

Bulk damage study in gamma irradiated n-in-p silicon diodes

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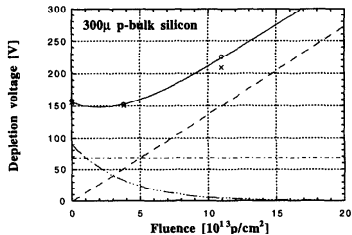


19th November 2021

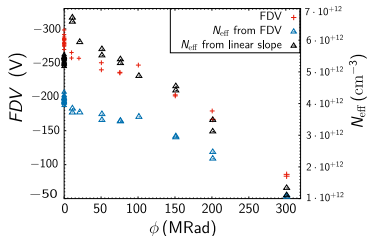


- 14 Hamamatsu (HPK) diodes (8×8) mm², standard FZ, p-bulk, crystal orientation 100.
- Wafer oxygen concentration ($1.5 \cdot 10^{16} - 6.5 \cdot 10^{17}$) atoms/cm³ (Technical specification of silicon sensors for ATLAS ITk).
- Tested IV, CV with grounded guard ring at room temperature and relative humidity (RH) below 10 %.
- Gamma irradiated to various doses: from 10 MRad to 366 MRad. Dose TID will be in further plots and formulae referred to as Γ [MRad].
- Re-measured IV and CV after gamma irradiation at room temperature and relative humidity (RH) below 10 %.
- Performed standard annealing for 80 min at 60 °C.
- Re-measured IV and CV after annealing at room temperature and relative humidity (RH) below 10 %.

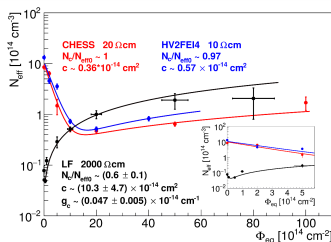
Motivation And Previous Results (Examples)



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



Gamma irr. p-bulk silicon strip sensors.
[\[M. Mikeštková, V. Latoňová et. al., 34th RD50 Workshop, 2019\]](#)



Neutron irr. CMOS pixel detectors.
[\[I. Mandić et. al., JINST 12 P02021, 2017\]](#)

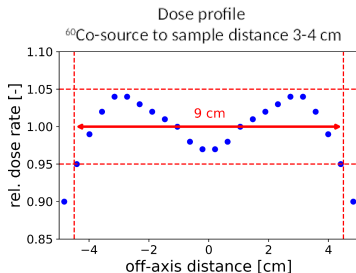
Motivation

- Type inversion in case of standard FZ n-bulk sensors.
- Several studies revealed initial decrease of full depletion voltage (V_{dep}) also in case of p-bulk silicon, particularly after irr. by protons or neutrons.
- Acceptor removal.
- 2019 in Prague sensors showed V_{dep} decrease after gamma irr. → more detailed study using diodes with grounded guard ring.

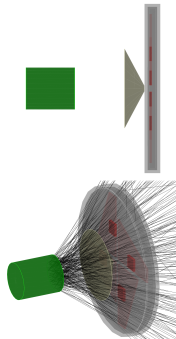
Gamma Irradiation



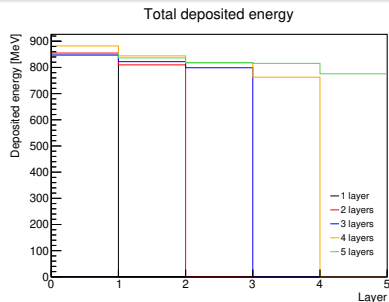
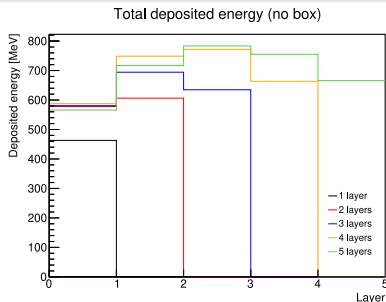
5 layers of Sensors
Al 1 mm holder
Pb 1.5 mm



- Sensors in 5 layers surrounded by equilibrium material (1.5 mm Pb + 1 mm Al).
- Irradiation time from (3.9 – 142.7) h for TID (10 – 366) MRad.
- Dose rate 19.45 krad/min, max temperature 35 °C.
- Homogeneity of $\pm 5\%$ in irradiation area of 9 cm (lead homogenizer).

