Study of Bulk Damage Induced by Gamma Irradiation in n-in-p Silicon Diodes

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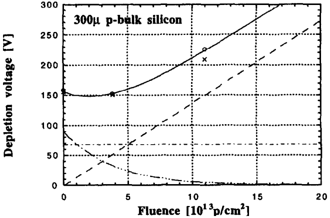
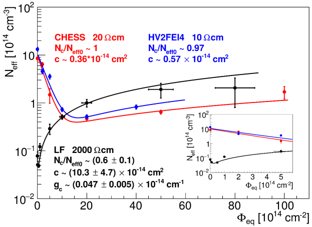
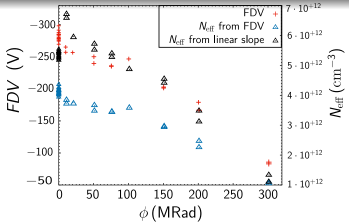


Proton irr. p-bulk silicon strip detectors. [S. Terada et. al., NIMA A 383, 1996]



Neutron irr. of p-bulk CMOS pixel detectors. [I. Mandić et. al., JINST 12 P02021, 2017]



Gamma irr. p-bulk silicon strip sensors. [M. Mikeštíková, V. Latoňová et. al., 34$^{\mathrm{th}}$ RD50 Workshop, 2019]

Motivation

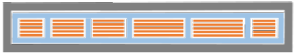
- N-bulk: type inversion after irr. by p, n and γ known.
- P-bulk: initial decrease and further large increase in effective doping concentration observed (n and p irr.).
- P-bulk: lack of detailed studies after γ irr.
- Preliminary studies up to 300 MRad of γ irr. p-bulk mini sensors showed decrease of full depletion voltage with higher TID.

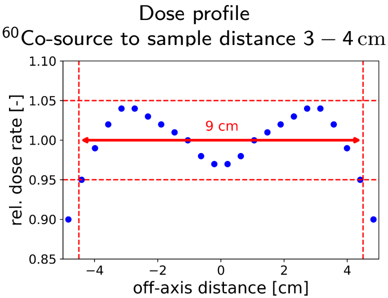
→ More detailed studies of p-type diodes with grounded guard ring after γ irr. up to 564 MRad were performed to better understand bulk damage.

- Samples:
  - 14 Hamamatsu (HPK) diodes $(8 \times 8)\,\mathrm{mm}^2$, standard FZ, p-bulk, crystal orientation 100.
  - Wafer oxygen concentration $(1.5 \cdot 10^{16} - 6.5 \cdot 10^{17})\,\mathrm{atoms/cm^3}$.*
- Studies:
  1. IV and CV tests with grounded guard ring at room temperature and relative humidity (RH) below 10 %.
  2. Gamma irradiation to various total ionizing doses (TID), which will be further indicated as $\Gamma\,[\mathrm{MRad}]$.
  3. IV and CV measurements after gamma irradiation.
  4. Standard annealing for 80 min at 60 °C.
  5. IV and CV measurements after annealing.

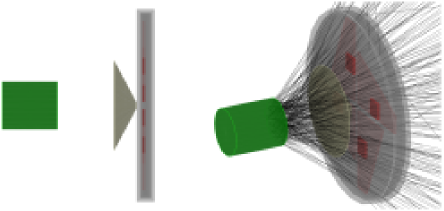
*Technical specification of silicon sensors for ATLAS ITk

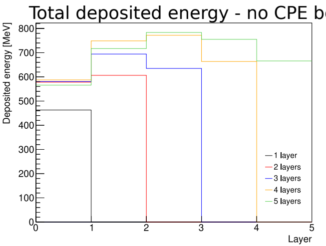
Gamma Irradiation

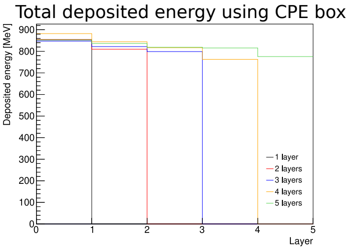




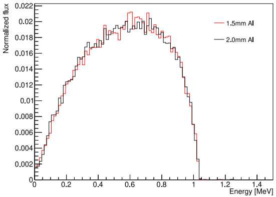
- Sensors positioned in 5 layers surrounded by charge particle equilibrium box (1.5 mm Pb +1 mm Al).
- Dose rate $(19 - 16)\,\mathrm{krad/min}$, max temperature during irradiation $35\,^{\circ}\mathrm{C}$.
- Homogeneity of $\pm 5\,\%$ in irradiation area of $9\,\mathrm{cm}$ (lead homogenizer).





