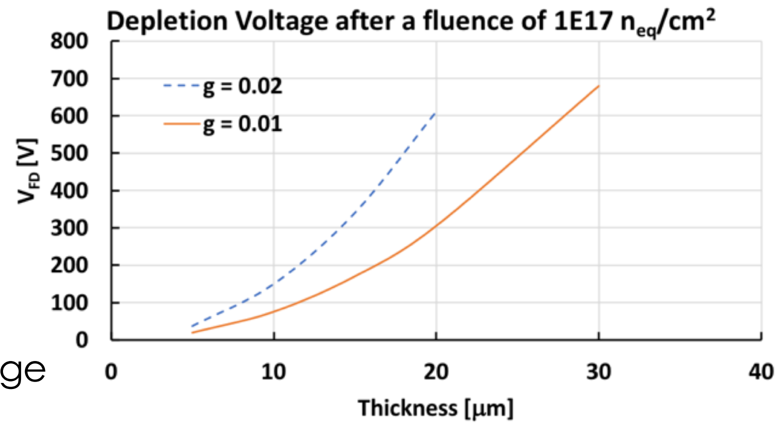


Not really…. We cannot start with a thin PiN diode

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

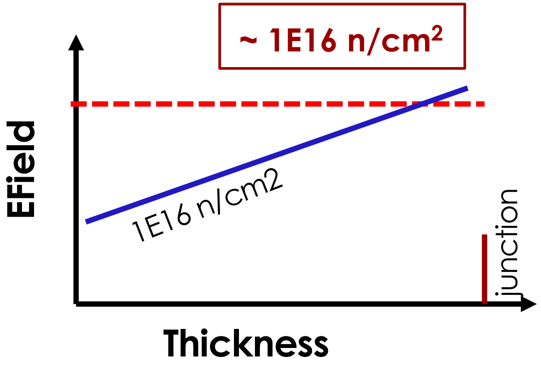
Let’s start with an LGAD, n-in-p

Less gain layer and more p-doping to the bulk

The plan - II

2) **In the ~ 0.5- 1E16 n/cm^2**

- The gain layer doping is removed
- The gain from V_{bias} and the bulk doping starts to be important

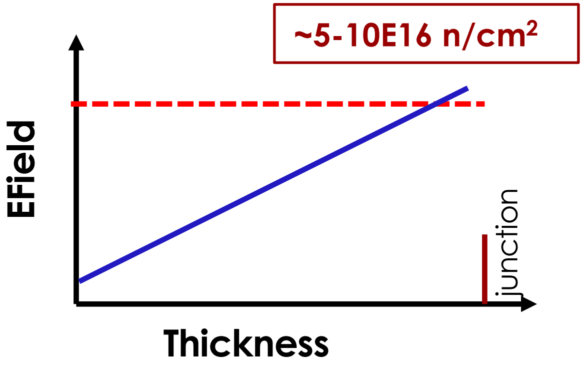


the bulk contribution start to be important

3) **Above 5-10 E15 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



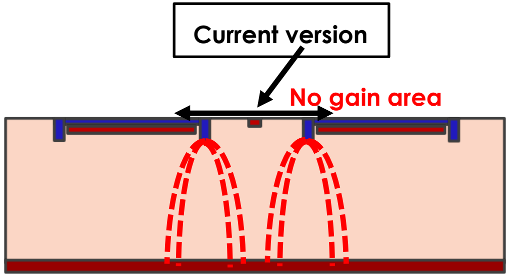
Limiting fluence: Bias barely manages to deplete the sensors

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

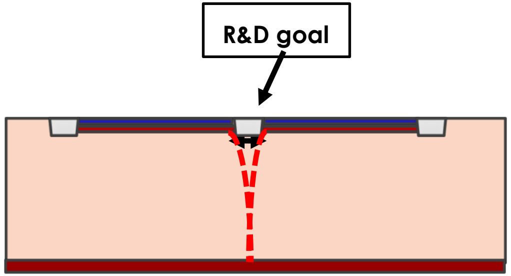
Gain termination for 100% fill factor: trenches

Trenches (the same technique used in SiPM):

- No pstop,
- No JTE ➔ no extra electrode bending the field lines



JTE + p-stop design

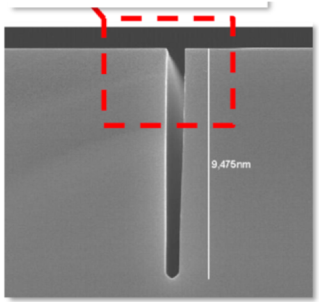


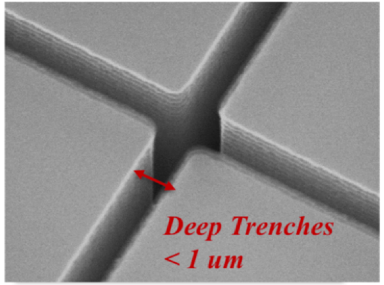
Trench design

Trench isolation technology

- Typical trench width < 1 um
- Max Aspect ratio: 1:20
- Trench filling with: SiO_2, Si_3N_4, PolySi

CMM
CENTRE FOR MATERIALS AND MICROSYSTEMS





Conclusions

Goal: design a simple sensor that can deliver good signals for fluences 1E16 – 1E17 n/cm²

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

- Due to Gain Layer
- Due to Vbias
- Due to the bulk doping

Below 2E15 n/cm²

➔ 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/cm²

➔ The initial gain layer is disactivated,

➔ gain comes from V_{bias} and bulk doping

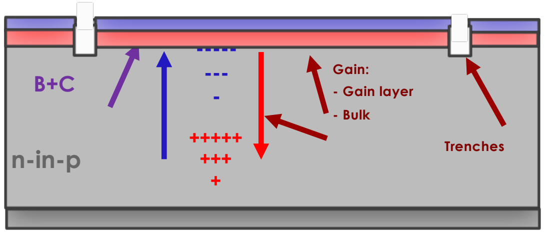
above 1E16 n/cm²

➔ 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?



25 microns LGAD trench sensor

Good signal above 1E16 n_{eq}/cm² ?

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