RADIATION DAMAGE INDUCED BY 800 MEV PROTONS IN SILICON PAD DIODES

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OUTLINE

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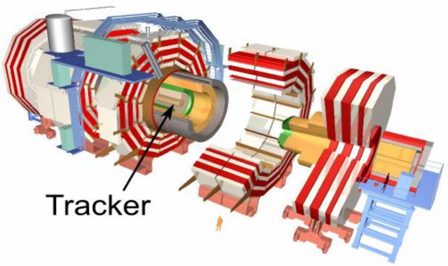
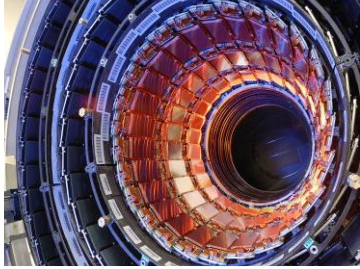


Motivation



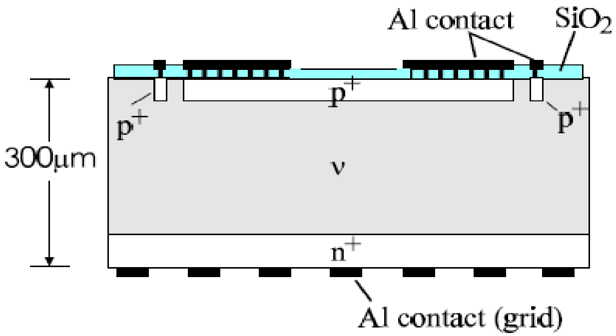
- we report on results from irradiation of silicon diodes with 800 MeV protons at LANSCE
- material is well known to RD-50 and has been studied previously after irradiation with pions and 23 GeV protons
- CERN accelerator complex will be down in 2013 and 2014 and 23 GeV protons will not be available
- are 800 MeV protons a viable substitute?

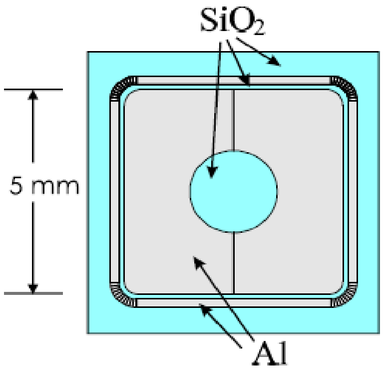
Sensor Overview

Following diodes provided by RD50 collaboration have been studied:

Material	**Type**	**Thickness (μm)**	**Active Area (mm^2)**	**Initial Dep. Voltage (V)**	**Initial N_{eff} (cm^{-3})**	**Resistance (kΩcm)**	**Manufacturer (Erfurt)**
DOFZ	n	285	25	46.30	7.497E+11	5.560	CiS
FZ	n	285	25	76.42	1.237E+12	3.710	CiS
MCz	n	300	6.25	281.45	4.128E+12	1.049	CiS
Epi	n	150	6.25	146.24	8.048E+12	0.534	CiS
Epi	n	50	25	124.94	6.573E+13	0.066	CiS

- **FZ** = Float Zone
- **DOFZ** = Diffusion Oxygen Enriched FZ
- **MCz** = Magnetic Czochralski
- **Epi** = Epitaxially grown





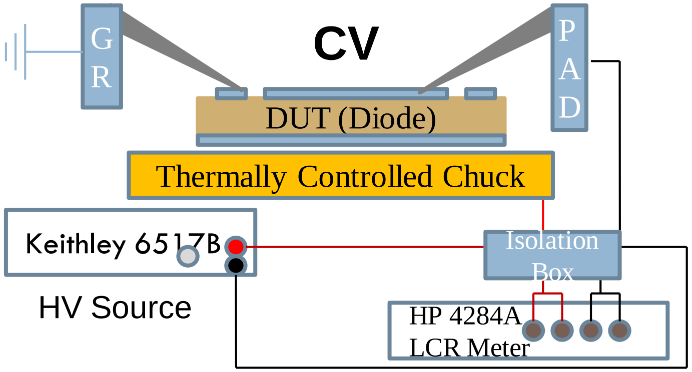
Irradiation & Annealing

Sensors were irradiated with 800 MeV protons at LANSCE proton facility (Los Alamos):

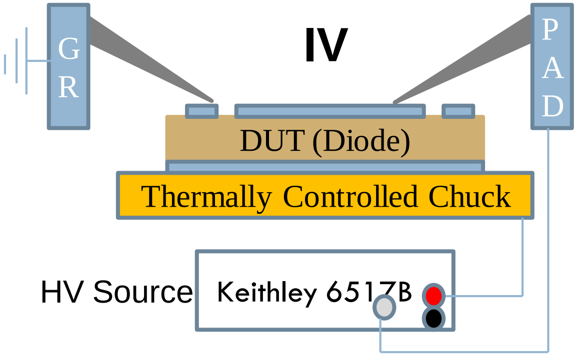
Fluences ($\kappa = 0.71$):	**FZ**	**DOFZ**	**Epi50**	**Epi150**	**MCz**
1.8×10^{13} MeV n_{eq} /cm^2	✓	✓	✓	✓	✓
4.3×10^{13} MeV n_{eq} /cm^2	✓	✓	✓	✓	✓
1.3×10^{14} MeV n_{eq} /cm^2	✓	✓	✓	✓	✓
4.6×10^{14} MeV n_{eq} /cm^2	✗	✗	✓	✓	✓

Annealing Temperature	80^0C
Annealing Steps (min)	2, 4, 8, 16, 20, 40, 80, 160, 240, 480, and 960 minutes

The sensors have been kept at < -20^0C when no measurement is ongoing to avoid further unknown annealing.



CV-IV Measurement

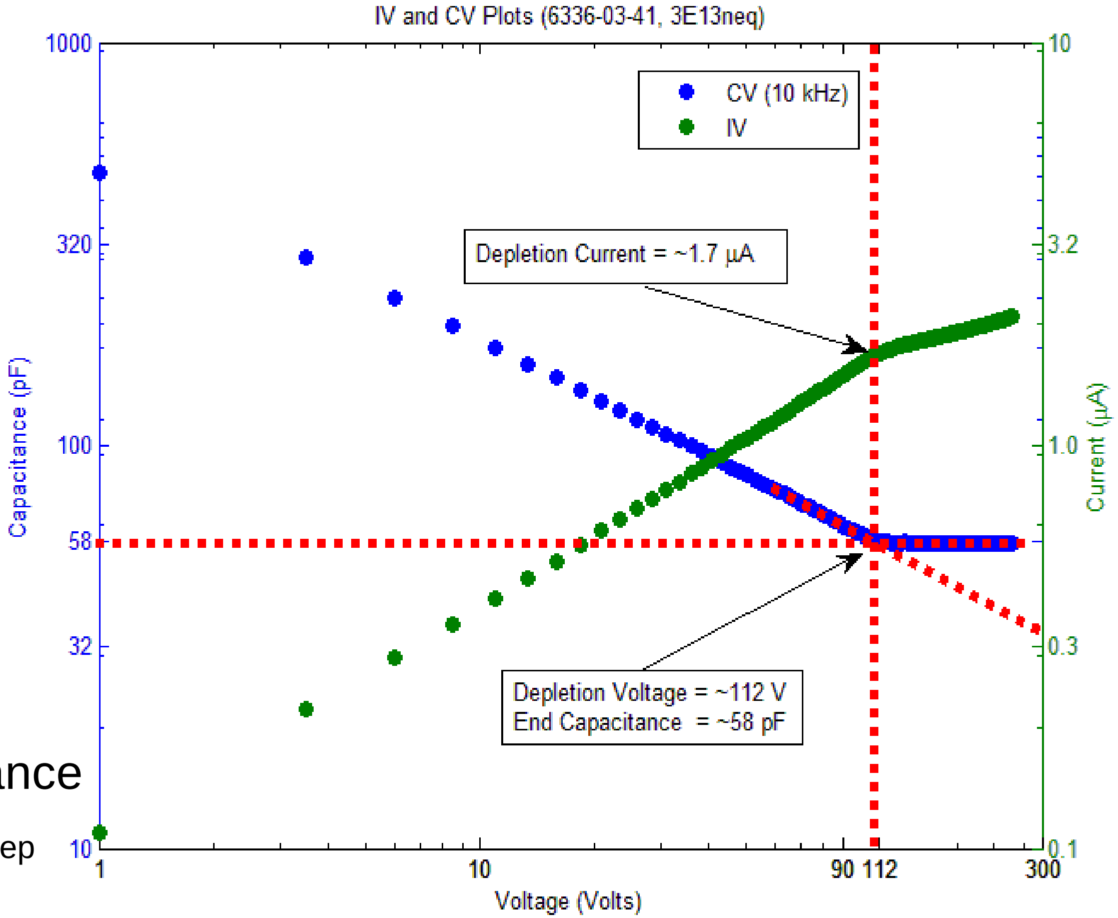


Measurements:

- with GR grounded
- at room temperature (~ 20^{0}C)
- at 10kHz for CV

Determination of sensor characteristics from IV-CV measurements:

- Scale current to 20^{0}C ref. value
- Plot CV in log-log scale
- Two linear fits on CV plot to find depletion voltage and end capacitance
- Leakage current is found from V$_{dep}$