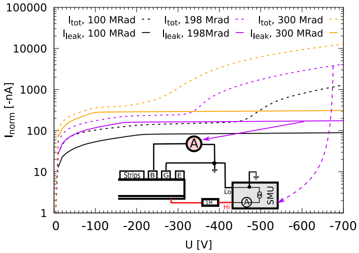


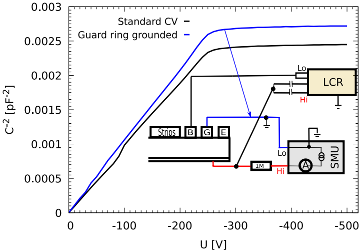
- Geant4 simulation performed to ensure that the deposited energy in all layers is roughly the same:
    - Emission of $50 \cdot 10^6$ photons with energy of $1.25\,\mathrm{MeV}$ (Average of 1.17 and $1.33\,\mathrm{MeV}$).
    - Lead homogenizer - shape of truncated cone with dimensions: height $10\,\mathrm{mm}$, diameter 40 and $2.6\,\mathrm{mm}$.
- Comparison of total deposited energy in individual layers clearly demonstrates the purpose of charge particle equilibrium (CPE) box.
- Maximal irradiation inaccuracy for samples in different layers is $\approx 10\,\%$.
- Recorded energy of each electron leaving Al ($2\,\mathrm{mm}$ for comparison and $1.5\,\mathrm{mm}$ - CPE box)



Spectrum of secondary electrons generated by gamma rays. Comparable with [E. El Allam et al., J. Appl. Phys. 123, 2018]

- **Separation of bulk and surface current.**





- Dashed lines represent the total current measured by SMU (bulk and surface current).
- Solid lines represent the bulk current measured by ammeter.
- Soft breakdowns visible in the dashed lines whereas the solid lines remain smooth.

→ Soft breakdowns caused by surface currents.

- For normalization of bulk current to volume, the area under outer edge of bias ring ≈ 51.53 mm^2 and the width ≈ 290 $\mu\mathrm{m}$ was used.

- Black line represents CV measurement without grounded guard ring.

→ Capacitance value without grounded guard ring is higher as the volume defined by field lines in this case is larger.

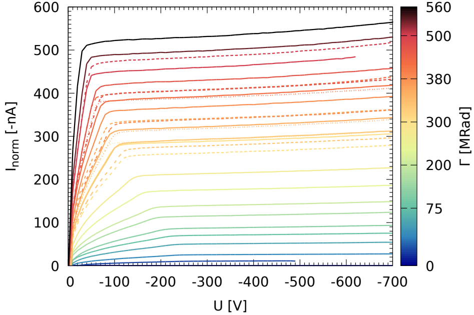
- Blue line represents CV measurement with grounded guard ring.

→ Capacitance value with grounded guard ring is smaller as only the volume under the bias ring is read out (outer edge of bias ring).

