Simulation of irradiated silicon detectors: an update

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Motivation

• SLHC vs LHC: larger fluences, higher track density, faster readout.
• Silicon detectors operation will require fast, rad-hard, sensitive front-end electronics, smaller pixel size, new (more rad-hard) sensors (DOFZ, Cz, epitaxial, thin silicon, ?)
• Simulation of irradiated silicon detectors allows
  – To connect material properties (\(N_{\text{eff}}\) and fluence) with detector performance
  – To understand the effect of geometry (electrode size and thickness) on performance
  – To understand if silicon detectors can be operated with high efficiency at fluence around \(10^{16}\) cm\(^{-1}\)
Our simulation

From parameterizations of $N_{\text{eff}}$ and lifetime as a function of fluence/annealing it computes the performances of irradiated silicon pixel detectors for different

- materials
  - StFZ, DOFZ, epi Si, Cz
- doping
  - n+/p, p+/n
- geometries
  - pixel size, thickness
- operating conditions
  - bias, temperature
- front-end electronics parameters
  - threshold, noise
What is new?

In November, we have presented results for StFZ, DOFZ, thin DOFZ detectors with ATLAS pixel size (50 x 400 µm²)

(Main) upgrades:
• added Cz and epitaxial Si.
• Pixel size is now a job parameter (strip simulation also possible). This talk: smaller pixel size (70 x 70 µm²) to cope with increased track density at SLHC (use 0.13 µm electronics?).
• Pulse time profile and charge collection time.
Basics of simulation

- Ionizing particles interactions in the sensors simulated with **Geant4**
- **Charge drift** in silicon (drift, diffusion, trapping).
- Signal induced on pixel electrodes with **Ramo** potential
- **Front-end electronics** response (threshold, noise)
- See the presentation of November for more detailed info.
Small pixels vs pad diode

- In a detector with small electrodes most of the signal comes from charges moving near the electrodes.
- Example: in a 250 μm thick detector with 50 μm depletion a charge traversing the depleted region would give 80% CCE on the nearest pixel. The response of a pad detector (= sum of negative and positive signals on all pixels) is only 20% of the charge!

In this talk the charge collected is the sum of positive signals (because of electronics threshold, negative signals are useless). Can be very different from pad diode CCE.
Electric field

- The field distribution in irradiated silicon has a double peak structure and is a function of dose and temperature. [1-3]
- Power consumption and noise issues require operation at low (about -10°C) temperature to control leakage current.
- At these temperatures the linear field approximation is good for small strips/pixels: charge drift far from the electrodes contributes very little to detector response.

[2] V. Eremin et al., NIM A360, 458
[3] V. Eremin et al., NIM A476, 556

Presently we use the linear field approximation.
Comparison with data

Simulation validated with experimental data

Comparison with ATLAS Pixel detectors irradiated to $1.1 \times 10^{15}$ n$_{eq}$ cm$^{-2}$

All parameters from measured values [4-5]

Radiation damage

- $N_{\text{eff}} = g\Phi$
  - $g = 0.023 \, \text{cm}^{-1}$ StFZ
  - $g = 0.009 \, \text{cm}^{-1}$ DOFZ
  - $g = -0.009 \, \text{cm}^{-1}$ Cz
  - $N_{\text{eff}} = -5.79 \times 10^{13} \, \text{cm}^{-3}$ epitaxial ($V_{\text{fd}} = 100 \, \text{V}$ for 50 $\mu\text{m}$ sensor)
- $1/\tau = \beta\Phi$
  - $\beta_e = \beta_h = 5 \times 10^{-16} \, \text{cm}^2/\text{ns}$

At high fluences charge collection is limited by trapping mean free path

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The readout have been chosen to be on the side where the electric field is maximum after irradiation, since this choice results in a better CCE and allows operation in partial depletion mode:

- n-side readout for FZ and DOFZ
- p-side readout for Cz
- p-side readout for epitaxial (first RD50 samples had n-type bulk).
Other parameters

- Thickness 250 µm (as in ATLAS), 50 µm for epitaxial (as first RD50 samples). See November’s talk for a DOFZ threshold scan.
- Temperature = -10 °C
- Bias voltage: 600 V irradiated FZ and Cz (as in ATLAS), 150 V not irradiated and epitaxial.
- Zero incidence angle, no magnetic field

With these parameters leakage current for DOFZ detectors after $10^{16} n_{eq} \text{ cm}^{-2}$ is
- 2x smaller (per pixel): less shot noise (35 e for 10 ns integration time)
- 2x larger (per unit area): more power consumption than for ATLAS pixels after $10^{15} n_{eq} \text{ cm}^{-2}$ (larger fluence compensated by smaller active volume and temperature)

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**Charge Collection Vs Fluence**  

10^{15} fluence:  
- DOFZ better than StFZ when the latter is no longer fully depleted at 600 V  
- DOFZ slightly better than Cz (because of n-side signal)  
- epitaxial signal very low (because of thin sensor)  

10^{16} fluence:  
- All detectors are similar (trapping dominant)  

Results should be very similar for strip detectors
Charge collection vs bias voltage

$\Phi = 10^{15}$ n/cm$^2$ : Cz and DOFZ fully depleted at 440 V, epitaxial at 100 V. Signal increases up to full depletion voltage and is (almost) constant above it.

$\Phi = 10^{16}$ n/cm$^2$ : Cz and DOFZ fully depleted at 4400 V, epitaxial at 100 V. Signal limited by trapping gradually saturates as drift velocity approaches the high-field limit.
Charge versus epi thickness

• Charge collected after $10^{16}$ n/cm$^2$ as a function of sensor thickness (assuming full depletion)
• First RD50 samples were 50 µm thick (2100 electrons).
• Asymptotic value is 3000 e$^-$, when the thickness is much larger than the mean free path (20 µm) and the pixel dimensions: charges drifting far from pixels/strip does not contribute to signal.
• Thicker samples are thus predicted to have a significantly larger signal
Threshold and detection efficiency

- The minimum charge which is detected within the trigger window is the in-time threshold.
- ATLAS Pixel detectors irradiated to $10^{15}$ n$_{eq}$ cm$^{-2}$ achieve a detection efficiency of 98.2% with an in-time threshold (at 40 MHz) of about 5000 e$^-$. 
- After $10^{16}$ n$_{eq}$ cm$^{-2}$ an in-time threshold of 1000 e$^-$ is needed (at 80 MHz) to have 97% detection efficiency.

Big challenge for front-end electronics!
Collection time

With stronger irradiation the signal on electrodes is faster (lower depletion, stronger electric field, shorter lifetime). For thin epitaxial sensors signal is always collected within 1 ns.
Conclusions

- The performance of pixel detectors using different silicon materials was simulated after irradiation up to $10^{16} \text{n}_{\text{eq}} \text{cm}^{-2}$.
- At the highest fluence, mean signal is **2000-2500 electrons** regardless of material, limited by charge trapping.
- Signal is lower if the thickness is below 100 $\mu\text{m}$.
- Sensitivity to **1000 electrons** (fast and low noise rad-hard front-end electronics) is required to operate with high (97%) detection efficiency.