“Why p-type is better than n-type?” or
Electric field in heavily irradiated silicon detectors

G. Kramberger, V. Cindro, I. Mandić, M. Mikuž, M. Milovanović, M. Zavrtanik
Jožef Stefan Institute
Ljubljana, Slovenia
Outline

- Introduction
- Technique(s)
- Electric field profile in FZ p–type detectors
  - where does the well known device model break down?
  - electric field in the neutral bulk
  - long term annealing behavior
- Impact of irradiation particle
- Homogeneity of the response over the strip/charge sharing (Top-TCT)
- What about MCz-n?
- Conclusions
Why $n^+ \text{ readout is better} – \text{ in short?}$

It is a “common knowledge” today that in harsh radiation environments:

1. “electrons should be collected” at the segmented side
   - less trapping $\mu_e \tau_e > \mu_h \tau_h$
   - favorable weighing field

2. performance in terms of CCE improves with higher the voltage more that expected – effects of multiplication

If the field (blue region) shrinks with fluence the electric field becomes larger and at very high voltages result in impact ionization = multiplication of the charge.

$p^+$ diode $\quad n^+$ diode

Segmented readout

$$\text{small} \quad (\bar{E}_w \bar{E})$$

worse $\text{ better}$

even worse: $p^+$ readout (p$^+$-n detector)

even better: $n^+$ readout (n$^+$-p, n$^+$-n detector)

$$\text{large} \quad (\bar{E}_w \bar{E})$$

electrons
But:
• It is not clear what the E field is - our device model is unclear
• It is not clear what are the long term annealing effects
• It is not clear if the charge collection is homogenous in the cell area (implants)
• What about MCz?
Measuring induced currents with fast current amplifiers after e-h generation with the laser pulse!


Probing the field in depth (average)
- Charge collection profile: \( Q(y) = \int_0^{2\alpha ns} I(y, t) dt \)
- Velocity profile: \( I(y, t \sim 0) \propto (v_e + v_h)(y) \)

Probing the lateral field (average)
- Properties of the mid-strip region
- Multiplication profiles
- Trapping induced charge sharing

**n+p SSD detectors (1x1 cm\(^2\)) of ATLAS geometry (300 um, 75-100 um pitch)**
a textbook behavior of non-irradiated sample ($V_{fd}$, no field region ...)
maximum velocity is similar for all fluences – almost saturated at the strips
For the first time in highly irradiated silicon detector one can directly probe the electric field profile

- The velocity profile (i.e. electric field) has a "double junction profile", high field region at the strips and back with lower field region between.
- The border between the regions is defined by \( y_{\text{act}} \) and \( y_{\text{back}} \) defined as shown in the figures.

\[
\begin{array}{c}
\text{irradiated} \\
\text{p bulk}
\end{array}
\]

\[
\begin{array}{c}
\text{main} \\
\text{junction}
\end{array}
\]

\[
\begin{array}{c}
\text{active bulk} \\
\text{highly} \\
\text{resistive}
\end{array}
\]

\[
\begin{array}{c}
y_{\text{act}} \\
y_{\text{back}}
\end{array}
\]

\[
\begin{array}{c}
N_{\text{eff}}<0 \\
N_{\text{eff}}=0
\end{array}
\]

Electric field

"double junction profile"

D. Menichelli et al., NIM A426 (1999) 135.,
I. Mandic et al., NIM A512 (2004) 343 and many, many more …
**Electric field - main junction** ($y_{\text{act}}$)

Hamburg model (everybody knows it is questionable at high fluences yet it is still used)

$$y_{\text{act}} = \sqrt{\frac{2\varepsilon\varepsilon_0 V_{\text{bias}}}{e_0 N_{\text{eff}}}}$$

$$N_{\text{eff}} = \frac{2\varepsilon\varepsilon_0 V_{fd}}{e_0 W^2}$$

$$N_{\text{eff}} \approx g_c \Phi_{eq} + g_a \exp\left(-\frac{t}{\tau_a}\right)$$