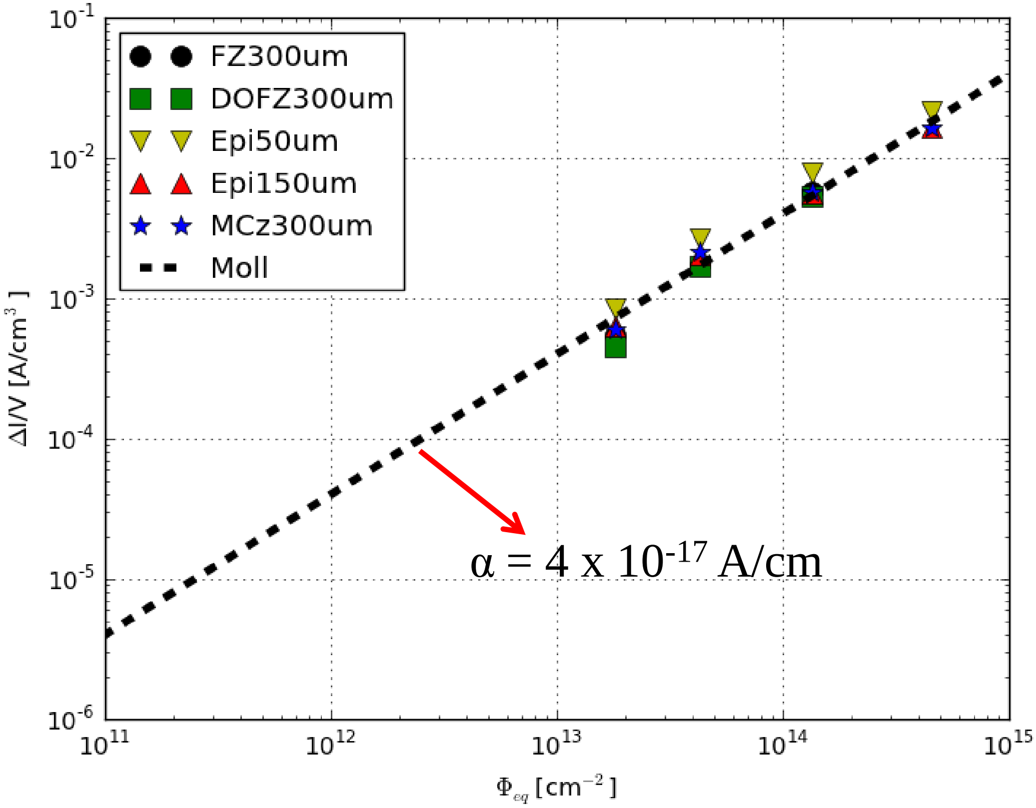

IV and CV Plots (6336-03-41, 3E13neq)

Depletion Current = ~1.7 µA

Depletion Voltage = ~112 V
End Capacitance = ~58 pF

Current related damage rate (α)

Change of current with **irradiation** after 8 min annealing at 80^0C:



$\alpha = 4 \times 10^{-17}$ A/cm

$$\Delta I = \alpha \Phi_{eq} V$$

- Measurement at room temperature.
- Current was scaled to 20^0C.
- Change of volume current agrees with expected value of $\alpha = 4 \times 10^{-17}$ A/cm * within uncertainties.

→ Irradiation process is OK

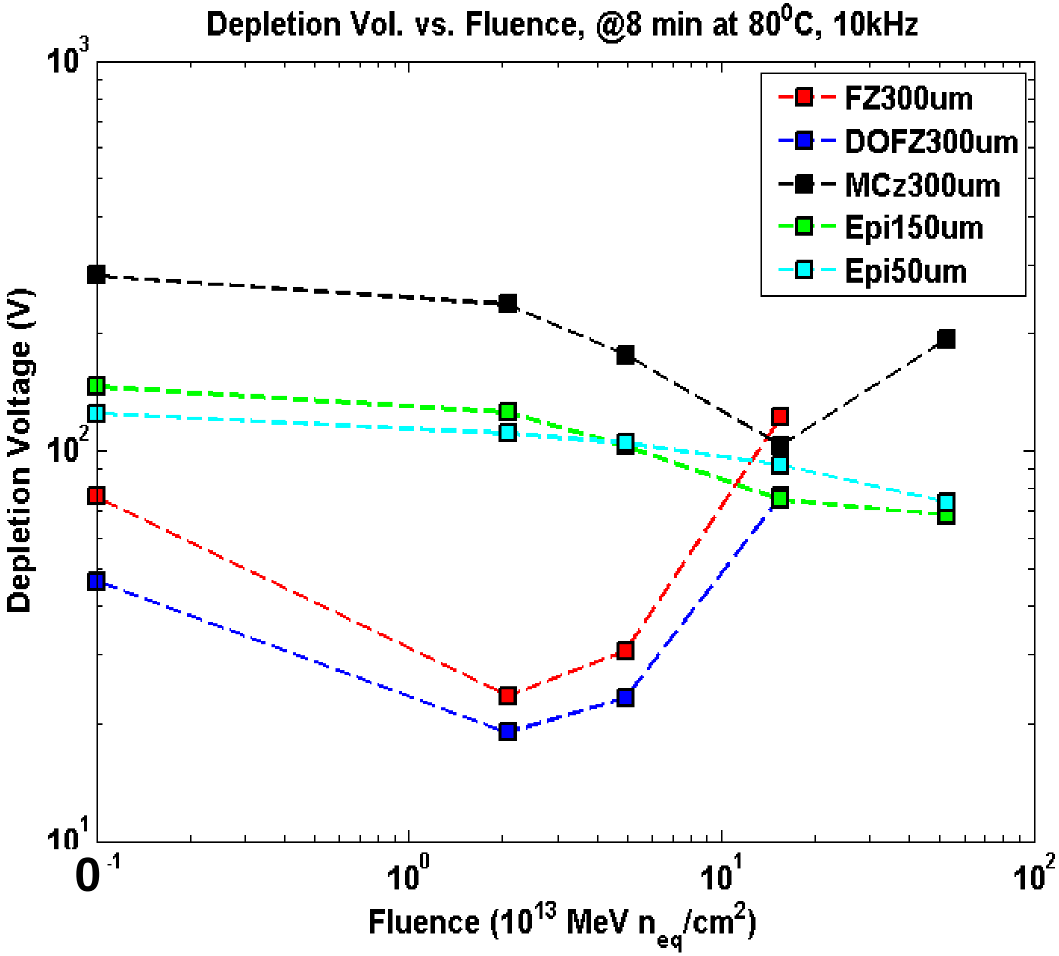
* Michael Moll, “Radiation Damage in Silicon Particle Detectors”, Ph.D. thesis, Hamburg, 1999

Depletion Voltage vs. Fluence

After 8 min annealing at 80^{0}C:

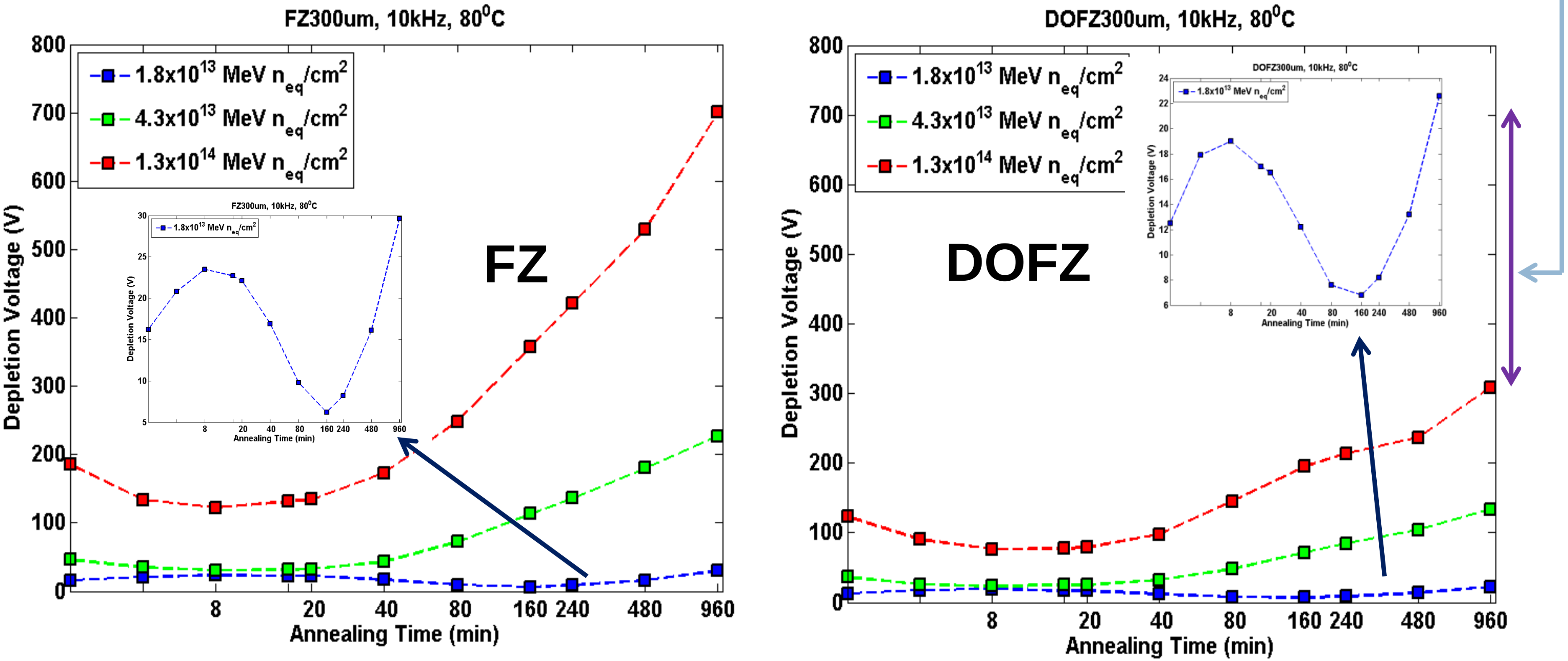
- Depletion voltage drops for all materials after irradiation with lower fluences.
- for FZ, DOFZ and MCz, depletion voltage increases at higher fluences.
- for Epi there is no increase in the depletion voltage.
- Carry out annealing study to understand changes in material.

