Silicon Sensors for Extreme Fluences

QUESTIONS

✎ Is it possible to design a silicon sensor able to work in the fluence range $10^{16} - 10^{17} \, n_{eq}/cm^2$?

If so

✎ Does such sensor generate enough charge to be used in a detector exposed to extreme fluences?

⇒ The R&D to answer these questions is starting now
EFFECTS OF RADIATION ON SILICON SENSORS

Irradiation results in 3 main effects:

- Decrease of the collected charge due to trapping effects
- Increase of the dark current
- Change in effective doping
  → increase of the reverse bias to operate the sensor
  → distortion of the electric field inside the sensor

Irradiation models developed in the fluence range $10^{14} - 10^{15}$ $n_{eq}/cm^2$ predict standard silicon detectors ($\sim 200 \, \mu m$) are almost impossible to operate.
SOME OPTIMISM – SATURATION

At fluences above $5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \rightarrow \text{Saturation of radiation effects observed}$

Leakage current saturation

\[ I = \alpha \sqrt{\Phi} \]

$\alpha$ from linear to logarithmic

Trapping probability saturation

\[ \frac{1}{\tau_{\text{eff}}} = \beta \Phi \]

$\beta$ from linear to logarithmic

Silicon detectors irradiated at fluences $10^{16} - 10^{17} \text{n}_{\text{eq}}/\text{cm}^2$ do not behave as expected $\rightarrow$ They behave better

[G. Kramberger et al., doi:10.1088/1748-0221/8/08/P08004]

[G. Kramberger et al., doi:10.1016/j.nima.2018.08.034]

Acceptor-like defect creation

Accepter creation saturation

\[ N_{A,\text{eff}} = g_c \Phi \]

$g_c$ from linear to logarithmic

[O. Ferrero et al., 34th RD50 Workshop, Lancaster, UK]
WHY SATURATION?

Possible explanation:

The distance between two atoms, the so called Silicon radius, is

\[ r_{\text{Si}} = 1.18 \cdot 10^{-8} \text{ cm} \]

The probability that a circle of radius \( r_{\text{Si}} \) has been crossed by a particle becomes 1 at \( 10^{16} \) particles/cm\(^2\)

Above \( 10^{16} \) particles/cm\(^2\):

damage happening on already damaged Silicon might be different
GO THIN

\[ V_{FD} = e |N_{eff}| d^2/2\varepsilon \]

**Saturation**

**Reduce thickness**

Thanks to saturation effects, thin sensors can still be depleted and operated at \( V_{bias} \leq 500 \text{ V} \)

**What does it happen to a 25 \( \mu \text{m} \) sensor after a fluence of \( 5 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2 \)?**

- It can still be depleted
- Trapping is almost absent
- Dark current is low (small volume)

**However:** charge deposited by a MIP \( \sim 0.25 \text{ fC} \)

\[ \rightarrow \text{This charge is lower than the minimum charge requested by the electronics (~1 fC)} \]

\[ \rightarrow \text{Need a gain of at least ~ 5 in order to provide enough charge} \]
Impact ionisation occurs when $E_{\text{field}} > E_c = 250$ kV/cm

→ How to get internal multiplication of 5-10? Stable gain if:

1) $E_{\text{field}} > E_c$ for a short distance
2) This length is controlled by applied $V_{\text{bias}}$

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### Depth

**n-in-p**

- $p \sim 10^{12}$ cm$^{-3}$
- $E_{\text{field}}$ above $E_c$ over long distance

**AVALANCHE**

- $p \sim 10^{14}$ cm$^{-3}$
- Difficult to precisely control $E_{\text{field}}$

**RISK OF AVALANCHE**

- LGAD
- $p \sim 10^{12}$ cm$^{-3}$, $p^+ \sim 10^{16}$ cm$^{-3}$
- $E_{\text{field}}$ above $E_c$ for short distance well controlled by $V_{\text{bias}}$

**CONTROLLED GAIN**
Start with a thin LGAD, 20 – 35 µm thick (to be optimized)

- $2 \cdot 10^{15} - 5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$: with increasing fluence, the gain layer is deactivated

- $5 \cdot 10^{15} - 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$: compensate the decrease power of the gain layer by shifting the multiplication region to the bulk

- $10^{16} - 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$: rely solely on bulk multiplication

→ Does bulk multiplication exist at these fluences?
Thinner sensors provide higher gain after irradiation

Predictions from Weightfield2 using van Overstraeten – de Man model for 20 and 30 µm thick sensors, providing 5 fC of charge at 120 V when new

[R&D efforts with the FBK foundry]

R&D on the gain layer to retard multiplication shift from the gain layer to the bulk region

Defect engineering and different gain layer implantation strategies will be investigated
INFN awarded for funding the Silicon Sensor for Extreme Fluences (eXFlu) project[*] to develop, produce, irradiate and study thin silicon sensors (V. Sola as PI)

The eXFlu project aims to

→ Optimise the design of thin silicon sensors
→ Measure the onset and the magnitude of saturation effects in thin sensors
→ Map the shift of multiplication from the gain layer to the bulk
→ Study the signal multiplication mechanism in highly irradiated sensors – does it disappear at very high fluences?
→ Collaborate with colleagues to extend radiation damage models (RD50, Perugia, ...)

