University of New Mexico

Annealing Effects on Depletion Voltage and Capacitance of Float Zone and Magnetic Czochralski Silicon Diodes After 800 MeV Proton Exposure

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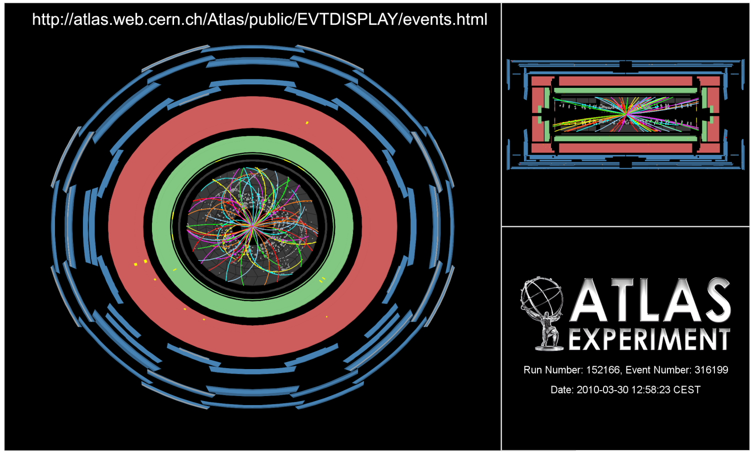
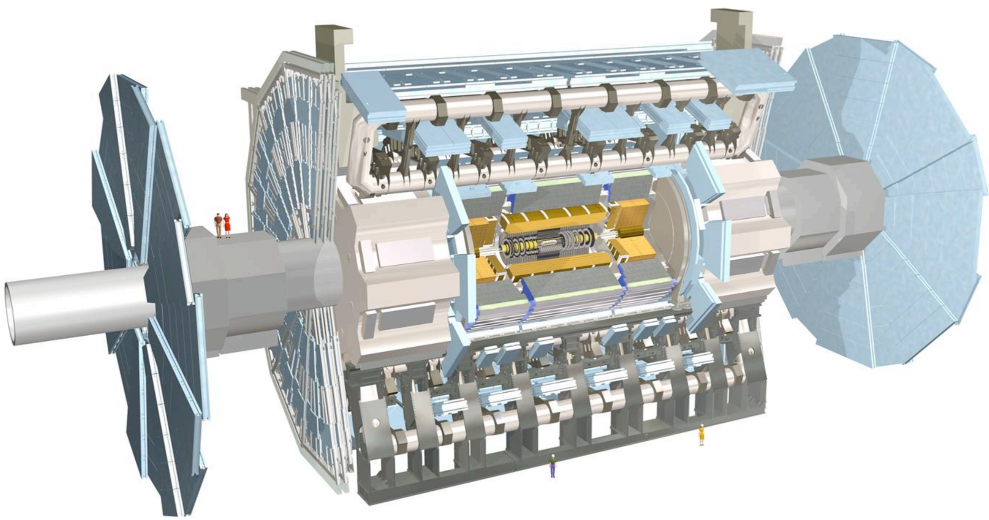
Outline

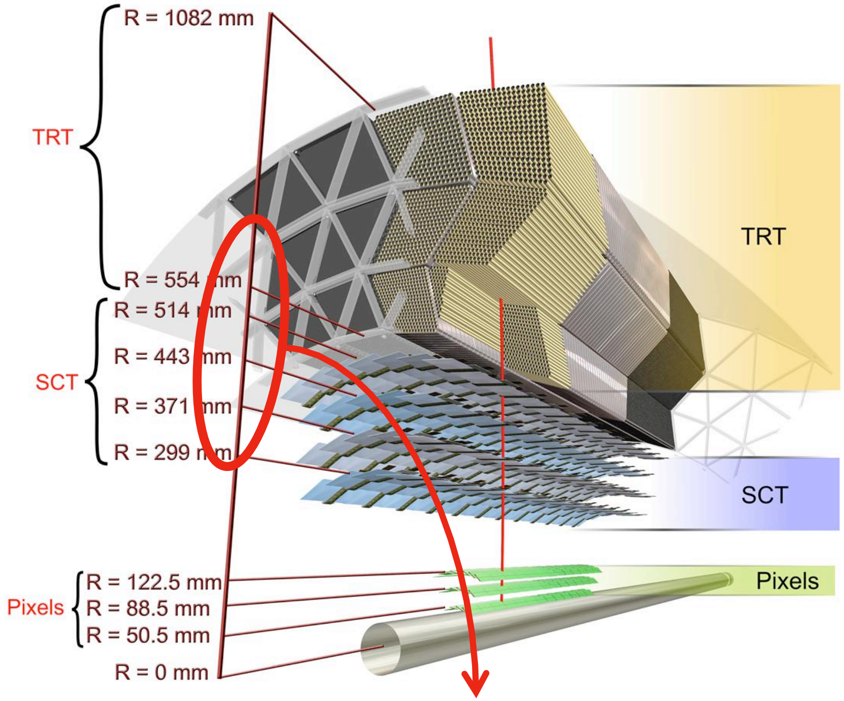
- Motivation
- Experiment Set up
- V_{fd} Extraction
- V_{fd} dependence on fluence and annealing
- Comparison of V_{fd} inversion after annealing