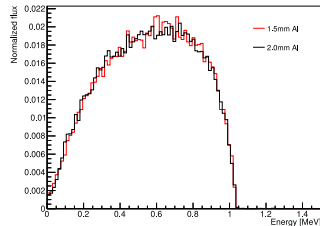


Gamma Irradiation – Simulation Results

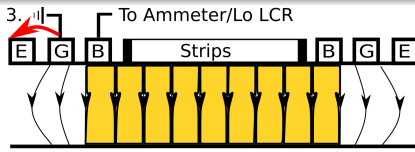
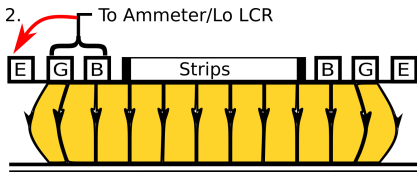
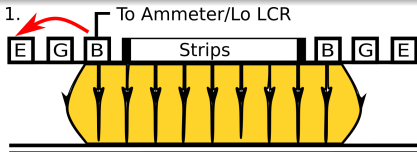


- Emission of $50 \cdot 10^6$ photons with energy of 1.25 MeV (Average of 1.17 and 1.33 MeV).
- Lead homogenizer - frustum-shaped with dimensions: height 10 mm, diameter 40 and 2.6 mm.
- Comparison of total deposited energy in individual layers clearly demonstrates the purpose of charge particle equilibrium (CPE) box.
- Recorded energy of each electron leaving Al (2 mm for comparison and 1.5 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 by Contacting Guard Ring



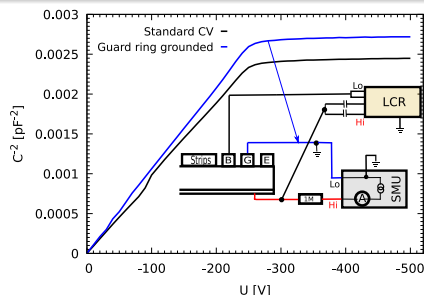
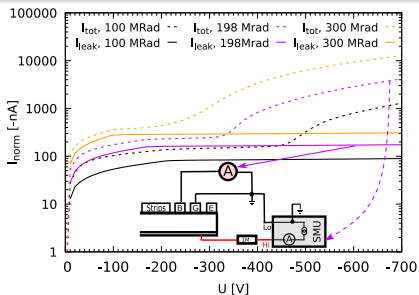
- 1 Guard ring floating - CV measurements of large area sensors (no contactable guard ring).
- 2 Guard ring connected to bias ring - floating.
- 3 Guard ring grounded.

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.

Effect of Grounded Guard Ring in IV And CV Characteristics



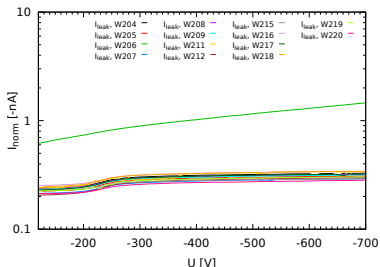
- Dashed lines represent the total measured current by SMU (bulk and surface current).
- Solid lines represent the measured bulk current by ammeter.
- Bulk current separated from surface current.
- Soft breakdowns visible in the dashed lines whereas the solid lines remain smooth.
- Soft breakdowns caused by surface currents.
- For normalization of bulk current to volume, the area under outer edge of bias ring $\approx 51.53 \text{ mm}^2$ and the width $\approx 290 \mu\text{m}$ was used.

- Black line represents CV measurement without grounding the guard ring (Fig. 1 on previous slide).
- 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 (Fig. 3 on previous slide).
- Capacitance value with grounded guard ring is smaller as only the volume under the bias ring is read out (outer edge of bias ring).

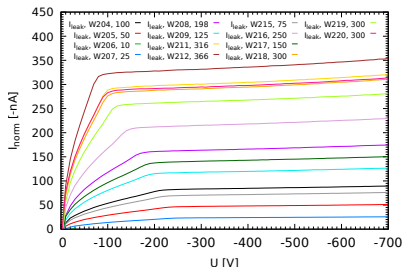
Diving into IV Measurements

Comparison of IV Characteristics Before And After Gamma Irradiation

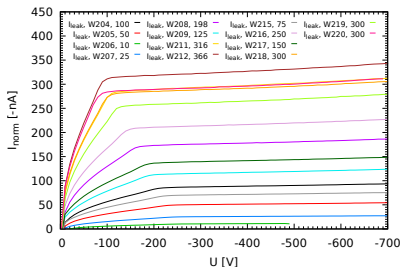
IV before irr. - normalized to 20 °C



IV after irr., annealed - normalized to 20 °C



IV after irr., not annealed - normalized to 20 °C

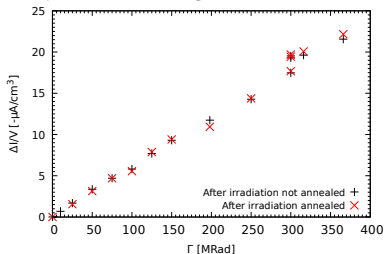


Summary

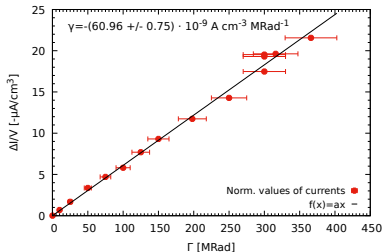
- All IV curves were measured at room temperature and normalized to 20 °C.
- Relative humidity (RH) below 10 %.
- Smooth IV curves - no breakdown voltages up to 700 V.
- In case of irradiated samples visible leakage current saturation for voltages higher than full depletion voltage.