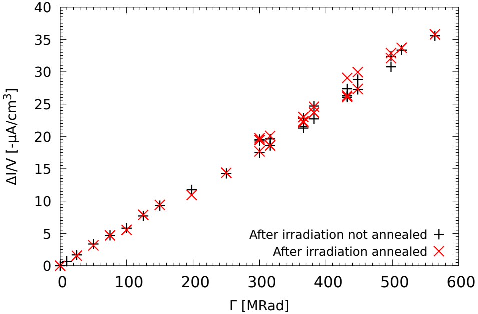
Diving into IV Measurements

Comparison of IV Characteristics Before And After Gamma Irradiation

IV after irr., not annealed - normalized to 20 °C, RH< 10%



Comparison of leakage current values at $-300\,\mathrm{V}$



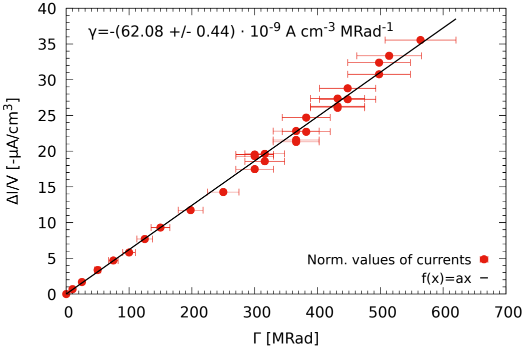
$$\Delta I = I_{\mathrm{irr}} - I_{\mathrm{unirr}},\ A = 51.53\,\mathrm{mm}^2,\ w = 290\,\mathrm{\mu A}$$

Summary

- Bulk current increases with TID.
- Smooth IV curves - no breakdown voltages in bulk leakage current up to $-700\,\mathrm{V}$.
- Bulk leakage currents saturate after reaching full depletion voltage.
- After gamma irradiation no changes in bulk leakage currents after annealing were observed.

Dependence of Leakage Current on TID

Lin. fit of current values at $-300\,\mathrm{V}$ before ann.



$\Delta I = I_{\mathrm{irr}} - I_{\mathrm{unirr}}$, $A = 51.53\,\mathrm{mm}^2$, $w = 290\,\mu\mathrm{A}$

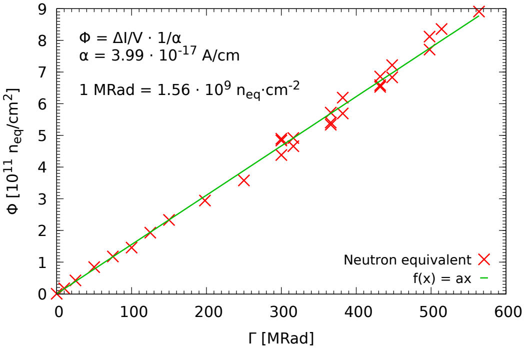
Fit Results for Various Bias Voltages, Before And After Annealing(=ann.)

	$-\gamma\left[\cdot 10^{-9}\ \frac{\mathrm{A}}{\mathrm{cm}^3\mathrm{MRad}}\right]$	
$U\,[-\mathrm{V}]$	Before ann.	After ann.
300	62.08 ± 0.44	63.18 ± 0.52
400	62.83 ± 0.44	63.90 ± 0.52
500	63.71 ± 0.45	64.77 ± 0.52

Observation

- Leak. current is linearly dependent on TID (in the studied range up to 564 MRad).
- For voltages higher than full-depletion voltage the fit parameters γ are equivalent.

Before annealing at $-300\,\mathrm{V}$

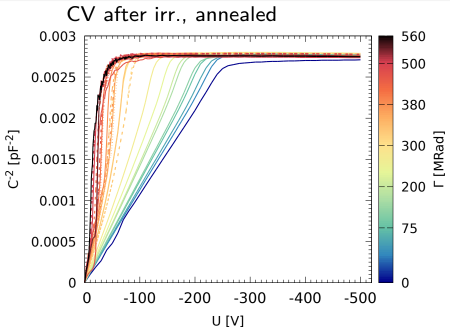


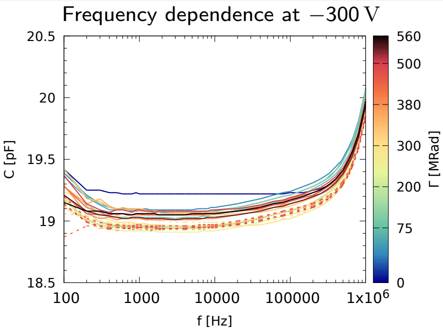
Fit Results for Various Bias Voltages, Before And After Annealing(=ann.)