Motivation: ATLAS



The Si tracking detectors in ATLAS are an integral part of finding new physics. The luminosity of the sLHC will require more radiation hard Si detector technologies.





sLHC short strips: $7x10^{14}\ n_{eq}/cm^2$

Motivation

ATLAS Upgrade will reach fluences of 7×10^{14} n_{eq}/cm^2 for the short Si strip detectors. The work presented here is part of a larger effort by the RD50 collaboration to fully characterize different types of Si sensors.

Electrical Properties:

- Type Inversion (N_{eff})
- *Depletion Voltage (V_{fd})*
- Efficiency (from CCE)

Dependence on:

- *Proton*, Neutron, Pion Irradiation
- *Annealing*

This Talk: a detailed study on V_{fd} behavior after proton irradiation and annealing.

Annealing behavior is critical to predict the performance of the detectors during maintenance periods when cooling may be turned off. It may also be used to recover the depletion voltage of the detector if the annealing is well understood.

Irradiations/Annealing

Irradiations:

- 800 MeV protons at Los Alamos
- Hardness Factor: 0.71
- 5e11 protons per pulse at 1 Hz
- stored in freezer immediately after
- Fluences:
    - 1.1×10^{14} p/cm^2 = 7.8×10^{13} n_{eq}/cm^2
    - 2.2×10^{14} p/cm^2 = 1.5×10^{14} n_{eq}/cm^2
    - 1.5×10^{15} p/cm^2 = 1.1×10^{15} n_{eq}/cm^2

Annealing:

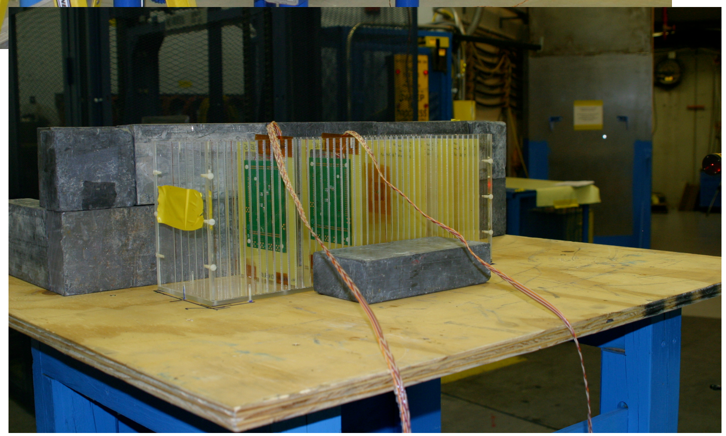
- Steps: 0, 10, 20, 40, 60, 80, 100, 120, 140, 160, 200, 300, 500, 1,000 and 10,000 minutes at 60 °C

Devices:

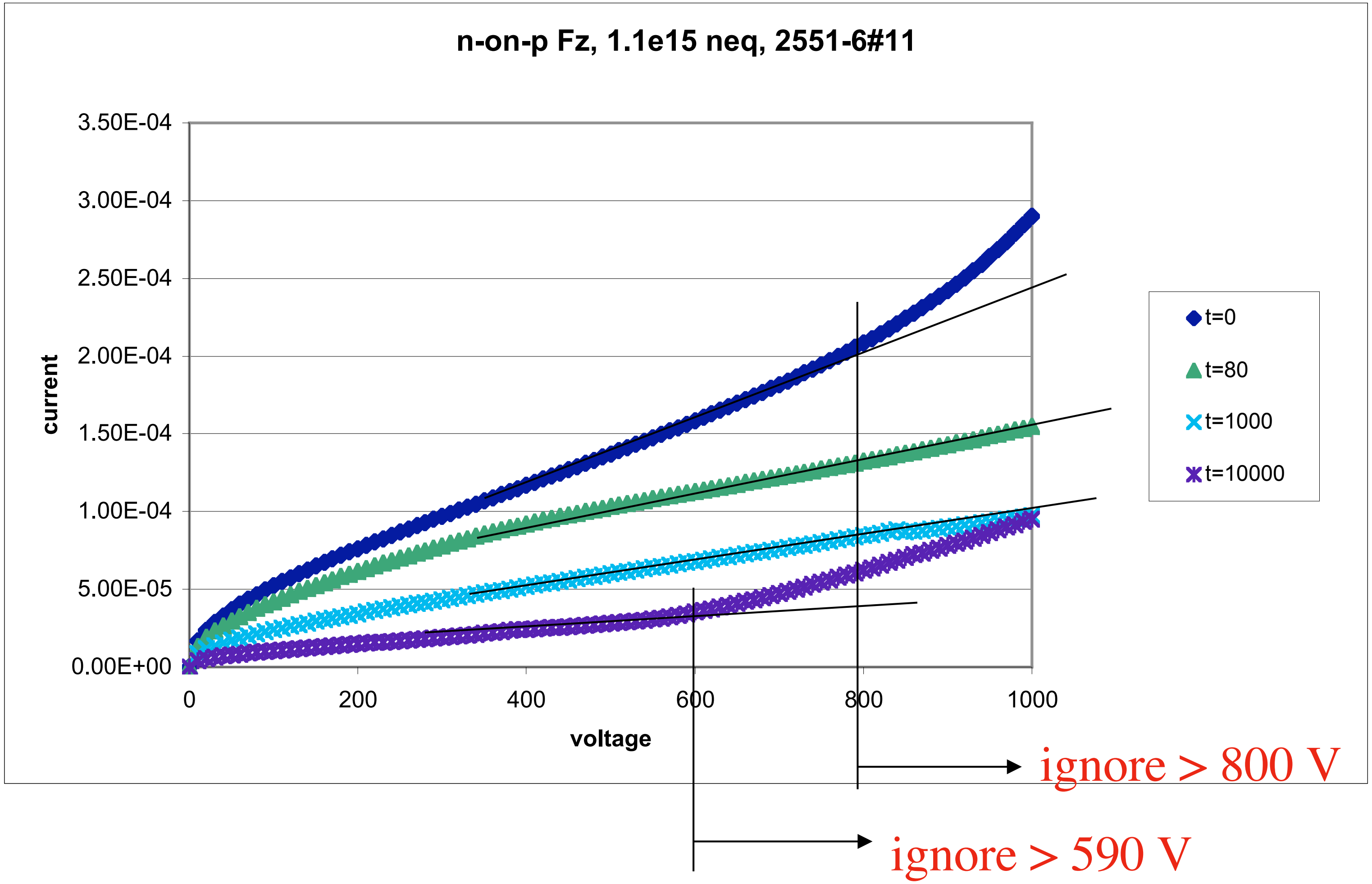
- Micron and HPK 300 μm thick Si diodes

Measurements:

- IV and CV at UNM at 20 °C



IV Measurements

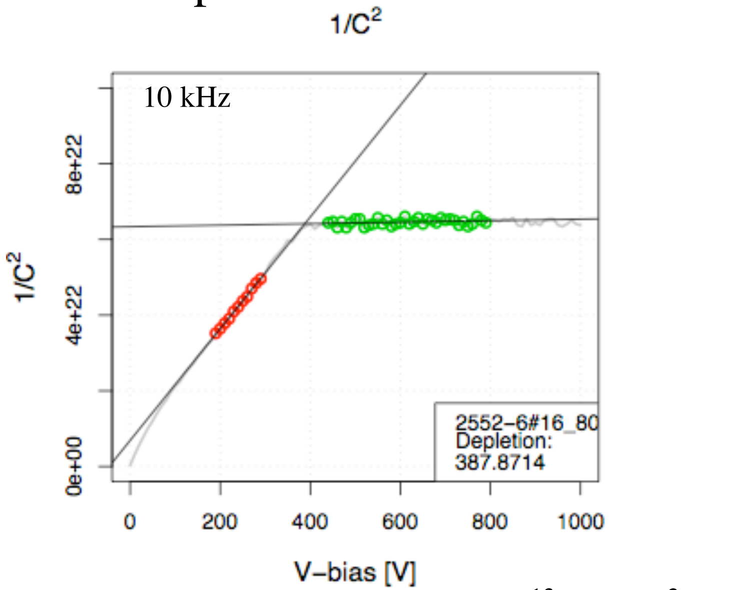


IV Measurements:

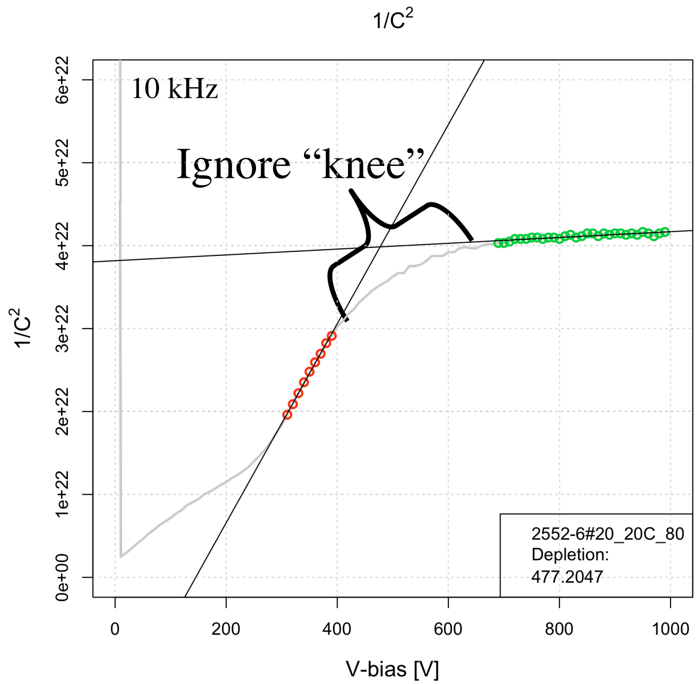
- All measurements at 20 ºC
- Identify "superlinear" behavior for each IV curve--possible indication of thermal runaway
- Ignore data on CV curves above superlinear threshold

Depletion Voltage

800 MeV protons



n-on-p MCz irradiated to 7.8×10^{13} n_{eq}/cm^2 after 80 minutes anneal time at 60 °C.



n-on-p MCz irradiated to 1.1×10^{15} n_{eq}/cm^2 after 80 minutes anneal time at 60 °C.

<u>Fit Method:</u>

The depletion voltage was determined from the intersection of two linear fits of $1/C^2$. When there is more complicated structure beyond two linear segments, the linear segment before the "knee" and after the knee were used. An error for the fit was estimated in each case using the prescribed fit method and included in the error bars in the plots of the depletion voltage.

Errors

	Source	Error
Systematic Errors:	LCR meter	± 0.3%
	LCR correction	120 fF
	Temperature	± 1°C => ±2%
	Vfd Fit	10-100 V
Statistical Errors:	LCR meter	50 fF

Capacitance Error:

$$\sigma_C = \sqrt{\sigma^2_{LCR} + \sigma^2_{LCRcorr.} + \sigma^2_{LCRstat.} + \sigma^2_{Temp}} \approx 425 fF$$

Capacitance error propagated to V_{fd} error:

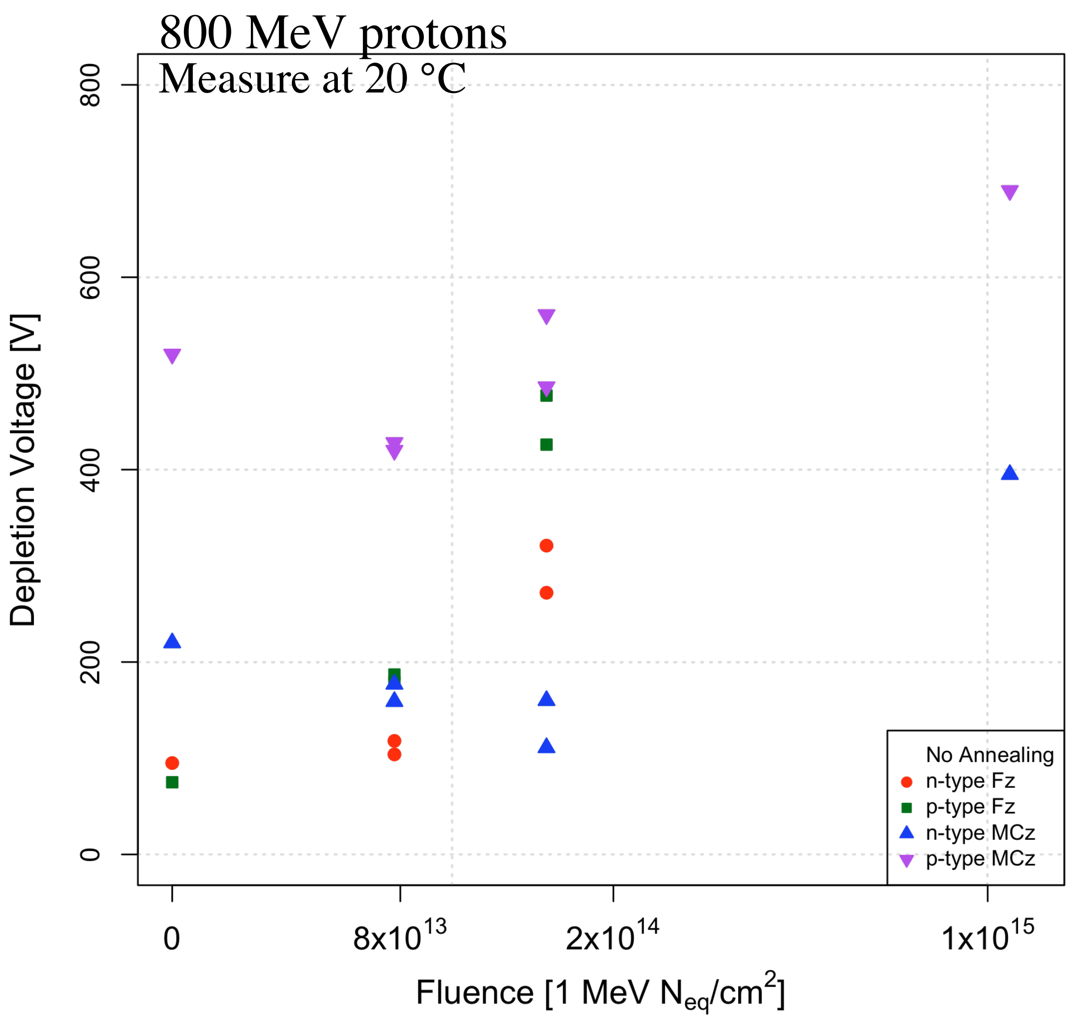
$$\sigma_{V_fd}(Cap) = V_{fd}\sqrt{\frac{\sigma^2_{\beta-b}}{\beta - b} + \frac{\sigma^2_{a-\alpha}}{a-\alpha}}$$

where for Fit 1: C=aV+b and Fit 2: C=αV+β
V_{fd} is given by: $aV_{fd}+b=\alpha V_{fd}+\beta \Rightarrow V_{fd}= (\beta-b)/(a-\alpha)$
And error associated with fit 1 = 5%, fit 2 = 7%

Total V_{fd} Error:

$$\sigma_{V_{fd}TOT} = \sqrt{\sigma^2_{V_{fd}(Cap)} + \sigma^2_{V_{fd}(Fit)}}$$

Depletion Voltage vs Fluence



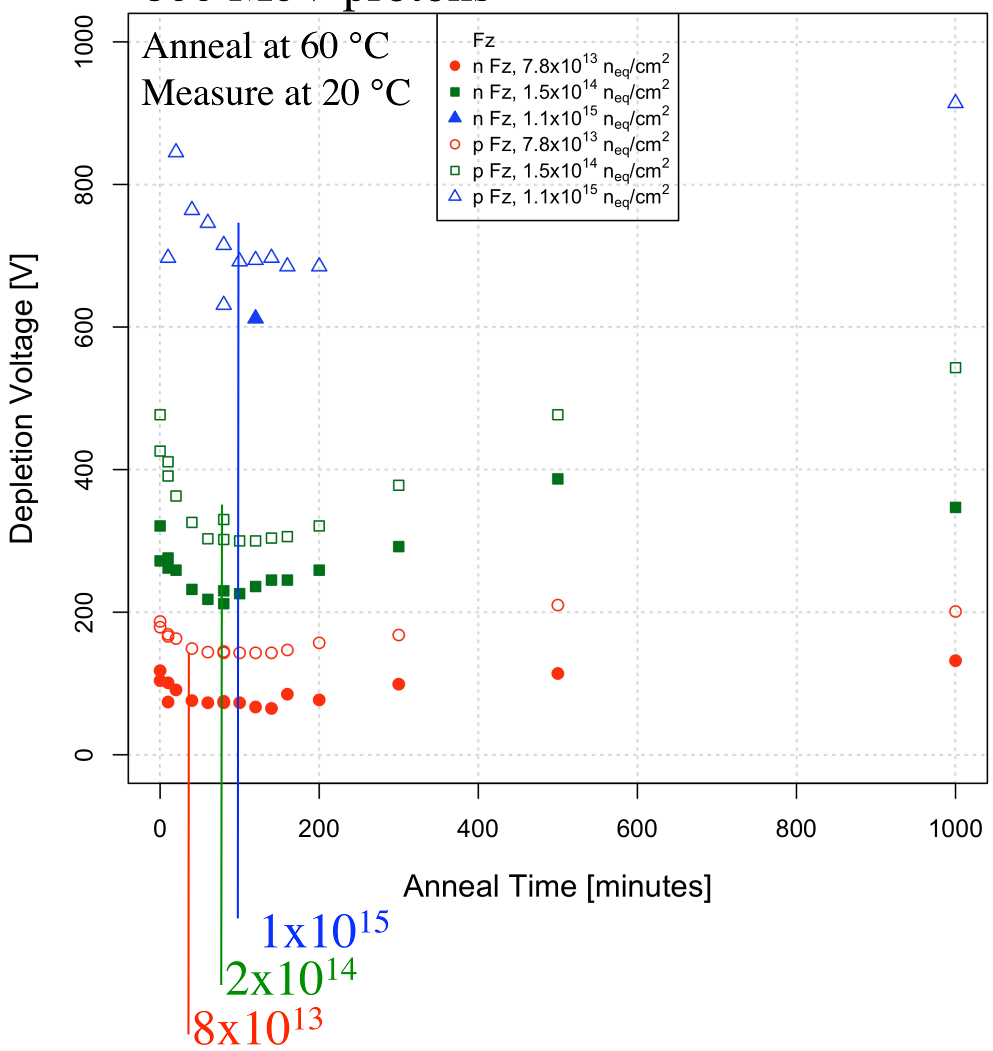
<u>Fluence Dependence:</u>

- Fz diodes start with lower depletion voltage, but break down before full depletion at highest fluence

- MCz diodes improve with low fluence and show gradual increase in depletion voltage at higher fluences