$$\left|N_{eff}\right| = \frac{2\varepsilon\varepsilon_0}{e}\frac{V_{dep}}{d^2}$$



FZ and DOFZ Annealing Results

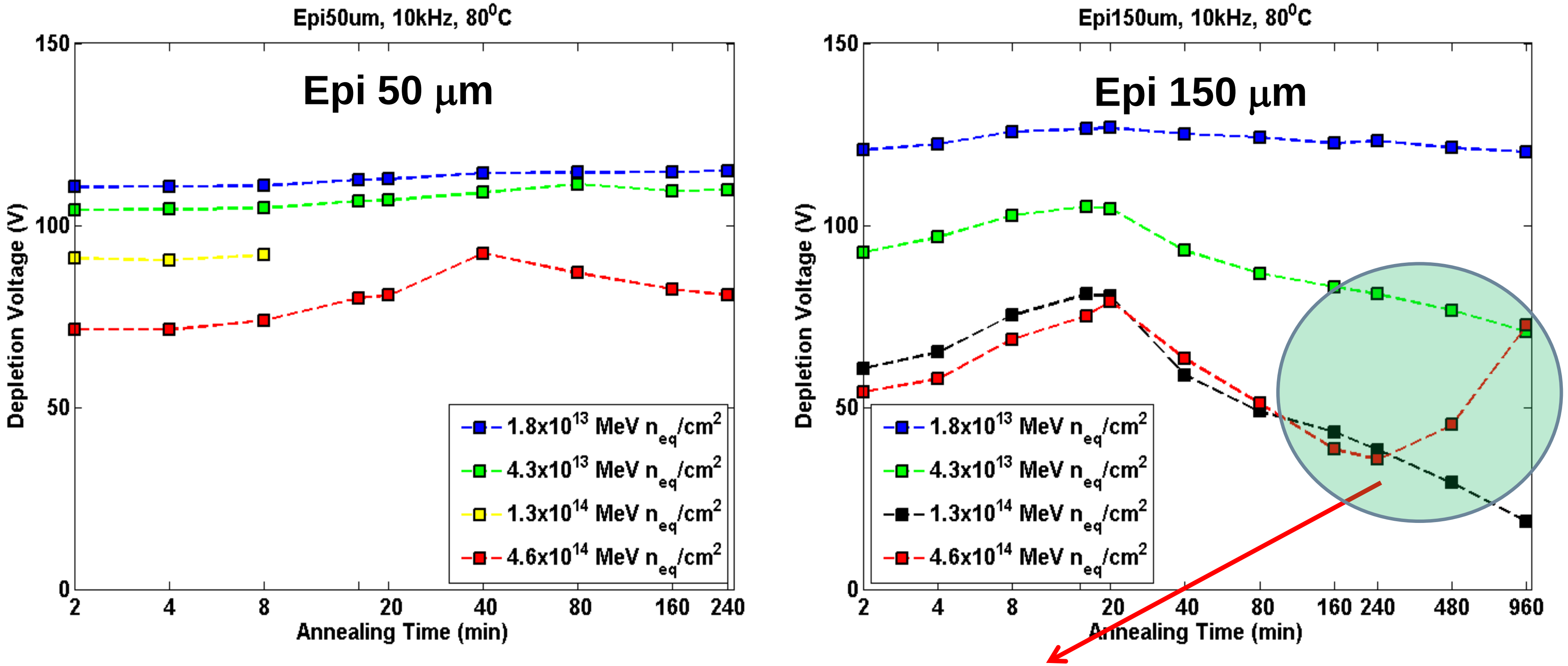
- Type inversion for both sensors after 1.8×10^{13} cm^{-2} (blue).
- DOFZ has much lower depletion voltage comparing to FZ.



Typical **n-type** and **p-type** sensor behaviors

Epi 50μm and 150μm Annealing Results

No type-inversion on Epi 50 μm and 150 μm diodes after irradiation.

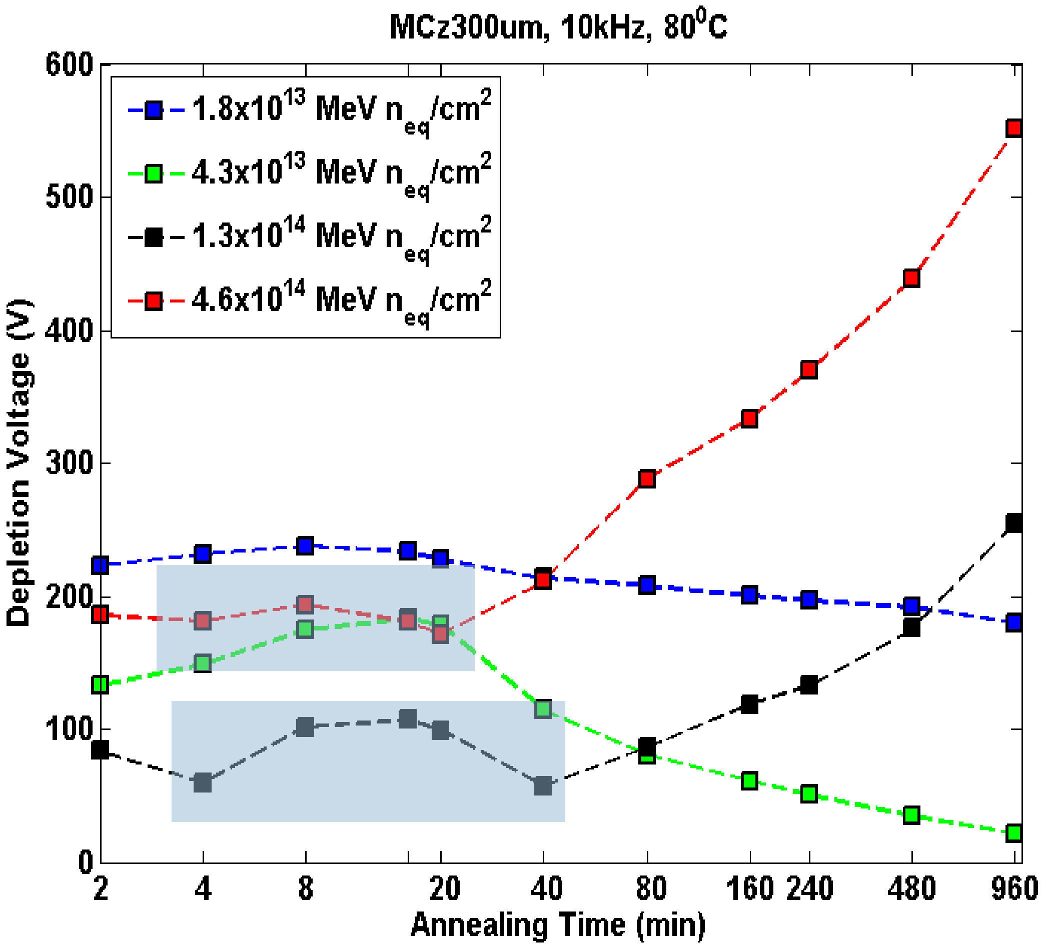


However, depletion voltage for highest irradiated Epi 150 μm is increasing after 240 min.

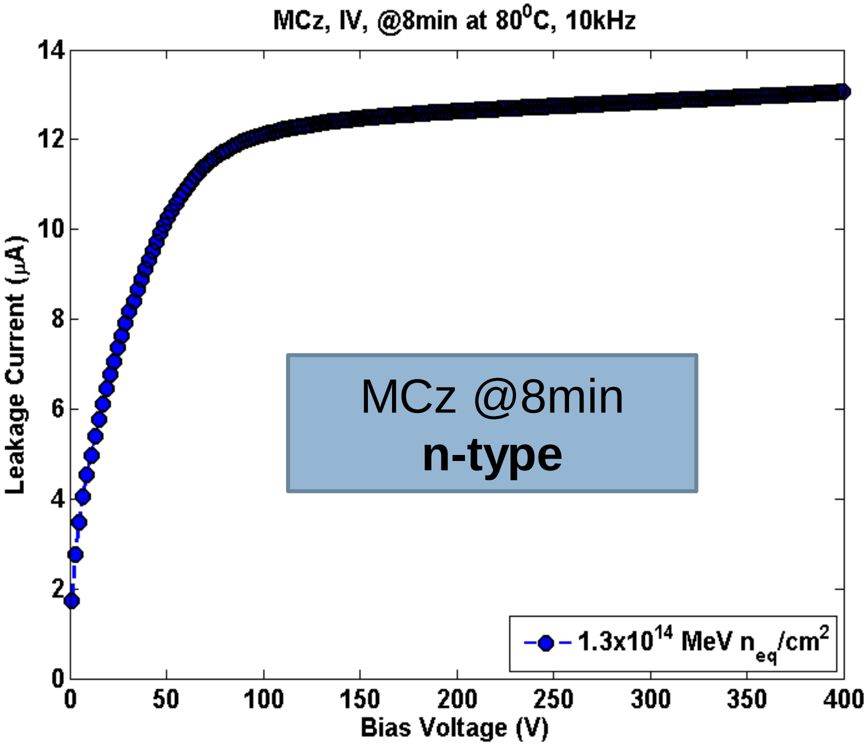
Looks like a type-inversion to a p-type-like diode!