Comparison of IV Results Before And After Gamma Irradiation

Comparison of leakage current values at 300 V



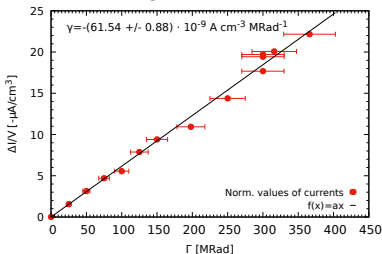
Lin. fit of current values at 300 V before ann.



$$\Delta I = I_{irr} - I_{unirr},$$

$$A = 51.53 mm^2, w = 290 \mu A$$

Lin. fit of leakage values at 300 V after ann.

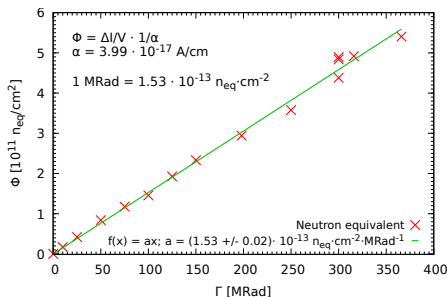


Summary

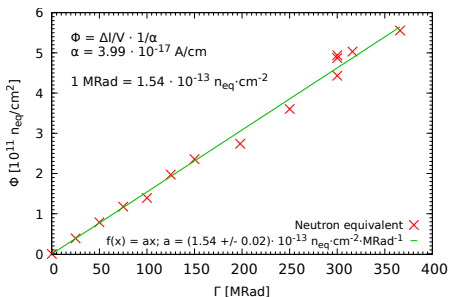
- From comparison of leak. current values at 300 V it is obvious that:
 - Annealing does not significantly change leakage current values.
 - Leak. current is linear dependent on TID (in the studied range up to 366 MRad).
- Fitting the data by $\frac{\Delta I}{V} = \gamma \Gamma$ we obtain:
 - $\gamma = (61.5 \pm 0.9) \cdot 10^{-9} \frac{A}{cm^3 MRad}$ before ann.
 - $\gamma = (61.0 \pm 0.8) \cdot 10^{-9} \frac{A}{cm^3 MRad}$ after ann.

Parameters Extracted From IV

Before annealing



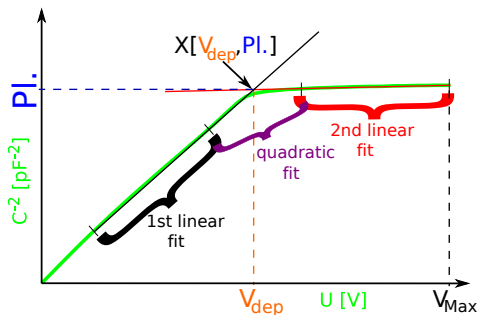
After annealing



- 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 $\text{n}_{\text{eq}}/\text{cm}^2$.
- Fluence was calculated using the formula $\frac{\Delta I}{V} = \alpha \Phi$, where $\alpha = 3.99 \cdot 10^{-17} \text{ A/cm}$ [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 $\Phi = \frac{\Delta I}{V} \frac{1}{\alpha}$.

Diving into CV Measurements

Parameters Extracted From CV-Characteristics



- $C_{bulk} = \epsilon_0 \epsilon_{Si} \frac{A}{w_d}$,
 $\epsilon_0 \approx 8.85 \cdot 10^{-12} \text{ F/m}$, $\epsilon_{Si} = 11.75$,
 $q = 1.602 \text{ C}$
- X = Intersection point of two linear fits
 x -coordinate of X = Full depletion voltage ($= V_{dep}$)
 y -coordinate of X = Plateau ($= Pl.$)
- Assuming constant space charge over the volume of the diode.
- For calculation of parameters scripts written by [D. Roussio and D. Jones](#) used.

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

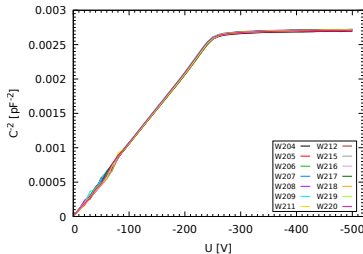
- $C_{bulk} = A \sqrt{\frac{\epsilon_0 \epsilon_{Si} q N_{eff}}{2U}}$
- Fit: $\frac{1}{C^2} = Sl. \cdot U + \frac{1}{C_0^2}$
- $N_{eff} = \frac{2}{\epsilon_0 \epsilon_{Si} q A^2 Sl.}$
- $D_{full} = \sqrt{\frac{2 \epsilon_0 \epsilon_{Si} V_{dep}}{q N_{eff}}}$