Fz

800 MeV protons

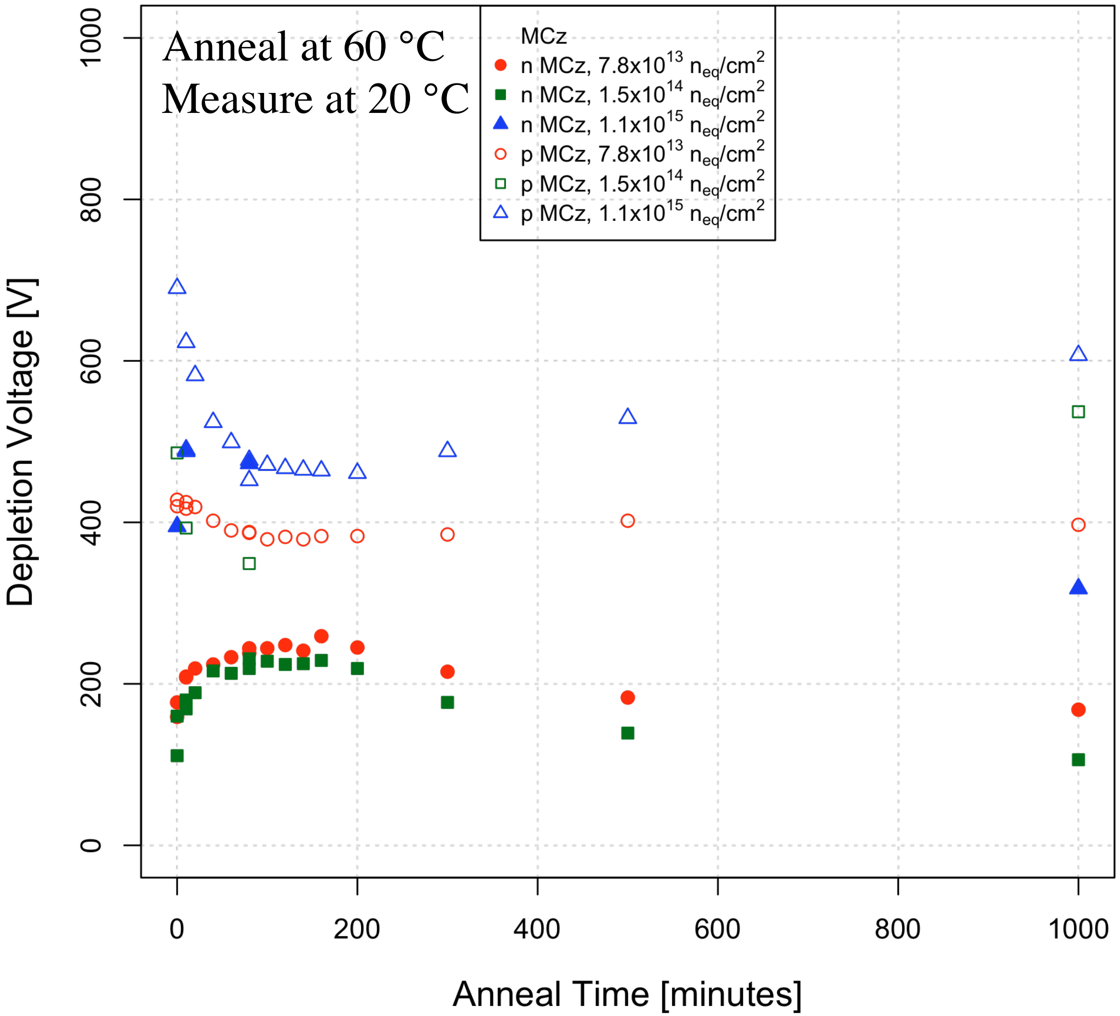


<u>Observations:</u>

- beneficial annealing before 100 minutes
- more beneficial annealing for a longer period as fluence increases
- Initial beneficial annealing is consistent with n-on-p (p-type) Fz starting with -sc before irradiation, stays -sc after 800 MeV proton irradiation, then while positive space charge is introduced in the first part of annealing we observe beneficial annealing, and in the later part of annealing -sc is introduced and we see reverse annealing.
- n-type Fz shows consistent annealing behavior for +sc before proton irradiation and -sc after proton irradiation—again a period of beneficial then reverse annealing