[*] Award funding for one over six projects presented by young researchers in the fields of research and technological development carried out by the Institute (Announcement No.21188)
Involved institutes:
INFN Torino and FBK

Work Packages:
WP1: sensor simulation and design
WP2: sensor production
WP3: irradiation (n, p, π ...)
WP4: laboratory characterisation and signal analysis
WP5: beam test

Total budget:
~ 130k euro
A key aspect of eXFlu project is to be able to perform measurement on irradiated sensors at low temperatures

→ Preparation of cold setups in progress

MPI TS200-SE Manual Probe Station with temperature range from -40 to +300°C will arrive soon in Torino Laboratory

Vötsch VCL4010 Test Chamber with temperature range from -40 to +180°C available in Torino Laboratory

Particulars Large Scanning TCT setup connected to Lauda chiller down to -20°C available in Torino Laboratory
eXFlu EXPECTED OUTCOMES

- Measure silicon properties in an unexplored region of radiation fluences
- Study of saturation of radiation effects in thin silicon sensors
- Understanding of impact ionisation mechanism in highly irradiated sensors
- Contribute to building models for very irradiates silicon detectors

⇒ The ultimate goal is to pave the way for the design of silicon sensors able to efficiently record charged particles up to $10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$ and beyond
We kindly acknowledge the following funding agencies, collaborations:

- Horizon 2020, grant INFRAIA
- Horizon 2020, grant UFSD669529
- AIDA-2020, grant agreement no. 654168
- U.S. Department of Energy, grant DE-SC0010107
- Ministero degli Affari Esteri, Italy, MAE, “Progetti di Grande Rilevanza Scientifica”
- MIUR, Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337)
- Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia, FARE, R165xr8frt_fare
- INFN, Gruppo V
- RD50, CERN
BACKUP
HOW THIN?

To efficiently record a hit, electronics require at least 1 fC

MPV charge from a MIP crossing silicon ~ 75 e-h/µm
50 µm thick → 0.5 fC
20 µm thick → 0.2 fC

Signal multiplication by a factor of 5-10 is needed
UFSD suffer for gain reduction due to irradiation.

FBK used both Boron and Gallium as gain layer dopant, and added Carbon in the gain layer volume.

⇒ The usage of Carbon double the radiation hardness of UFSD.
UFSD suffer for gain reduction due to irradiation.
FBK used both Boron and Gallium as gain layer dopant, and added Carbon in the gain layer volume.

⇒ The usage of Carbon double the radiation hardness.
Goal: retard multiplication transition from the gain layer to the bulk region

Acceptor removal:
\[ N_{A,\text{eff}} = N_{A,0} \cdot e^{c\Phi} \]

Adding carbon protects boron from removal
Different carbon concentrations have different impact on boron protection

→ Gain layer engineering to extend its contribution to \(5 \cdot 10^{16} \text{n}_{\text{eq}}/\text{cm}^2\)

Possible?

[M. Ferrero et al., doi: 10.1016/j.nima.2018.11.121]
**Goal:** retard multiplication transition from the gain layer to the bulk region

Acceptor removal:

\[ N_{A,\text{eff}} = N_{A,0} \cdot e^{c \Phi} \]

Defect engineering and different gain layer implantation strategies will be investigated

\[ c \cdot N_{A,0} = 60 \text{ cm}^{-1} \rightarrow < 10 \text{ cm}^{-1} \]

for \( N_{A,0} = 10^{17} \text{ atoms/cm}^3 \)
\[ N_{A,\text{eff}}(\Phi) = g_c \cdot \Phi + N_A(0) \cdot e^{-c \cdot \Phi} \]
The eXFlu project consists of 2 Research Units: one centered on the sensor design, irradiation and test (INFN – Torino) while the other on the sensor fabrication (FBK)

➢ INFN, Torino

➢ Valentina Sola (PI), particle physicist expert both in data analysis and detector R&D, involved in the development and characterisation of Ultra-Fast Silicon Detectors, actively participating to laboratory and beam tests, organisation of irradiation campaign, and supervision of students

➢ Simona Giordanengo, researcher at INFN Torino; Ennio Monteil, technician at the Physics Department of the University of Torino; Marta Tornago, Ph.D. student at Torino University

➢ FBK, Trento

➢ Maurizio Boscardin, senior researcher at Fondazione Bruno Kessler in Trento; Giacomo Borghi, researcher at Fondazione Bruno Kessler in Trento

→ The team includes a diverse composition of expertise, well fitted to the project
→ The project can rely on a fully functional laboratory
# eXFlu BUDGET TABLE

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Next generation high-energy and high-intensity hadronic collider → FCC-hh

FCC-hh reference detector

Running conditions:
- Pile-up per bunch crossing ~ 1000
- Vertex region $\sigma_z \sim 44$ mm, $\sigma_t \sim 165$ ps
- Average distance between vertices at $z = 0$ is 125 $\mu$m

Tracker requirements:
- $\sigma_{r\phi} = 7.5 - 9.5$ $\mu$m
- Low material budget $N_{\text{layers}} = 12$
- Effective pile-up = 1 $\sigma_t = 5$ ps
RADIATION BUDGET - TRACKER VOLUME

Fluence foreseen at $L_{\text{int}} = 30 \text{ ab}^{-1}$

![Graph showing radiation budget with Z in meters on the x-axis and R in centimeters on the y-axis. The color scale represents 1 MeV neutron equivalent fluence in $\text{cm}^{-2}$. The image is courtesy of M.I. Besana.](image-url)