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

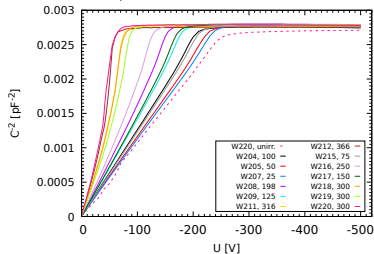
- $C_{bulk} = A \frac{\epsilon_0 \epsilon_{Si}}{D_{full}} = \text{const} = \frac{1}{\sqrt{Pl.}}$
- $Pl. = \frac{D_{full}^2}{\epsilon_0^2 \epsilon_{Si}^2 A^2}$
- $D_{full} = \epsilon_0 \epsilon_{Si} A \sqrt{Pl.}$
- $N_{eff} = \frac{2 \epsilon_0 \epsilon_{Si} V_{dep}}{q D_{full}^2}$

Comparison of CV Characteristics Before And After Gamma Irradiation

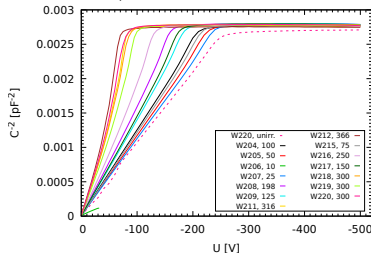
CV before irr.



CV after irr., annealed



CV after irr., not annealed



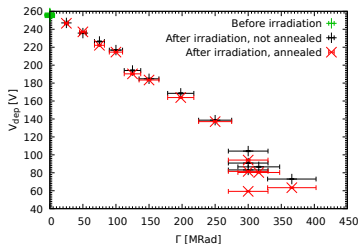
Measurement Conditions

- All CV curves were measured at room temperature, at 1 kHz with RC-series.
- Relative humidity (RH) below 10 %.
- CVs before irr. were measured with amplitude 0.1 V in equidistant 10 V steps and voltages below 50 V were left out of the fit (see previous slide).
- CVs after irr. were measured with amplitude 0.5 V in in-equidistant voltage steps - smaller steps at the beginning - and voltages below 30 V were left out of the fit (previous slide).

Summary

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

CV Results Before And After Annealing



Values after annealing calculated from PI.

Test chip	Dose [MRad]	V_{dep} [-V]	N_{eff} [$\cdot 10^{12} / \text{cm}^3$]	D_{full} [μm]	ρ [$k\Omega \cdot \text{cm}$]
Avg not irr.	0	255.8 ± 0.9	4.33 ± 0.02	277.0 ± 0.5	3.20 ± 0.02
W207	25	246.7 ± 0.5	4.02 ± 0.01	282.3 ± 0.4	3.45 ± 0.01
W205	50	237.1 ± 0.5	3.88 ± 0.01	281.9 ± 0.4	3.57 ± 0.01
W215	75	222.2 ± 0.6	3.63 ± 0.02	282.1 ± 0.5	3.82 ± 0.02
W204	100	214.5 ± 0.6	3.53 ± 0.02	281.0 ± 0.5	3.93 ± 0.02
W209	125	190.3 ± 0.7	3.09 ± 0.02	282.8 ± 0.5	4.49 ± 0.02
W217	150	183.4 ± 0.8	2.98 ± 0.02	282.7 ± 0.6	4.65 ± 0.03
W208	198	163.9 ± 0.7	2.66 ± 0.02	282.9 ± 0.6	5.21 ± 0.03
W216	250	137.1 ± 0.7	2.23 ± 0.01	282.5 ± 0.6	6.22 ± 0.04
W218	300	81.5 ± 0.5	1.33 ± 0.01	282.6 ± 0.6	10.46 ± 0.08
W219	300	94.2 ± 0.7	1.53 ± 0.01	282.5 ± 0.6	9.05 ± 0.07
W220	300	59.3 ± 0.4	0.966 ± 0.008	282.4 ± 0.5	14.4 ± 0.1
W211	316	80.4 ± 0.6	1.32 ± 0.01	281.1 ± 0.6	10.50 ± 0.09
W212	366	63.4 ± 0.7	1.05 ± 0.01	280.6 ± 0.7	13.3 ± 0.2

- Average bulk resistivity before irradiation was $\rho = (3.20 \pm 0.02) k\Omega \cdot \text{cm}$.
- Average full depletion voltage before irradiation was $V_{dep} = (-255.8 \pm 0.9) \text{ V}$
- V_{dep} and N_{eff} decreases with increasing TID.
- No significant difference between V_{dep} values before and after annealing.
- Significant decrease of N_{eff} of $\approx 76 \%$ between not irr. diode and max. TID of 366 MRad.

Fitting N_{eff}

"With four parameters I can fit an elephant, with five I can make him wiggle his trunk."

(John Von Neumann)

Inspired by [\[1\]](#).

N_{eff} Dependence on TID

- Initial concentrations of donors and acceptors unknown.

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

- Assuming 2 possibilities of evolution of $N_A(\Gamma)$ and $N_D(\Gamma)$ with TID:

- Effective doping concentration evolution:

$$N_A(\Gamma) = (N_{A,0} - N_{A,p})e^{-c_A\Gamma} + N_{A,p} - \gamma\Gamma \quad [2],$$

where $N_{A,p}$, c_A and γ represent initial impurity concentration, acceptor removal coefficient and introduction rate respectively. ($A \rightarrow D$) → evolution for $N_D(\Gamma)$.