	$k\left[\cdot 10^9 \frac{\mathrm{n_{eq}}}{\mathrm{cm^2 MRad}}\right]$	
$U\,[-\mathrm{V}]$	Before ann.	After ann.
300	1.56	1.58
400	1.57	1.60
500	1.60	1.62

- Thanks to the linear dependence of leakage current on the TID (previous slide), it is possible to find a relation between TID in MRad and Fluence in $\mathrm{n_{eq}/cm^2}$, i.e. $1\mathrm{MRad} = k \cdot \mathrm{n_{eq}/cm^2}$.
- Fluence was calculated using the formula $\frac{\Delta I}{V} = \alpha\Phi$, where $\alpha = 3.99 \cdot 10^{-17}\,\mathrm{A/cm}$ [M. Moll, IEEE Transactions on Nuclear Science, 65, 2018].
- Using the fraction $\frac{\Delta I}{V}$ obtained by our measurements for a given TID, we can calculate $\Phi(\Gamma) = \frac{1}{\alpha}\frac{\Delta I}{V}(\Gamma)$.

Diving into CV Measurements





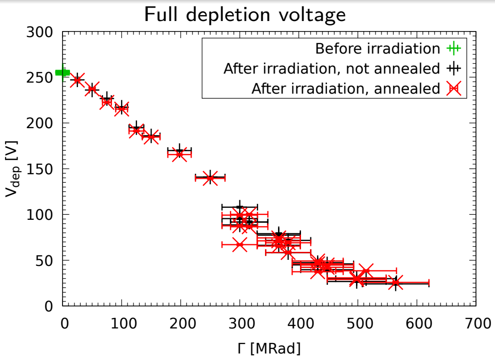
Measurement Conditions

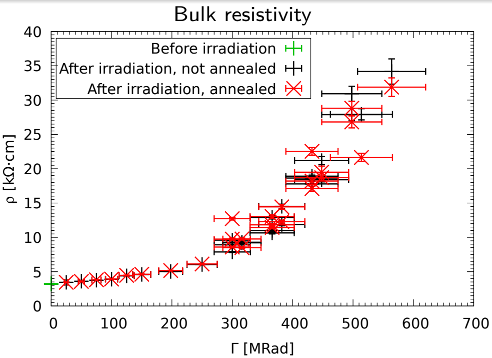
- Measurement at room temperature, RH below 10 %.
- LCR-meter frequency 1 kHz with RC-series.
- CVs before irr. were measured with amplitude 0.1 V in equidistant 10 V steps.
- CVs after irr. were measured with amplitude 0.5 V in non-equidistant voltage steps - smaller steps at the beginning.

Observation

- Visible significant decrease of V_{dep} with increasing TID.

Full Depletion Voltage And Bulk Resistivity





- Initial bulk resistivity was $\varrho = (3.21 \pm 0.02)\,\mathrm{k\Omega \cdot cm}$ *.
- Initial full depletion voltage $V_{\mathrm{dep}} = (-255.2 \pm 0.9)\,\mathrm{V}$
- After gamma irradiation no changes in V_{dep} after annealing were observed.
- V_{dep} and N_{eff} decrease significantly with increasing TID.
- Significant increase of bulk resistivity.

$^*\varrho = \frac{1}{q \cdot \mu_h \cdot N_{\mathrm{eff}}}$, where $\mu_h = 450\,\mathrm{cm^2 V^{-1} s^{-1}}$ represents the hole mobility, $q = 1.6 \cdot 10^{-19}\,\mathrm{C}$ the electric charge and N_{eff} the effective doping concentration.

Fitting N_{eff}

N_{eff} Dependence on TID

- Initial concentrations of donors and acceptors are unknown.

→ From CV curves we can calculate only their difference $N_{\mathrm{eff}}(\Gamma = 0) = |N_{D,0} - N_{A,0}|$, where $N_{\mathrm{eff}}(\Gamma = 0)$ represents effective doping concentration for not irradiated samples, $N_{D,0}$ and $N_{A,0}$ are the initial concentrations of donors and acceptors respectively.