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$V_{\text{bias}} = 500\, \text{V}$$

$V_{\text{bias}} = 450\, \text{V}$$

$V_{\text{bias}} = 400\, \text{V}$$

$V_{\text{bias}} = 350\, \text{V}$$

$V_{\text{bias}} = 300\, \text{V}$$

$V_{\text{bias}} = 250\, \text{V}$$

$V_{\text{bias}} = 200\, \text{V}$$

$V_{\text{bias}} = 150\, \text{V}$$

$V_{\text{bias}} = 100\, \text{V}$$

$V_{\text{bias}} = 50\, \text{V}$$

$V_{\text{bias}} = 0\, \text{V}$

$y_{\text{act}} = 300\, \mu\text{m} \sqrt{\frac{V_{\text{bias}}}{V_{fd}}}$

$V_{fd} = 180\, \text{V}$ (fit parameter)
Electric field - main junction ($y_{act}$)

**DEPENDENCE ON FLUENCE**

- for fluences $<2\cdot10^{15}\text{cm}^{-2}$ the main junction extends as predicted by Hamburg model
  - the voltage drop in the rest of the detector must be much lower than in the main junction
  - this holds also for annealing – very good agreement with C-V measurements

- for fluences $>2\cdot10^{15}\text{cm}^{-2}$ the main junction is much bigger than predicted 😊
  - the square root dependence breaks down – not constant $N_{eff}$

**DEPENDENCE ON ANNELING**

- $10^{15}\text{ cm}^{-2}$
  - 80 min, $2135\text{ V}$
  - 10 min, $1860\text{ V}$
  - 20 min, $1700\text{ V}$
  - 40 min, $1550\text{ V}$
  - 80 min, $1510\text{ V}$
There is relatively high field in the “neutral/saddle region”

- The field increases with fluence and bias voltage
- The measured voltage drop in neutral region is typically few 10 V
  - at low/high voltages the region is large/small but the field is small/large
Electric field – back junction

- The electric field at the back junction grows with bias voltage, but remains of the same size (depth)
  - As the velocity is not saturated electric field can be estimated – from there the voltage drop of order 100 V
- The electric field strength grows with fluence
- The annealing has very little or no impact on size of the back junction
**Electric field – long term annealing**

**Long term annealing leads to increased charge multiplication**

- Decrease of $y_{act} \rightarrow$ larger voltage drop over smaller area $\rightarrow$ higher field $\rightarrow$ larger multiplication
- Widening of the signals $\rightarrow$ appearance of the second peak at larger depths when electrons arrive at the junction!

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**Graphs and Data**

- **HPK 800 V $10^{16}$ cm$^{-2}$**
- **Q(y) [arb.] vs. depth @800V, $t_{ann} = 0 \div 10240$ min.**
- **TCT Measurement @ T=20°C**
  - $80$ min: broader signal with second peak
  - $10240$ min: no second peak

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**9/17/2012**

- Clear onset of enhanced multiplication already at around 400 V.
- Before multiplication the signal decreases with long term annealing – expected
- The magnitude of multiplication decreases with time under bias
- However the current gets multiplied as well and the benefit for S/N is less obvious.

**CCE curve during long term annealing**

- Seen also with SCT128 A in I. Mandić et al., NIMA 629 (2011) p. 101.
Clear onset of enhanced multiplication already at around 400 V.

Before multiplication the signal decreases with long term annealing – expected

The magnitude of multiplication decreases with time under bias

However the current gets multiplied as well and the benefit for S/N is less obvious.

CCE curve during long term annealing

Charge for mip particle

Seen also with SCT128A readout -
- Clear onset of enhanced multiplication already at around 400 V.
- Before multiplication the signal decreases with long term annealing – expected
- The magnitude of multiplication decreases with time under bias
- However the current gets multiplied as well and the benefit for S/N is less obvious.