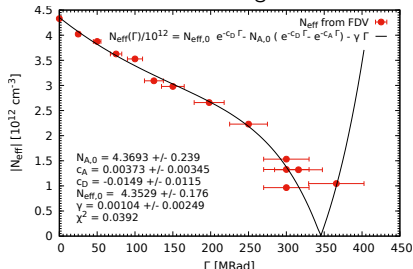
8 Free parameters!!!

- Effective doping concentration evolution:

$N_A(\Gamma) = (N_{A,0})e^{-c_A\Gamma} - \gamma\Gamma$ [3], where c_A and γ represent initial impurity concentration, acceptor removal coefficient and introduction rate respectively. ($A \rightarrow D$) → evolution for $N_D(\Gamma)$.

$$N_{\text{eff}} = N_{\text{eff},0}e^{-c_D\Gamma} - N_{A,0}(e^{-c_D\Gamma} - e^{-c_A\Gamma}) - \gamma\Gamma$$

After Annealing



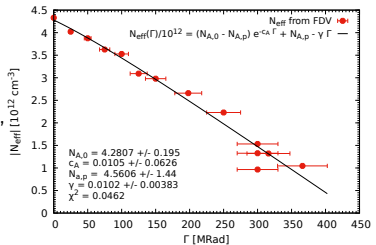
1 Neglecting donor concentration:

- $N_{\text{eff}}(\Gamma = 0) \approx N_{A,0}$

→ Effective doping concentration evolution:

$$N_A(\Gamma) = (N_{A,0} - N_{A,p})e^{-c_A \Gamma} + N_{A,p} - \gamma \Gamma \quad [2],$$

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

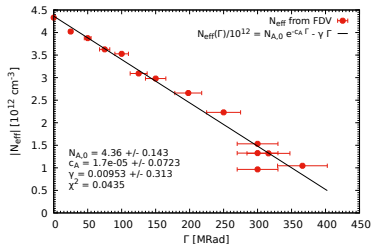


2 Neglecting impurities:

→ Effective doping concentration evolution:

$$N_A(\Gamma) = (N_{A,0})e^{-c_A \Gamma} - \gamma \Gamma \quad [3], \text{ where}$$

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



3 Assuming very small γ :

→ Effective doping concentration evolution:

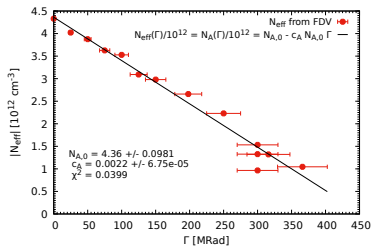
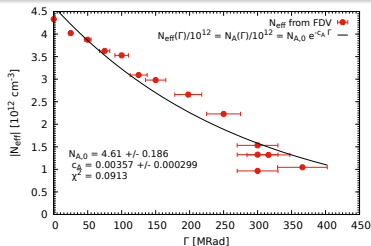
$$N_A(\Gamma) = N_{A,0} e^{c_A \Gamma} - \cancel{\gamma} = N_{A,0} e^{c_A \Gamma}, \text{ where}$$

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

4 For small TIDs we can rewrite:

$$\rightarrow N_A(\Gamma) = N_{A,0} e^{c_A \Gamma} \approx N_{A,0} - c_A N_{A,0} \Gamma \quad [3],$$

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



Summary

- All fits except for the purely exponential one predict type inversion: Model on slide 17, option 2 before 350 Mrad, others at about 450 Mrad.
- In order to choose the correct model more data in higher TIDs must be taken.

Summary And Conclusion

- 14 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:
 - Smooth IV curves with no breakdown observed up to 700 V.
 - Leakage current saturation for voltages higher than full depletion voltage.
 - Fitting the data by $\frac{\Delta I}{V} = \gamma \Gamma$ we received $\gamma = (61.5 \pm 0.9) \frac{\text{nA}}{\text{cm}^3 \text{Mrad}}$ for diodes before annealing and $\gamma = (61.0 \pm 0.8) \frac{\text{nA}}{\text{cm}^3 \text{Mrad}}$ for diodes after annealing.
- CV:
 - Significant decrease of full depletion voltage and space charge with increasing TID.
 - The decreasing trend of space charge was fitted by different functions under particular assumptions.
 - For choosing a certain model unambiguously it is necessary to irradiate the diodes to higher TIDs.

Future Outlook

- Further irradiation to higher TIDs.
- Improvement of fitting algorithms.