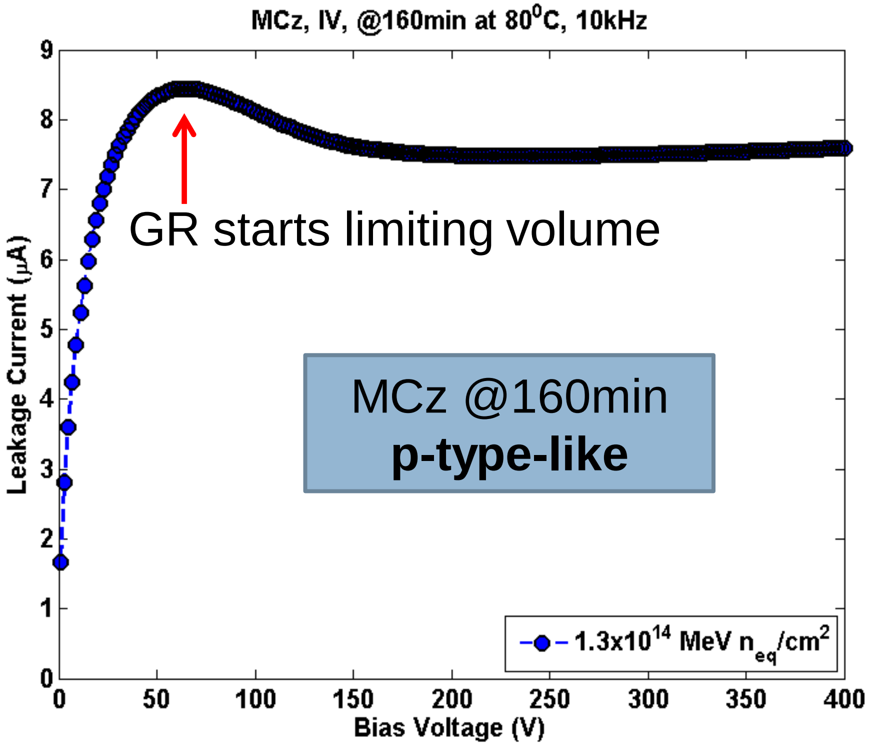
MCz Annealing Results

- MCz diodes type-inverted after irradiation with fluence ≥ 1.3E14
- During short term annealing, depletion voltage first decreases then increases (type inversion p→n)
- During long term annealing, depletion voltage first decreases then increases (second type inversion n→p).
- This behavior has been confirmed by TCT measurements at Hamburg University.

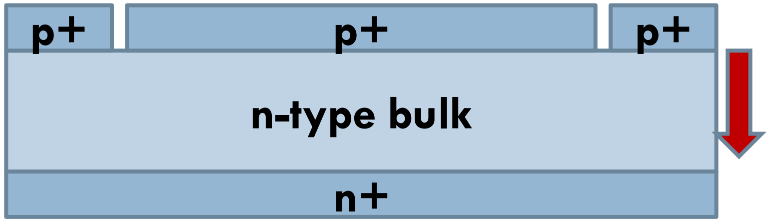


Another way to determine type inversion

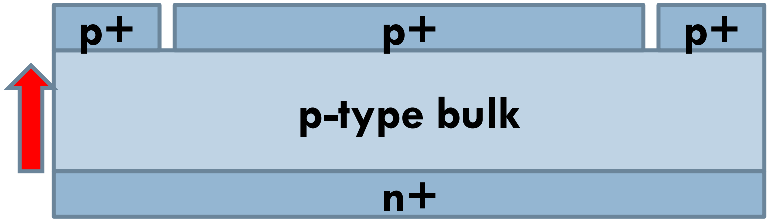




GR starts limiting volume



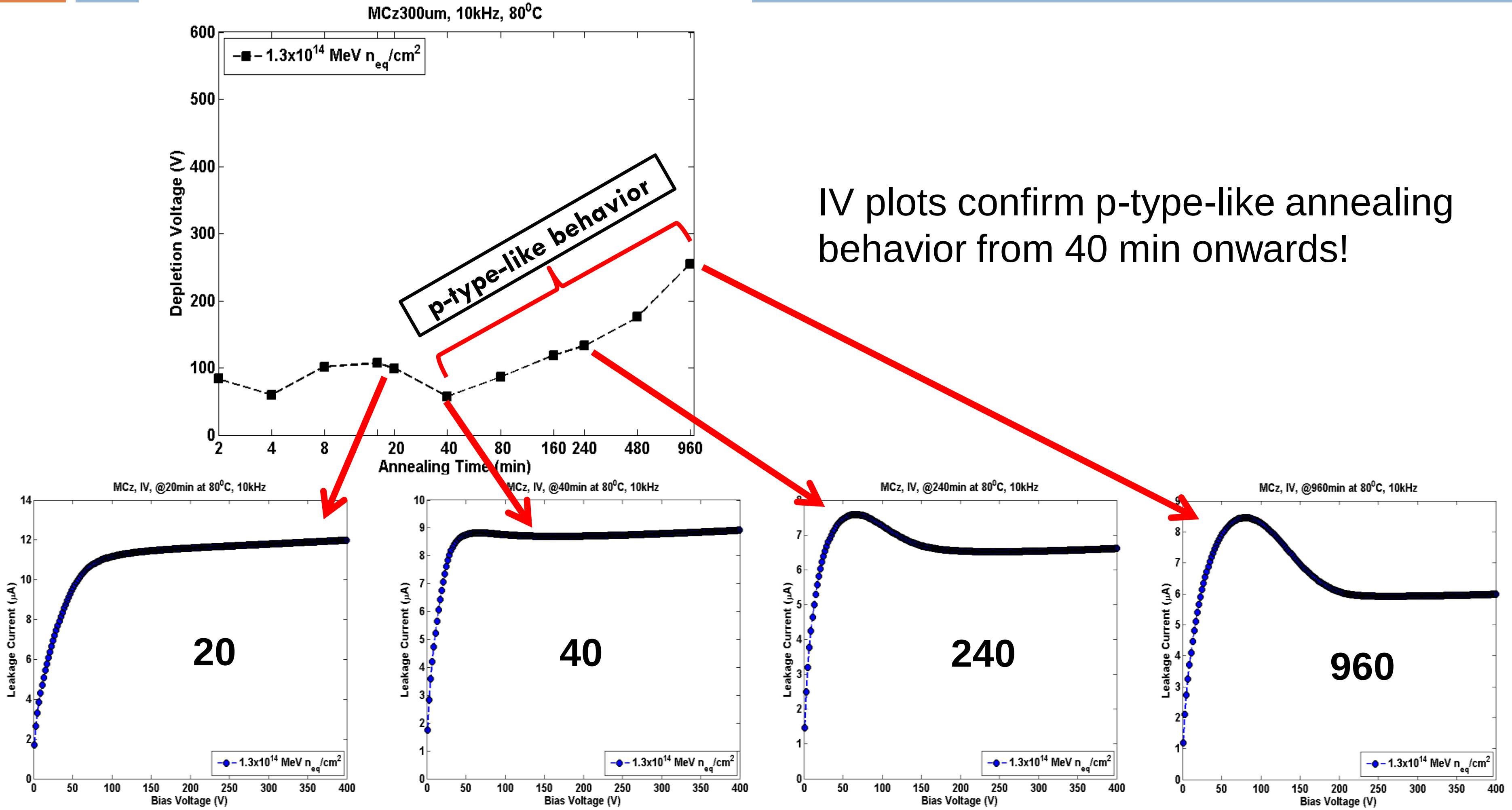
Depletion
Growth
Direction



Not type-inverted sensor

Type-inverted sensor

IV Plots for MCz ($1.3\text{x}10^{14}$ MeV n_{eq}/cm^2) at different annealing steps:



IV plots confirm p-type-like annealing behavior from 40 min onwards!

Hamburg Model (FZ and DOFZ)

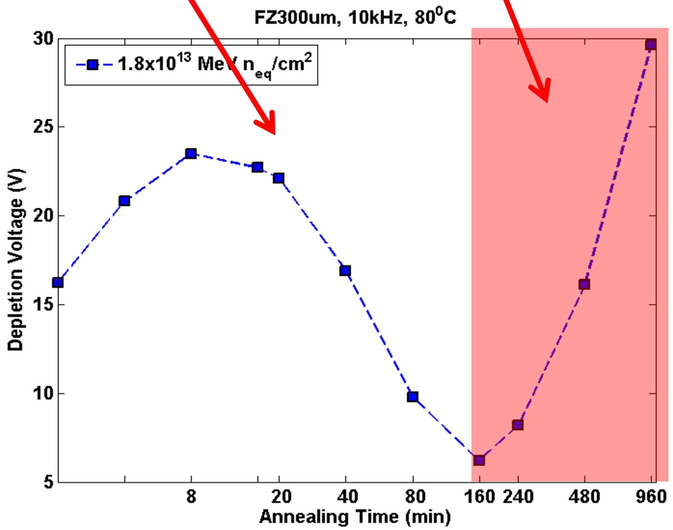
$$\Delta N_{eff} = N_{eff,0} - N_{eff}$$