- In order to simplify the fits, following approximations and assumptions were made:
  - In our p-bulk samples we assume that $N_{A,0} \gg N_{D,0} \rightarrow N_{\mathrm{eff}}(\Gamma = 0) \approx N_{A,0}$.
  - Effective doping concentration evolution: $\boxed{N_{\mathrm{eff}}(\Gamma) = N_{A,0} e^{-c_A \Gamma} - \gamma \Gamma}$ [M. Moll, PoS, 2019], where $N_{A,0}, c_A$ and γ represent initial acceptor concentration, acceptor removal coefficient, and introduction rate ($\in$ all other radiation induced space charge generation mechanisms), respectively.
    1. Initial exponential acceptor removal.
    2. Dominant linear behavior for higher TID.

1. Assuming just initial exponential decrease:
   - → Effective doping concentration evolution:

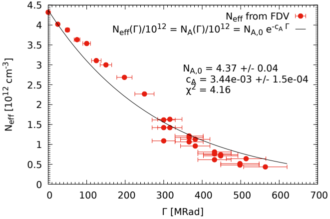
     $$\boxed{N_A(\Gamma) = N_{A,0}e^{c_A\Gamma} - \cancel{\gamma\Gamma} = N_{A,0}e^{c_A\Gamma}}$$, where

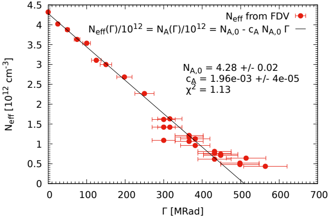
     $N_{A,0}, c_A$ and γ represent initial acceptor concentration, acceptor removal coefficient and introduction rate respectively.

- For small TIDs we can rewrite:
   - →

     $$\boxed{N_A(\Gamma) = N_{A,0}e^{c_A\Gamma} \approx N_{A,0} - c_A N_{A,0}\Gamma}$$ [M. Moll, PoS, 2019],

     where $N_{A,0}, c_A$ represent initial acceptor concentration and acceptor removal coefficient respectively.



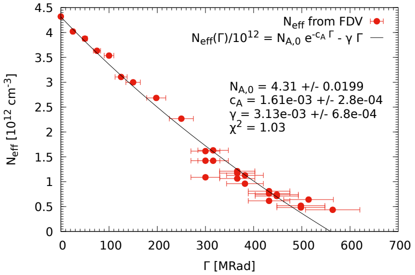


Preliminary Fit of Currrently Available Data by Complete Formula

2. Fitting the data by complete formula:
   - → Effective doping concentration evolution:

     $$\boxed{N_{\mathrm{eff}}(\Gamma) = N_{A,0}e^{-c_A\Gamma} - \gamma\Gamma}$$ [M. Moll, PoS, 2019],

     where $N_{A,0}$, c_A and γ represent initial acceptor concentration, acceptor removal coefficient, and introduction rate ($\in$ all other radiation induced space charge generation mechanisms), respectively.
   - More data taken for higher TID can possibly change the sign of γ.



Summary

- It seems that the acceptor removal could be very well described by the evolution $N_A(\Gamma) = N_{A,0}e^{-c_A\Gamma} - \gamma\Gamma$, which is in accordance with [M. Moll, PoS, 2019].
- Observed data flattening, could indicate coming change in effective doping concentration behavior, which will depend on the sign of γ.

- Standard FZ, p-bulk diodes were tested for IV and CV with grounded guard ring before and after irradiation.
- Annealing did not have any effect on measured values.
- IV:
  - No annealing effect in gamma irradiated diodes observed.
  - Linear increase of leakage current with TID.
  - Study showed that $1\,\mathrm{MRad}$ corresponds to $1.56 \cdot 10^9\,\mathrm{n_{eq}/cm^2}$.
- CV:
  - No annealing effect in gamma irradiated diodes observed, either.
  - Significant decrease of full depletion voltage and effective charge concentration with increasing TID.
  - The decreasing trend of space charge with increasing TID could be very well described by the formula $N_A(\Gamma) = N_{A,0}e^{-c_A\Gamma} - \gamma\Gamma$.

  → Irradiation to higher TID necessary to determine further development (sign of γ).

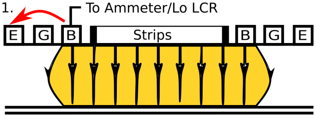
Acknowledges

- This research was supported by Charles University grant GAUK 942119, LTT17018 Interexcellence and LM2018104 Infra CERN-CZ.