Acknowledges

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

Backup

IV Summary Table

	Not irradiated			After irr. Not annealed			After irr. Annealed				
Test chip	Tot. [nA]	curr.	Leak. [nA]	curr.	Temp. [C]	Tot. [nA]	curr.	Leak. [nA]	curr.	Temp. [C]	Irr. Dose [MRad]
W206	-1.69		-1.15		22.88	-166.58		-16.81		25.35	10
W207	-0.74		-0.33		22.40	-164.62		-42.87		26.00	25
W205	-0.82		-0.38		23.18	-204.74		-84.47		25.92	50
W215	-0.66		-0.31		21.47	-205.22		-99.09		23.89	75
W204	-0.83		-0.39		22.98	-267.39		-144.08		25.78	100
W209	-0.82		-0.37		22.76	-272.27		-150.92		23.07	125
W217	-0.75		-0.36		22.27	-329.94		-200.09		24.14	150
W208	-0.82		-0.37		22.58	-469.98		-296.51		26.02	198
W216	-0.75		-0.37		21.84	-531.03		-303.12		24.00	250
W218	-0.80		-0.39		22.40	-1155.90		-416.01		24.18	300
W219	-0.76		-0.35		22.62	-781.11		-380.71		24.30	300
W220	-0.75		-0.33		22.82	-2143.80		-429.32		24.41	300
W211	-0.73		-0.35		22.42	-1168.00		-392.28		23.31	316
W212	-0.74		-0.34		22.54	-2047.50		-437.47		23.48	366

CV Summary Table

Test chip	Not irradiated			After irr. Not annealed			After irr. Annealed			Dose [MRad]
	V_{dep} [-V]	N_{eff} [$\cdot 10^{12} / \text{cm}^3$]	D_{full} [μm]	V_{dep} [-V]	N_{eff} [$\cdot 10^{12} / \text{cm}^3$]	D_{full} [μm]	V_{dep} [-V]	N_{eff} [$\cdot 10^{12} / \text{cm}^3$]	D_{full} [μm]	
W206	254.69	4.32	276.88	-	-	-	-	-	-	10
W207	256.97	4.34	277.21	247.08	4.02	282.61	246.68	4.02	282.25	25
W205	256.73	4.35	276.91	235.72	3.85	282.13	237.14	3.88	281.91	50
W215	255.16	4.32	276.82	226.38	3.69	282.32	222.15	3.63	282.06	75
W204	256.30	4.37	276.11	216.79	3.56	281.37	214.52	3.53	281.03	100
W209	254.19	4.29	277.35	194.06	3.15	282.99	190.32	3.09	282.75	125
W217	258.12	4.36	277.39	184.78	3.00	282.76	183.41	2.98	282.73	150
W208	256.18	4.32	277.54	168.57	2.74	282.74	163.86	2.66	282.89	198
W216	257.30	4.36	276.97	138.69	2.26	282.23	137.05	2.23	282.54	250
W218	254.91	4.31	277.28	90.87	1.48	282.25	81.54	1.33	282.55	300
W219	255.80	4.33	277.09	104.21	1.70	282.08	94.16	1.53	282.49	300
W220	253.08	4.29	276.90	83.20	1.36	282.04	59.31	0.97	282.44	300
W211	255.99	4.34	276.86	86.64	1.42	281.21	80.36	1.32	281.14	316
W212	255.40	4.35	276.22	73.05	1.21	280.50	63.43	1.05	280.60	366

- Calculated for $A \approx 51.53 \text{ mm}^2$ (outer edge of bias ring) and $\epsilon_0 \approx 8.85 \cdot 10^{-12} \text{ F/m}$, $\epsilon_r = 11.75$, $|e| = 1.602 \text{ C}$

Test chip	$V_{\text{dep}} [-V]$	$N_{\text{eff}} [\cdot 10^{12} / \text{cm}^3]$ from pl.	$D_{\text{full}} [\mu\text{m}]$ from pl.	$N_{\text{eff}} [\cdot 10^{12} / \text{cm}^3]$ from sl.	$D_{\text{full}} [\mu\text{m}]$ from sl.
W204	256.3 ± 0.6	4.37 ± 0.02	276.1 ± 0.4	4.42 ± 0.02	274.5 ± 0.7
W205	257 ± 1	4.35 ± 0.02	276.9 ± 0.5	4.33 ± 0.03	277 ± 1
W206	254.7 ± 0.6	4.32 ± 0.02	276.9 ± 0.4	4.32 ± 0.02	276.6 ± 0.7
W207	257.0 ± 0.5	4.34 ± 0.02	277.2 ± 0.4	4.38 ± 0.02	275.9 ± 0.6
W208	256 ± 1	4.32 ± 0.02	277.5 ± 0.5	4.32 ± 0.03	278 ± 1
W209	254.2 ± 0.5	4.29 ± 0.02	277.4 ± 0.4	4.34 ± 0.02	275.7 ± 0.6
W211	256 ± 1	4.34 ± 0.03	276.9 ± 0.6	4.35 ± 0.04	277 ± 1
W212	255.4 ± 0.9	4.35 ± 0.02	276.2 ± 0.5	4.40 ± 0.03	275 ± 1
W215	255 ± 1	4.32 ± 0.03	276.8 ± 0.6	4.27 ± 0.03	279 ± 1
W216	257.3 ± 0.8	4.36 ± 0.02	277.0 ± 0.5	4.38 ± 0.02	276.2 ± 0.9
W217	258.1 ± 0.7	4.36 ± 0.02	277.4 ± 0.5	4.39 ± 0.02	276.5 ± 0.8
W218	255 ± 1	4.31 ± 0.02	277.3 ± 0.5	4.29 ± 0.03	278 ± 1
W219	256 ± 1	4.33 ± 0.02	277.1 ± 0.5	4.32 ± 0.03	278 ± 1
W220	253.1 ± 0.9	4.29 ± 0.02	276.9 ± 0.5	4.29 ± 0.03	277 ± 1