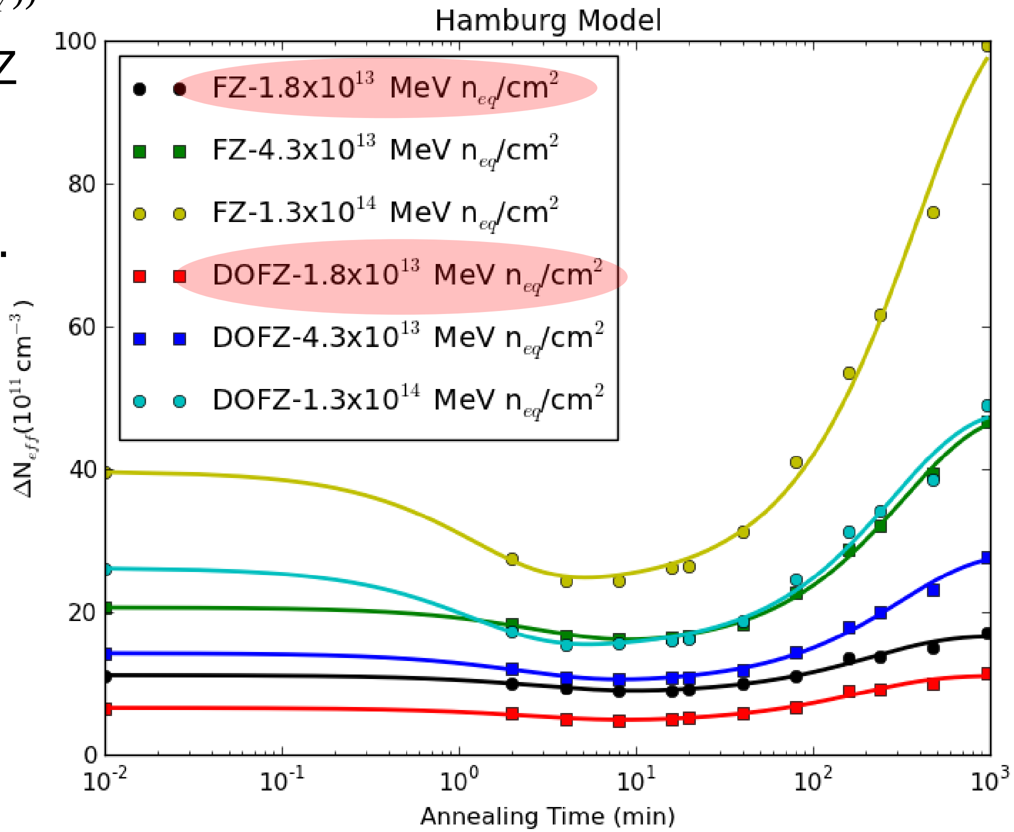
$$\Delta N_{eff} = N_A + N_C + N_Y$$

$$\begin{cases} N_A = g_a \Phi_{eq} \exp(-t/\tau_a) \\ N_C = N_{C0}\left(1-\exp(-c\Phi_{eq})\right) + g_c \Phi_{eq} \\ N_Y = g_Y \Phi_{eq} (1-\exp(t/\tau_Y)) \end{cases}$$

- For type-inverted diodes, the space charge is less than zero ($N_{eff} < 0$).

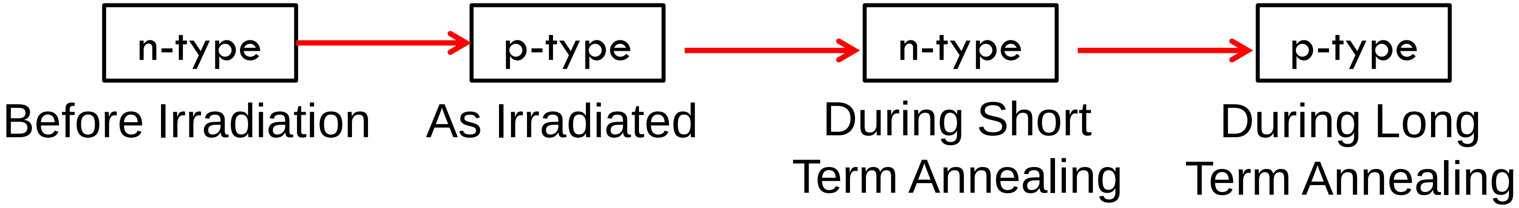
- For the least irradiated FZ and DOFZ diodes (highlighted in the legend): $N_{eff} > 0$ up to 80min and $N_{eff} < 0$ afterwards.





Summary

- Diode sensors made of n-type MCz, FZ and Epi grown silicon of different thicknesses were irradiated with 800 MeV protons at the LANSCE proton facility (Los Alamos).
- FZ, DOFZ and Epi diodes behave as expected from the results with pion and 23 GeV proton irradiations.
- The type-inverted MCz sensors after irradiation appeared to be having multiple type-inversions during annealing process as opposed to the results found by measurements using 23 GeV protons in which no type-inversion was observed:



n-type → p-type → n-type → p-type

Before Irradiation | As Irradiated | During Short Term Annealing | During Long Term Annealing

- The annealing study will be carried on for a few more steps up to 10000 minutes and the application of Hamburg Model to Epi and MCz diode results will be investigated.
- We will further compare these results to irradiation with pions and 23 GeV protons
- It looks like 800 MeV protons can replace 23 GeV protons for irradiation

References

- Michael Moll, “Radiation Damage in Silicon Particle Detectors”, Ph.D. thesis, Hamburg, 1999.
- Gerhard Lutz, “Semiconductor Radiation Detectors”, Springer-Verlag Berlin Heidelberg 1999, 2007.

BACK-UP

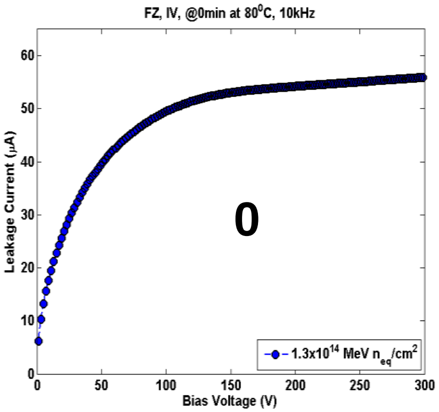
FZ and DOFZ Hamburg Model Fitting Parameters

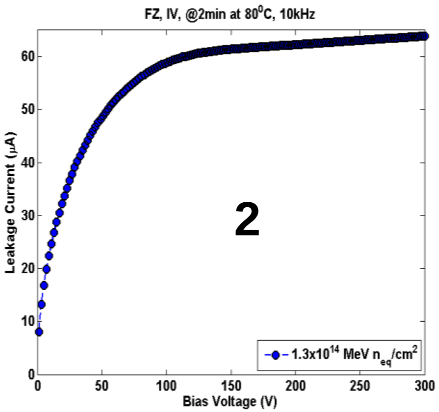
Sensor	Fluence [MeV n_{eq}/cm^2]	g_a [10^{-2} cm^{-1}]	$\tau_a(80^0C)$ [min]	g_Y [10^{-2} cm^{-1}]	$\tau_Y(80^0C)$ [min]	N_C [10^{11} cm^{-3}]	$N_C = \Delta N_{eff}$ (@8min) [10^{11} cm^{-3}]
FZ	1.8e13	1.47 ± 0.28	3.15 ± 1.39	4.53 ± 0.26	214 ± 35	8.52 ± 0.33	8.95
FZ	4.3e13	1.34 ± 0.17	3.13 ± 0.89	7.69 ± 0.20	324 ± 23	14.91 ± 0.42	16.27
FZ	1.3e14	1.21 ± 0.22	1.26 ± 0.67	6.01 ± 0.31	386 ± 50	23.49 ± 1.40	24.42
DOFZ	1.8e13	1.14 ± 0.26	2.84 ± 1.48	3.64 ± 0.22	187 ± 33	4.50 ± 0.30	4.792
DOFZ	4.3e13	0.99 ± 0.15	2.40 ± 0.83	4.25 ± 0.17	312 ± 34	9.96 ± 0.35	10.551
DOFZ	1.3e14	0.86 ± 0.16	1.23 ± 0.69	2.51 ± 0.17	282 ± 51	14.67 ± 1.06	15.689

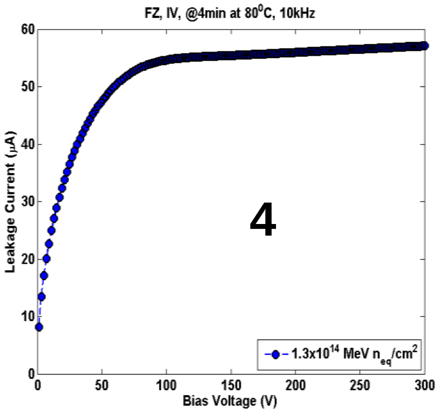
Calculated from Hamburg model fit

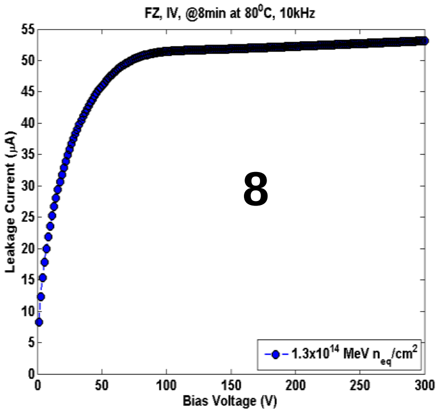
Closest annealing step to local minimum of ΔN_{eff} vs. annealing time plot.