CCE curve during long term annealing

Charge for mip particle
HPK-ATLAS07; FZ n-p, PSI pions $\Phi_{eq}=5\times10^{14}$ cm$^{-2}$

HPK-ATLAS07; FZ n-p, PSI pions $\Phi_{eq}=1.6\times10^{15}$ cm$^{-2}$

Note: Large difference between neutrons and pions in terms of electric field profiles
- velocity saturated in the whole thickness of the detector at large bias voltages
- Symmetric electric field growth from both sides
- Trapping of the holes is larger than of the electrons (not a surprise but nicely seen)
Homogeneity of the response (Top-TCT)

![Graph showing charge distribution with scan direction and amplifier strip]

- Charge [arb]
- Scan direction
- Amplifier strip
- 1000 V
- 900 V
- 700 V
- 500 V
- 300 V

Homogeneity of the response (TOP-TCT)

- **Graphs:**
  - **Top-left:** Charge vs. distance for various voltages (1000 V, 900 V, 700 V, 500 V, 300 V)
  - **Top-right:** Similar to top-left but with different y-axis range.
  - **Bottom-left:** Charge vs. distance for various voltages (1000 V, 900 V, 700 V, 500 V, 300 V)
  - **Bottom-right:** Similar to bottom-left but with different y-axis range.

- **Annotations:**
  - 2e14
  - 5e14
  - 1e15
  - 5e15

- **Axes:**
  - X-axis: Distance in μm
  - Y-axis: Charge in arb. units

- **References:**
Multiplication seen as second peak in signal

2nd peak is present for all positions within the strip

**Field focusing effect** *(possible explanation…)*

Electric field is larger at the implant edges,
- drift path 1. produces larger signal than drift path 2 for high electric fields
- position with maximum signal moves away from the implant edge – more carriers along the track ends the drift at the implant edge
**Trapping induced charge sharing**

- The bipolar pulse in the neighbors does not yield zero charge because of trapping!
  - Amount of charge increases with fluence – trapping
  - Charge induced in the neighboring strips can be substantial
  - Observation in test beam data
    - Liv Wiik et al., Proceedings of RESMDD 2010 conference

**n+ - higher signal in hit electrode**

**p+ - wider clusters**
What about MCz-n sensor?

- MCz; p-n-n sensor (CERN group), 280 $\Omega$cm, irradiated with neutrons to $\Phi_{eq}=3e15$ cm$^{-2}$
- no intentional annealing
- at 1000 V the sensor is equally efficient in the whole volume, even though the field at the back is stronger – larger hole trapping

N. Pacifico et al., presented at RESMDD 10
In addition damage compensates in mixed fields:
fast charged hadrons: + space charge
neutrons: - space charge

homogenous field and bias voltage high enough: $\mu_e \tau_e$ becomes comparable to $\mu_h \tau_h$
(saturation velocities and trapping times are only 20% apart)

CCE of >50% at 500 V was found after $\Phi_{eq} = 1 \times 10^{15}$ cm$^{-2}$ (26 MeV p)

Conclusions

- We start to understand electric field at large fluences better
  - The main junction grows according to expectations from RD48 data up to 1-2e15 cm$^{-2}$
  - Electric field in the neutral bulk is substantial and can reach up to 0.5 V/μm
  - Junction at the back grows about the same for all fluences with maximum field of the order 1 V/μm.
  - Long term annealing significantly enhances charge multiplication
- The use of oxygen rich material with charged hadrons results in more homogenous electric field
- Charge multiplication seems to be stronger at implant edges resulting in good charge collection efficiency in the mid-strip region
- Trapping induced charge sharing becomes important with multiplication
- MCz p-on-n detectors perform better than FZ ones and can be probably used in the 1e15 cm$^{-2}$ range.
Samples

- $n^+p$ SSD detectors (1x1 cm$^2$) of ATLAS geometry
  - 300 µm thick
  - 80 µm pitch

- Spaghetti diodes

- FZ (initial full depletion voltages – from 20-180V)

- Neutron irradiated at reactor in Ljubljana up to 1016 cm$^{-2}$, pion irradiation at PSI
  - Edge-TCT investigated samples in steps (CERN scenario) with 80 min annealing at 60°C between the steps