- Calculated for $A \approx 51.53 \text{ mm}^2$ (outer edge of bias ring) and $\epsilon_0 \approx 8.85 \cdot 10^{-12} \text{ F/m}$,
 $\epsilon_r = 11.75$, $|e| = 1.602 \text{ C}$

CV After Irradiation And Before Annealing

Test chip	$V_{\text{dep}} [-V]$	$N_{\text{eff}} [\cdot 10^{12} / \text{cm}^3]$ from pl.	$D_{\text{full}} [\mu\text{m}]$ from pl.	$N_{\text{eff}} [\cdot 10^{12} / \text{cm}^3]$ from sl.	$D_{\text{full}} [\mu\text{m}]$ from sl.
W204	216.8 ± 0.6	3.56 ± 0.02	281.4 ± 0.5	3.54 ± 0.01	281.9 ± 0.7
W205	235.7 ± 0.5	3.85 ± 0.02	282.1 ± 0.5	3.85 ± 0.01	282.1 ± 0.6
W207	247.1 ± 0.5	4.02 ± 0.02	282.6 ± 0.4	4.03 ± 0.01	282.2 ± 0.6
W208	168.6 ± 0.7	2.74 ± 0.01	282.7 ± 0.5	2.68 ± 0.02	286 ± 1
W209	194.1 ± 0.7	3.15 ± 0.02	283.0 ± 0.5	3.11 ± 0.02	284.6 ± 0.8
W211	86.6 ± 0.5	1.42 ± 0.01	281.2 ± 0.5	1.23 ± 0.02	302 ± 2
W212	73.1 ± 0.5	1.21 ± 0.01	280.5 ± 0.5	0.99 ± 0.01	309 ± 3
W215	226.4 ± 0.5	3.69 ± 0.01	282.3 ± 0.5	3.68 ± 0.01	282.5 ± 0.6
W216	138.7 ± 0.7	2.26 ± 0.01	282.2 ± 0.5	2.16 ± 0.02	289 ± 1
W217	184.8 ± 0.7	3.00 ± 0.02	282.8 ± 0.6	2.95 ± 0.02	285 ± 1
W218	90.9 ± 0.5	1.48 ± 0.01	282.3 ± 0.5	1.31 ± 0.01	300 ± 2
W219	104.2 ± 0.6	1.70 ± 0.01	282.1 ± 0.5	1.55 ± 0.02	296 ± 2
W220	83.2 ± 0.5	1.36 ± 0.01	282.0 ± 0.5	1.17 ± 0.01	303 ± 2

- Calculated for $A \approx 51.53 \text{ mm}^2$ (outer edge of bias ring) and $\varepsilon_0 \approx 8.85 \cdot 10^{-12} \text{ F/m}$, $\varepsilon_r = 11.75$, $|e| = 1.602 \text{ C}$

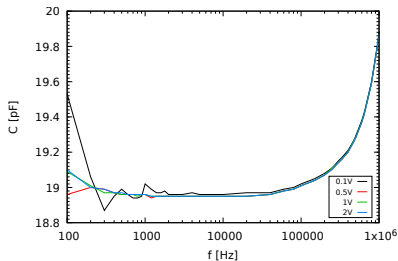
CV After Irradiation And Annealing

Test chip	$V_{\text{dep}} [-V]$	$N_{\text{eff}} [\cdot 10^{12} / \text{cm}^3]$ from pl.	$D_{\text{full}} [\mu\text{m}]$ from pl.	$N_{\text{eff}} [\cdot 10^{12} / \text{cm}^3]$ from sl.	$D_{\text{full}} [\mu\text{m}]$ from sl.
W204	214.5 ± 0.6	3.53 ± 0.02	281.0 ± 0.5	3.51 ± 0.01	281.8 ± 0.7
W205	237.1 ± 0.5	3.88 ± 0.01	281.9 ± 0.4	3.88 ± 0.01	281.7 ± 0.6
W207	246.7 ± 0.5	4.02 ± 0.01	282.3 ± 0.4	4.04 ± 0.01	281.8 ± 0.5
W208	163.9 ± 0.7	2.66 ± 0.02	282.9 ± 0.6	2.58 ± 0.02	287 ± 1
W209	190.3 ± 0.7	3.09 ± 0.02	282.8 ± 0.5	3.05 ± 0.02	284.7 ± 0.9
W211	80.4 ± 0.6	1.32 ± 0.01	281.1 ± 0.6	1.09 ± 0.02	310 ± 3
W212	63.4 ± 0.7	1.05 ± 0.01	280.6 ± 0.7	0.77 ± 0.02	326 ± 5
W215	222.2 ± 0.6	3.63 ± 0.02	282.1 ± 0.5	3.62 ± 0.01	282.4 ± 0.7
W216	137.1 ± 0.7	2.23 ± 0.01	282.5 ± 0.6	2.12 ± 0.02	290 ± 1
W217	183.4 ± 0.8	2.98 ± 0.02	282.7 ± 0.6	2.92 ± 0.02	286 ± 1
W218	81.5 ± 0.5	1.33 ± 0.01	282.6 ± 0.6	1.11 ± 0.02	309 ± 2
W219	94.2 ± 0.7	1.53 ± 0.01	282.5 ± 0.6	1.33 ± 0.02	303 ± 2
W220	59.3 ± 0.4	0.966 ± 0.008	282.4 ± 0.5	0.71 ± 0.01	329 ± 4