Backup

Separation of Bulk And Surface Current by Contacting Guard Ring

1.



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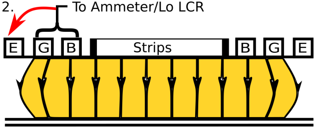

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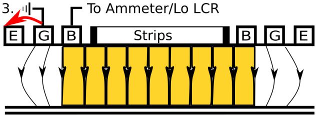
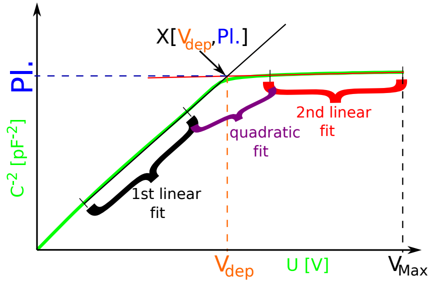


1. Guard ring floating - CV measurements of large area sensors (no contactable guard ring).
2. Guard ring connected to bias ring - floating.
3. Guard ring grounded.

Volume defined by field lines, Surface currents

Comments

- E = Edge ring, G = Guard ring, B = Bias ring.
- Goal: Read-out only bulk current.
- In schemes 1. and 2. the volume defined by field lines cannot be correctly estimated, surface currents measured together with bulk currents.
- In scheme 3. the volume defined by field lines corresponds very precisely to the volume defined by the diode's bias ring → IV and CV measurements performed with grounded guard ring and for calculations the volume/area defined by outer edge of bias ring was used. In this scheme surface currents are not measured.



- $C_{\mathrm{bulk}} = \varepsilon_0 \varepsilon_{\mathrm{Si}} \frac{A}{w_{\mathrm{d}}}$, $\varepsilon_0 \approx 8.85 \cdot 10^{-12}\,\mathrm{F/m}$, $\varepsilon_{\mathrm{Si}} = 11.75$, $q = 1.6 \cdot 10^{-19}\,\mathrm{C}$
- X = Intersection point of two linear fits
  x-coordinate of X = Full depletion voltage ($= V_{\mathrm{dep}}$)
  y-coordinate of X = Plateau ($=$ Pl.)
- Assuming constant space charge over the volume of the diode.
- For calculation of parameters scripts written by D. Rousso and D. Jones used.

$U < V_{\mathrm{dep}}$ (Slope = Sl.)

- $C_{\mathrm{bulk}} = A\sqrt{\frac{\varepsilon_0 \varepsilon_{\mathrm{Si}} q N_{\mathrm{eff}}}{2U}}$
- Fit: $\frac{1}{C^2} = \mathrm{Sl.} \cdot U + \frac{1}{C_0^2}$

$\rightarrow$ $N_{\mathrm{eff}} = \frac{2}{\varepsilon_0 \varepsilon_{\mathrm{Si}} q A^2 \mathrm{Sl.}}$

$\rightarrow$ $D_{\mathrm{full}} = \sqrt{\frac{2\varepsilon_0 \varepsilon_{\mathrm{Si}} V_{\mathrm{dep}}}{q N_{\mathrm{eff}}}}$

$U \geq V_{\mathrm{dep}}$ (Plateau = Pl.)

- $C_{\mathrm{bulk}} = A\frac{\varepsilon_0 \varepsilon_{\mathrm{Si}}}{D_{\mathrm{full}}} = \mathrm{const} = \frac{1}{\sqrt{Pl.}}$
- $\mathrm{Pl.} = \frac{D_{\mathrm{full}}^2}{\varepsilon_0^2 \varepsilon_{\mathrm{Si}}^2 A^2}$

$\rightarrow$ $D_{\mathrm{full}} = \varepsilon_0 \varepsilon_{\mathrm{Si}} A \sqrt{\mathrm{Pl.}}$

$\rightarrow$ $N_{\mathrm{eff}} = \frac{2\varepsilon_0 \varepsilon_{\mathrm{Si}} V_{\mathrm{dep}}}{q D_{\mathrm{full}}^2}$