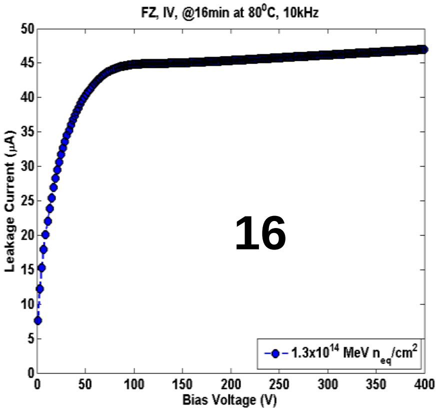
IV Plots for FZ (1.3x10^{14} MeV n$_{eq}$/cm^2) in successive annealing steps:

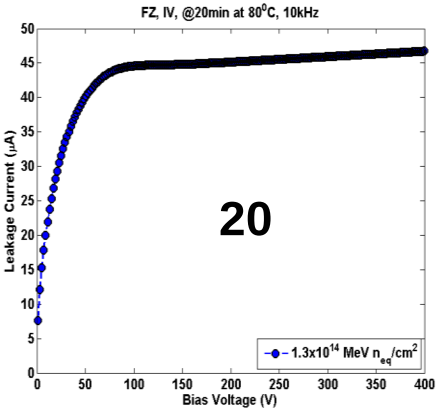


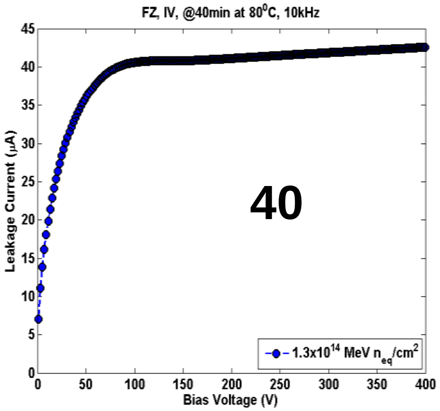


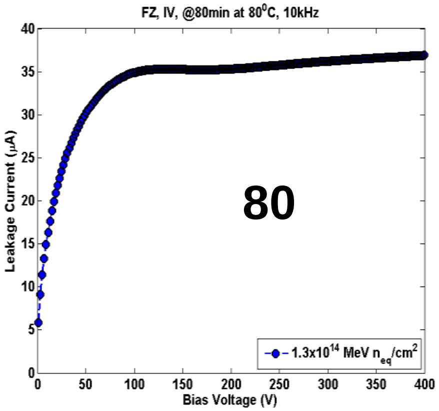


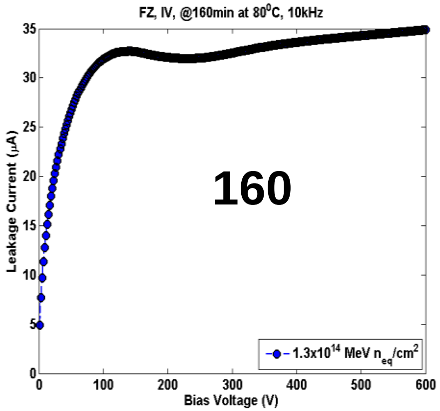


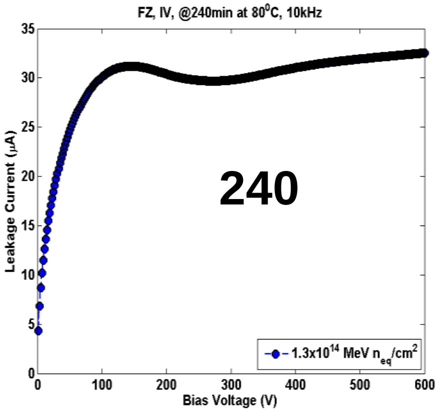


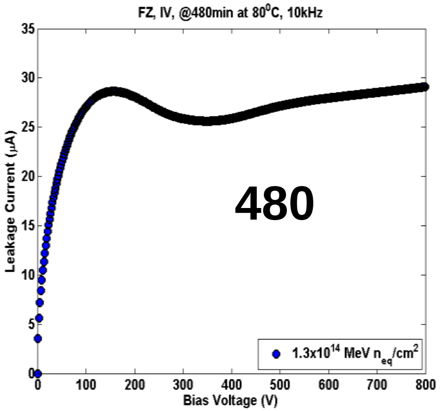


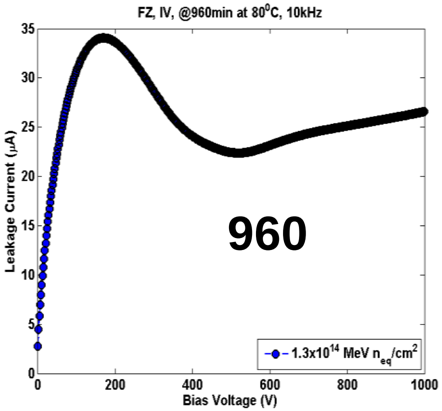




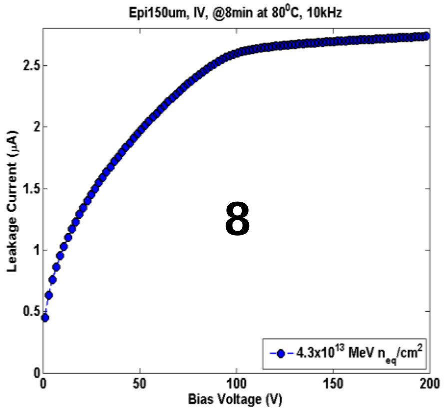


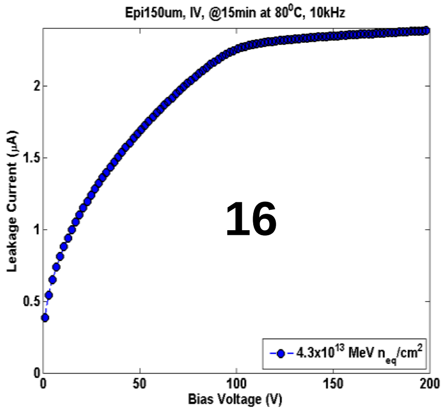


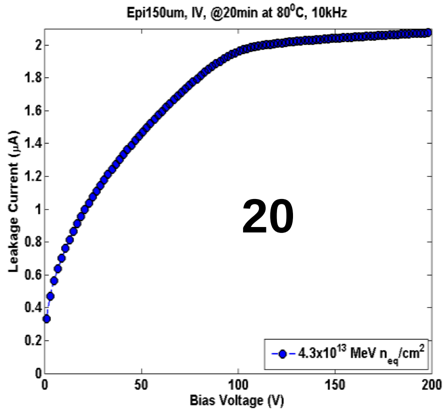


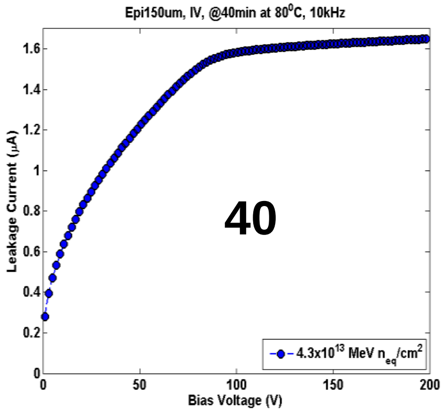


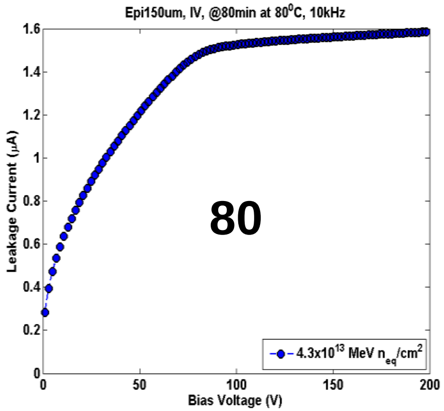
IV Plots for Epi (4.3x10^{13} MeV n$_{eq}$/cm^2) in successive annealing steps:

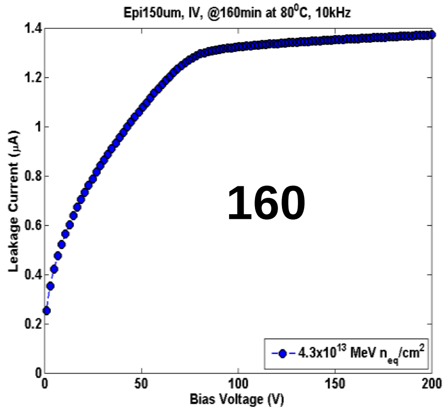

Epi150um, IV, @8min at 80^{0}C, 10kHz

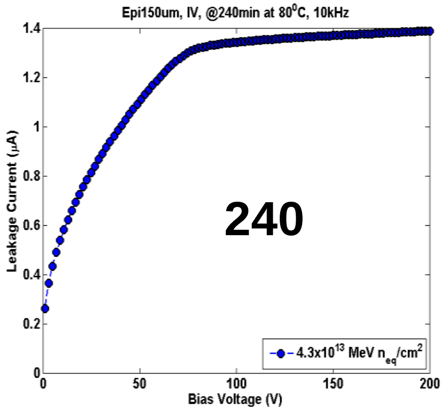

Epi150um, IV, @15min at 80^{0}C, 10kHz

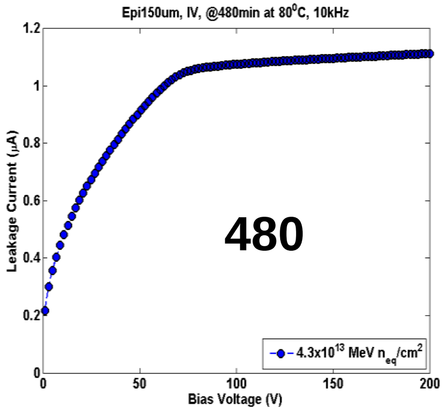

Epi150um, IV, @20min at 80^{0}C, 10kHz

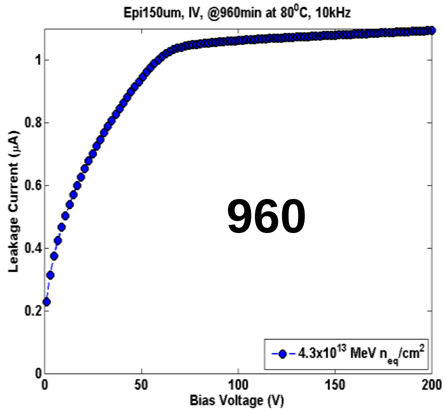

Epi150um, IV, @40min at 80^{0}C, 10kHz


Epi150um, IV, @80min at 80^{0}C, 10kHz

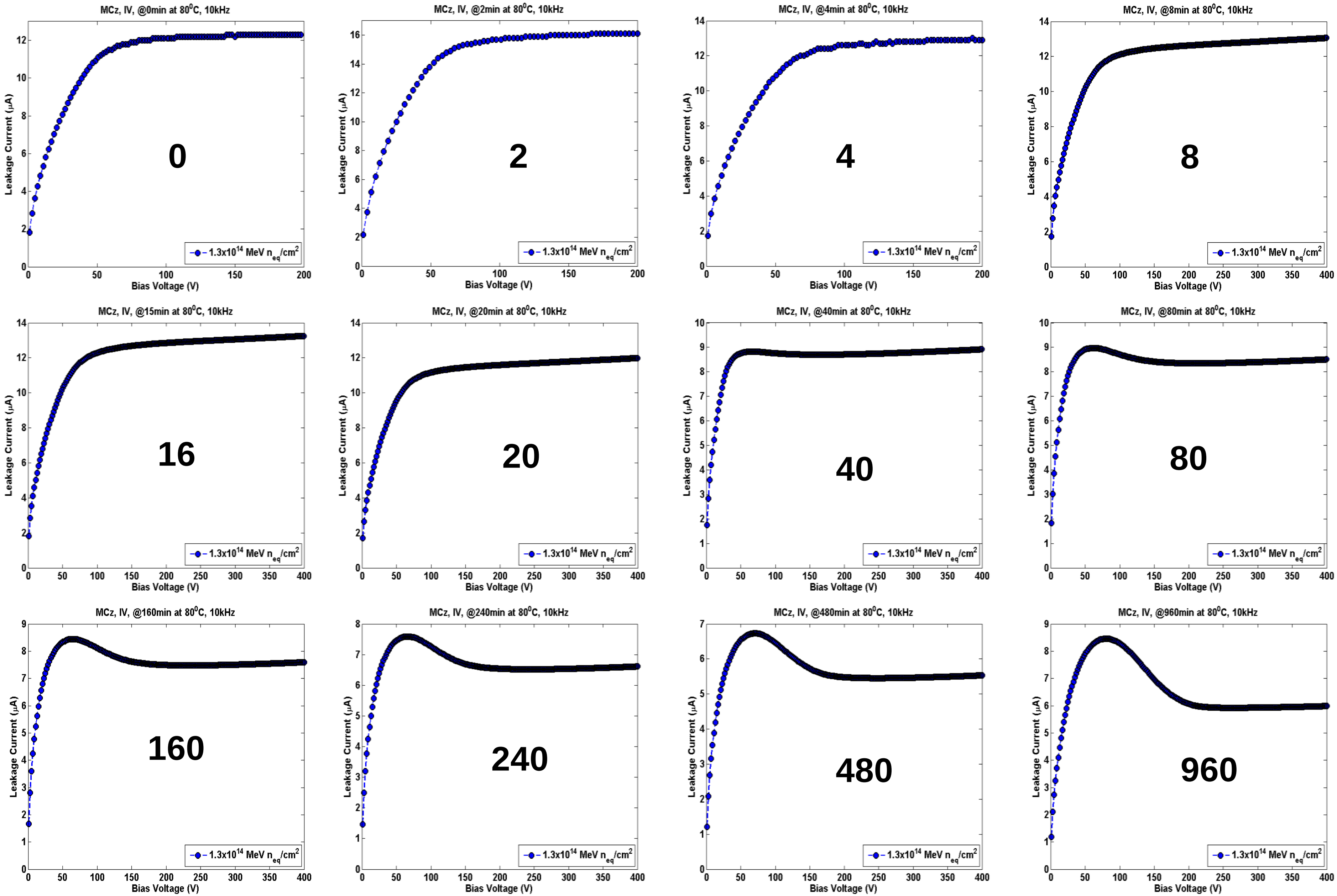

Epi150um, IV, @160min at 80^{0}C, 10kHz


Epi150um, IV, @240min at 80^{0}C, 10kHz

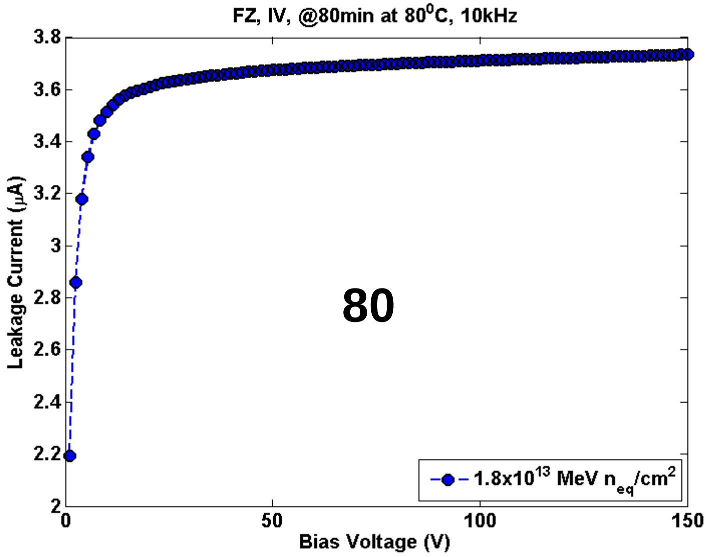

Epi150um, IV, @480min at 80^{0}C, 10kHz


Epi150um, IV, @960min at 80^{0}C, 10kHz

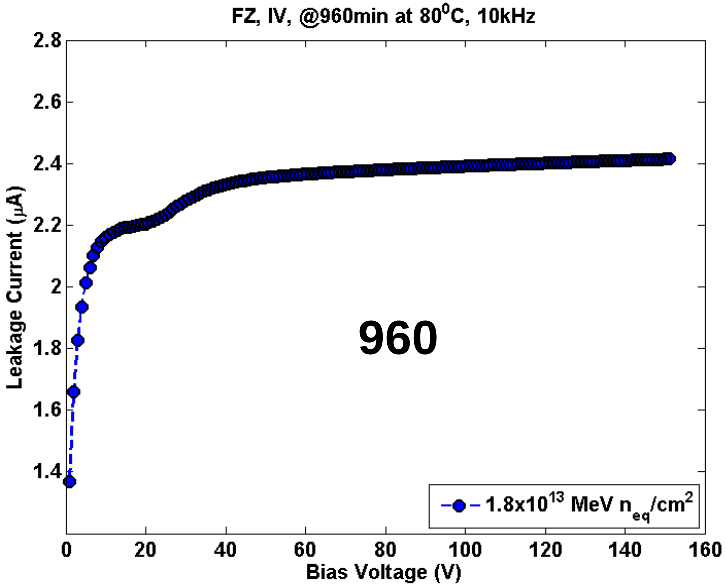
IV Plots for MCz (1.3x10^{14} MeV n_{eq}/cm^2) in successive annealing steps:

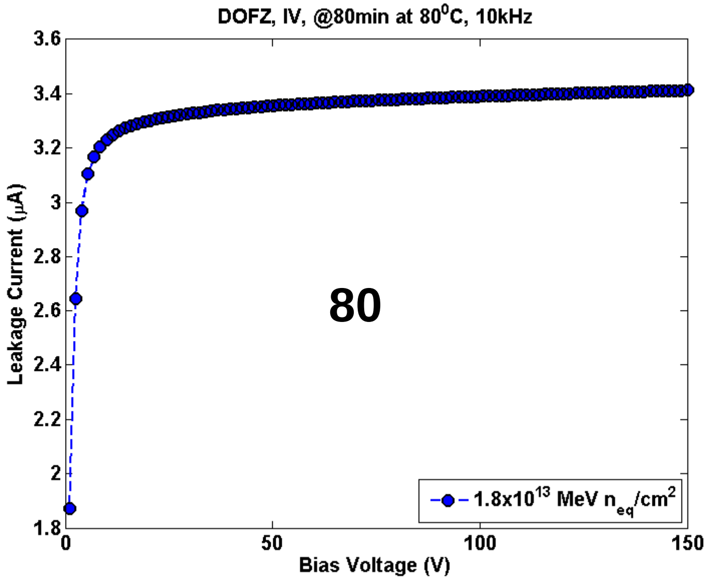


Current vs. Voltage for FZ&DOFZ

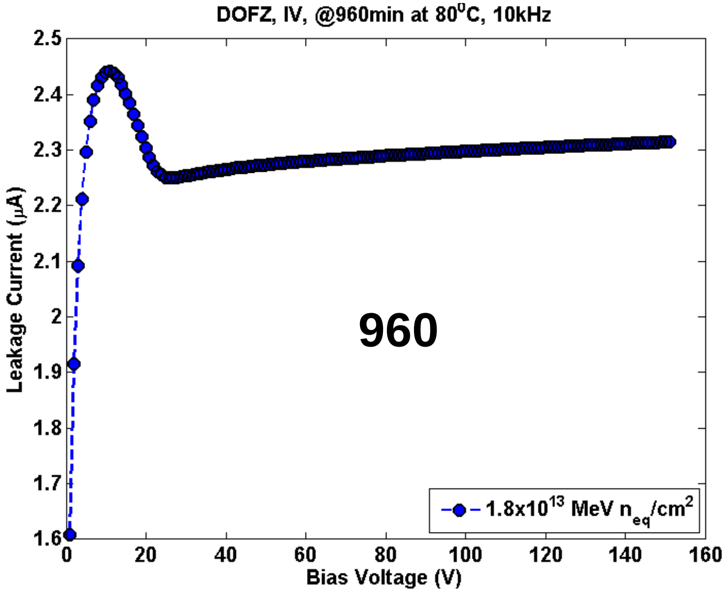


FZ

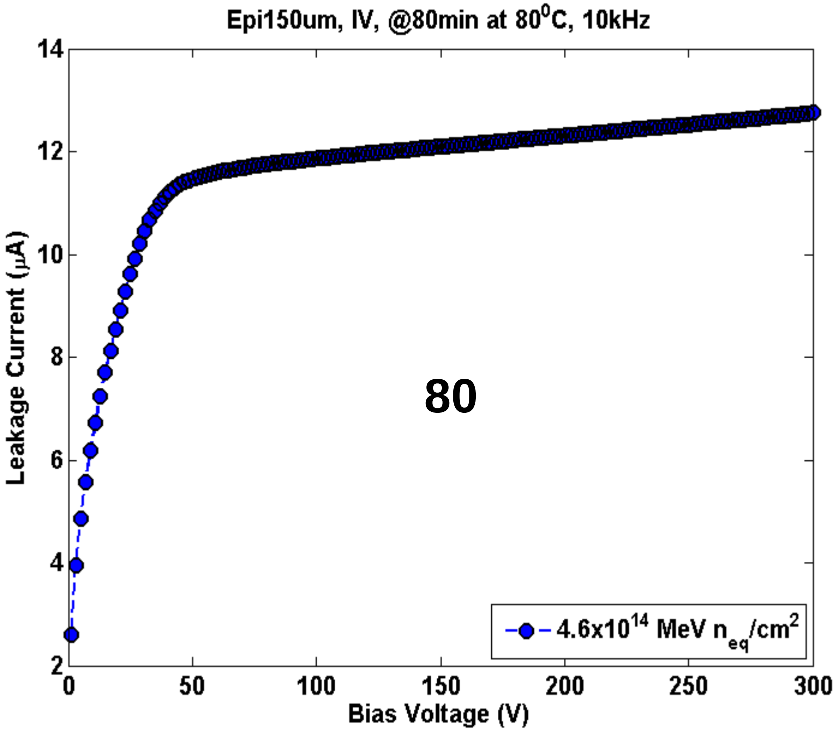


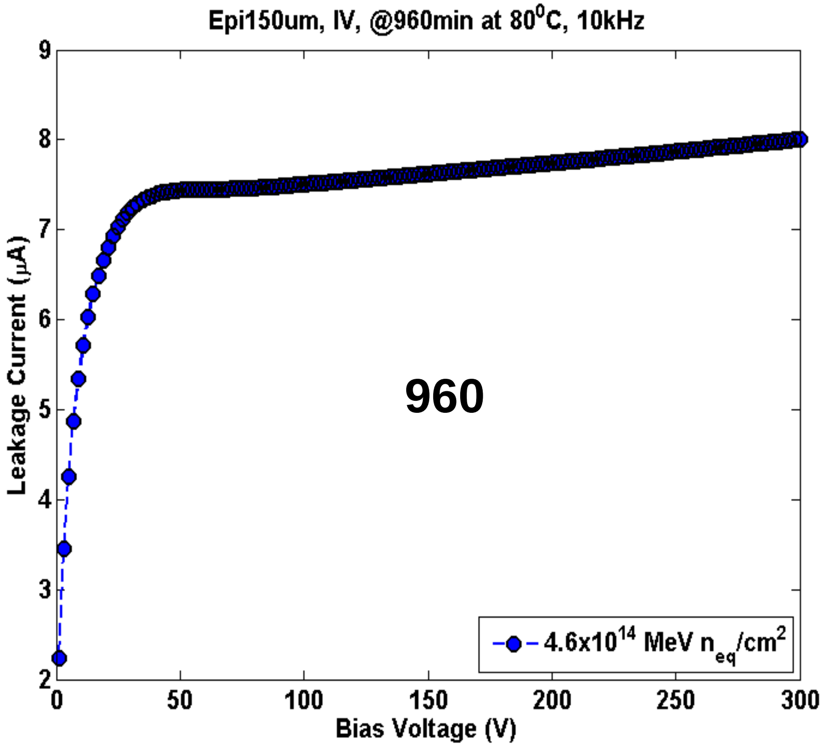


DOFZ



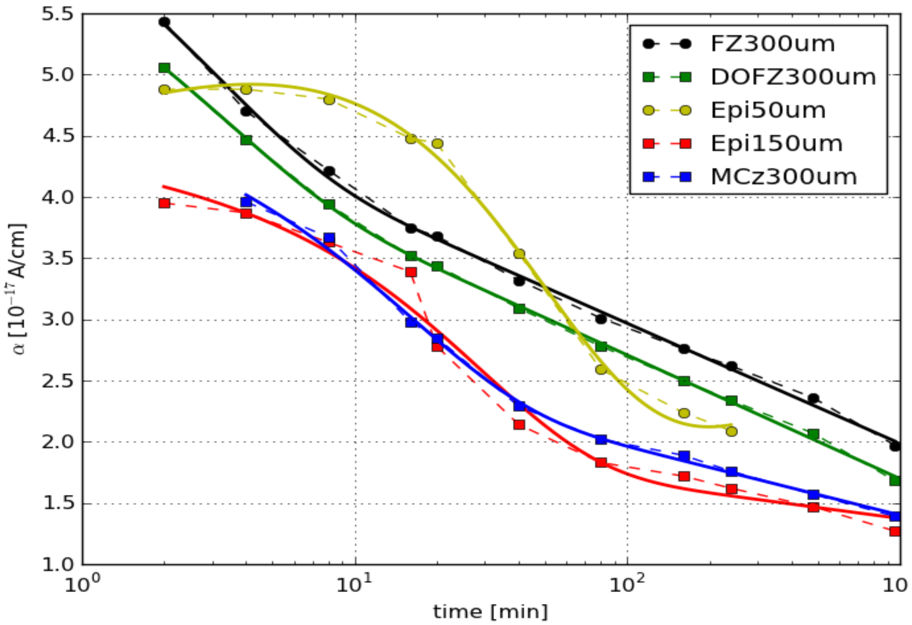
Current vs. Voltage for Epi150um



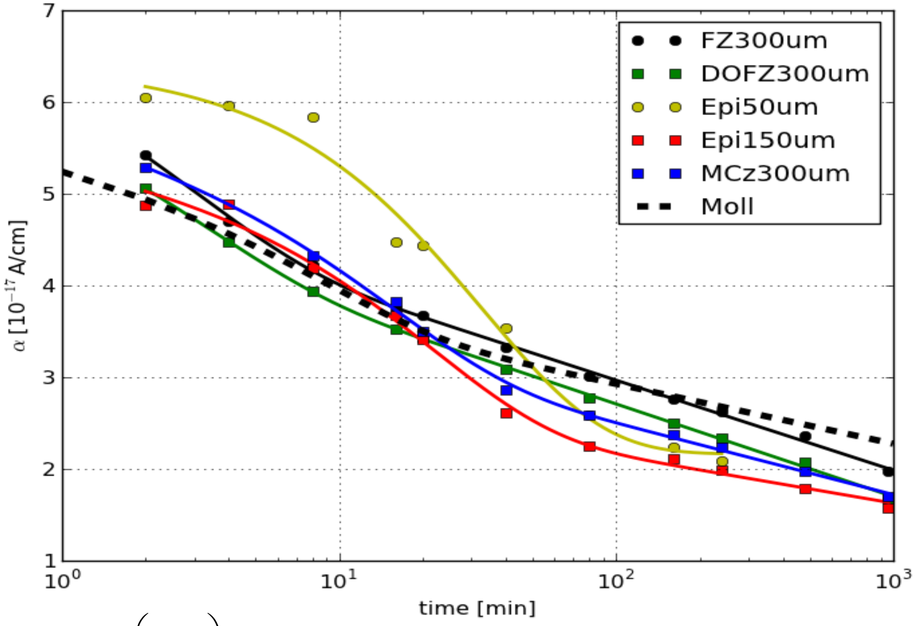


Annealing of current related damage rate (α)

Using all of the available data:



After removing 4th fluences for MCz and Epi150:



Annealing behavior of α at $T_a = 80^0$C:

$$\alpha(t) = \alpha_I \cdot \exp\left(-\frac{t}{\tau_I}\right) + \alpha_0 - \beta \cdot \ln(t/t_0)$$

t_0 = 1 min

Sensor	α_I 10^{-17} A/cm	τ_I min	α_0 10^{-17} A/cm	β 10^{-18} A/cm
FZ	1.57±0.21	3.15±0.62	4.93±0.06	4.26±0.30
DOFZ	1.11±0.10	3.53±0.50	4.73±0.04	4.39±0.08
Epi50	4.61±0.39	50.46±2.94	0.18±0.48	-3.50±0.92
Epi150	2.05±0.47	29.33±6.13	2.26±0.55	1.13±0.94
MCz	1.63±0.14	16.54±2.05	3.08±0.16	2.43±2.81

Sensor	α_I 10^{-17} A/cm	τ_I min	α_0 10^{-17} A/cm	β 10^{-18} A/cm
FZ	1.47±0.21	3.15±0.62	4.93±0.06	4.26±0.13
DOFZ	1.11±0.10	3.53±0.50	4.73±0.04	4.39±0.08
Epi50	4.21±1.18	33.16±4.67	2.21±1.40	0.08±2.71
Epi150	2.19±0.30	22.04±3.10	3.18±0.34	2.25±0.60
MCz	1.66±0.16	15.98±1.80	4.06±0.17	3.38±0.30