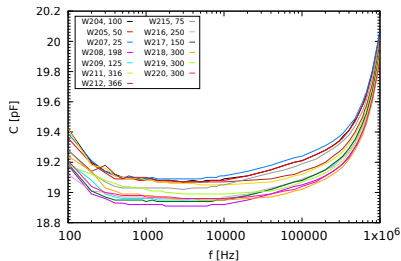
- Calculated for $A \approx 51.53 \text{ mm}^2$ (outer edge of bias ring) and $\epsilon_0 \approx 8.85 \cdot 10^{-12} \text{ F/m}$, $\epsilon_r = 11.75$, $|e| = 1.602 \text{ C}$

Frequency Dependence After Irradiation

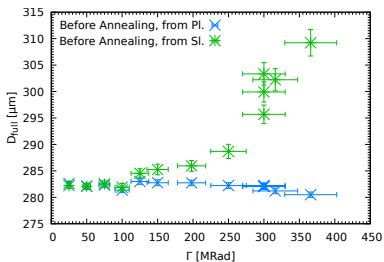
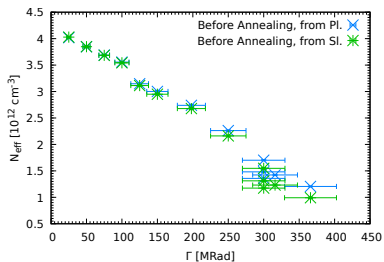
Before Annealing



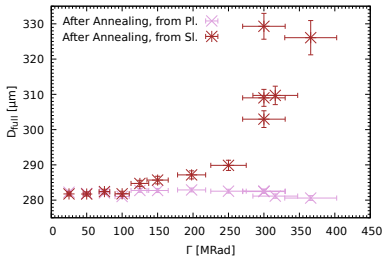
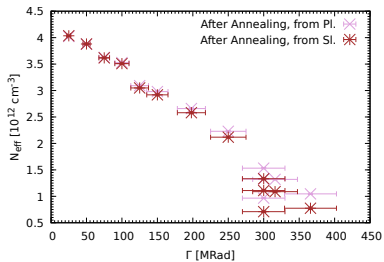
After Annealing



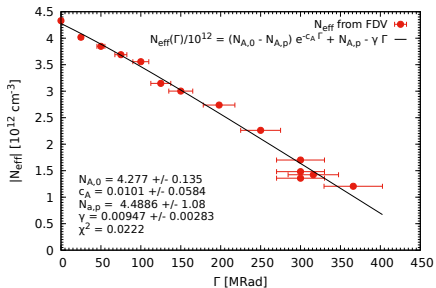
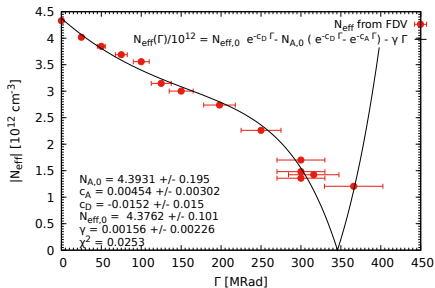
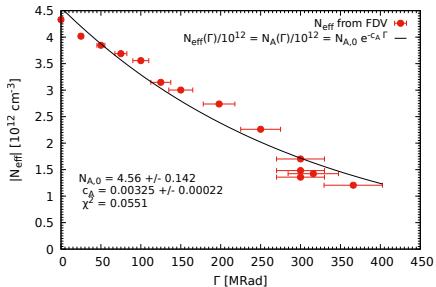
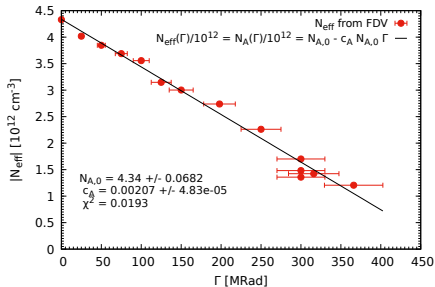
CV Parameters After Irradiation And Before Annealing



CV Parameters After Irradiation And Annealing



Acceptor Removal Parameters Acc. to Various Sources - Before Annealing



Acceptor Removal Parameters Acc. to Various Sources - After Annealing