MCz

800 MeV protons

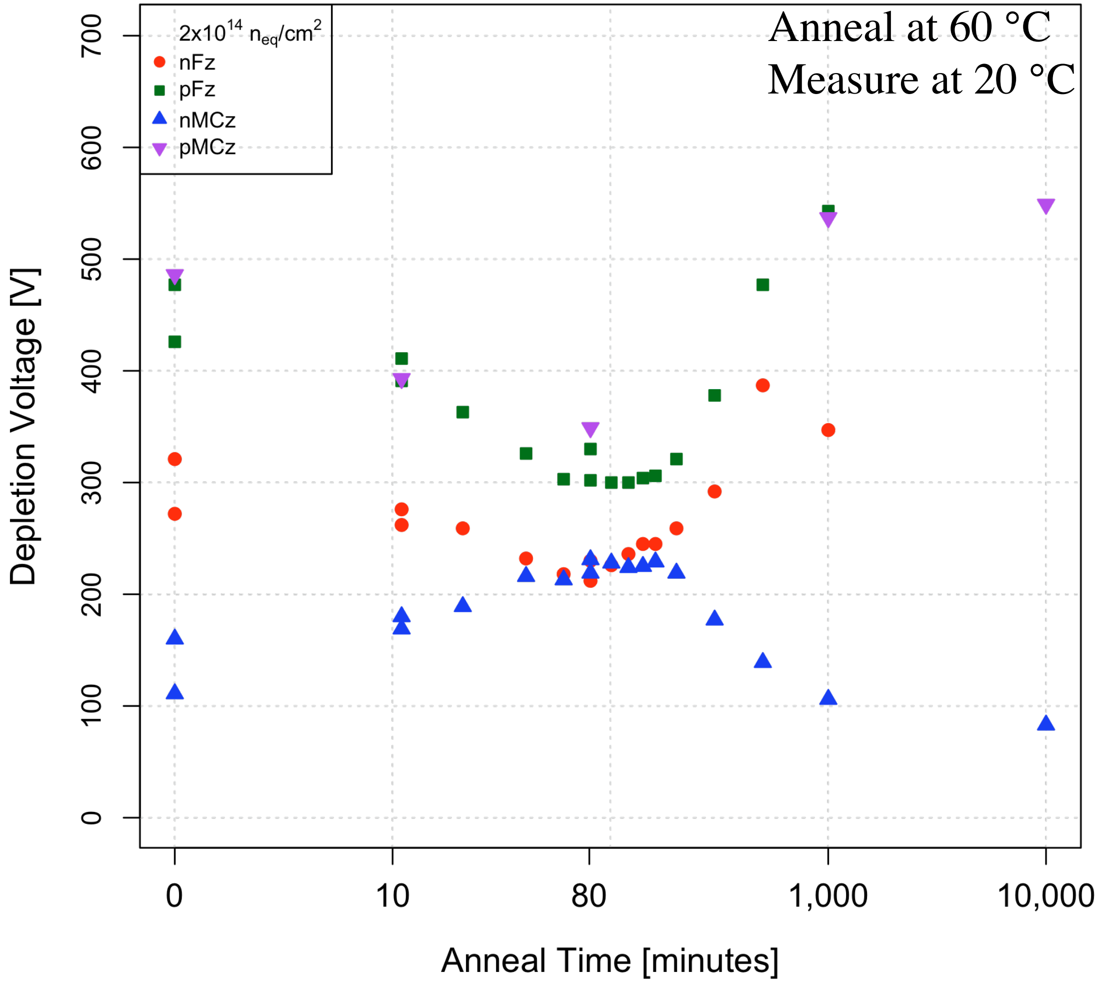


<u>Observations:</u>

- n-type and p-type MCz have opposite annealing behavior—explained by space charge
- For p-type MCz, results are consistent with a -sc after proton irradiation--period of beneficial then reverse annealing (same as Fz)
- n-type MCz starts with +sc before irradiation, stays positive after 800 MeV *proton* irradiation
- initial introduction of more +sc causes non-beneficial annealing in first annealing steps and then beneficial annealing when -sc is added
- p-type MCz results are consistent with previous observations [1] [2] [3] at 60 °C and 80 °C
- initial reverse annealing not observed for n-type MCz either due to lack of initial values, or could be a result of temperature (other results shown for 80 °C) or proton energy?

V_{fd} at $2x10^{14}$ n_{eq}/cm^2

800 MeV protons



Observations:

- annealing inversion between 60-160 minutes
- reached saturation for both MCz diodes, while Fz depletion is too high to measure after 10,000 minutes

Summary

- The method for depletion voltage extraction from capacitance measurements can have a large systematic impact on the depletion voltage.
- Beneficial annealing is observed for the first ~100 minutes anneal time and then V_{fd} begins to increase (reverse annealing) for samples shown to have -sc after proton irradiation:
    - p-type Fz
    - n-type Fz
    - p-type MCz
- n-type MCz was observed to have an initial reverse annealing followed by beneficial annealing--behavior typical of devices that have +sc after proton irradiation.
- All samples switch annealing behavior (between beneficial and reverse annealing) between 60 and 160 minutes at 60 °C.

References

[1] G. Segneri, et al., *Radiation hardness of high resistivity n- and p-type magnetic Czochralski silicon,* Nuclear Instruments and Methods in Physics Research A 573 (2007) 283–286.

[2] Nicola Pacifico, et al., *A TCT and annealing study on Magnetic Czochralski silicon detectors irradiated with neutrons and 24 GeV/c protons*, Nuclear Instruments and Methods in Physics Research A 612 (2010) 549–554.

[3] K. Hara, et al., *Testing of bulk radiation damage of n-in-p silicon sensors for very high radiation environments*, Nuclear Instruments and Methods in Physics Research A, in press.

Extra Slides

Fluence Calculation

	800 MeV p/ cm2:				Scaled (Jessica-Fz/MCz 0.5x0.5cm):	
Slot	Nominal	Error-%	Actual	Actual 1 MeV Neq	Actual 800 MeV p/cm2:	Actual 1 MeV Neq
17	1.40E+14	15	2.94E+14	2.09E+14	3.70E+14	2.63E+14
19	2.80E+14	15	3.24E+14	2.30E+14	4.08E+14	2.89E+14
21	5.40E+14	12	8.46E+14	6.01E+14	1.06E+15	7.56E+14
25	5.60E+14	12	8.83E+14	6.27E+14	1.11E+15	7.89E+14
28	9.00E+14	11	1.56E+15	1.11E+15	1.96E+15	1.39E+15
31	2.00E+15	11	2.78E+15	1.97E+15	3.50E+15	2.48E+15
35	2.80E+15	10	3.82E+15	2.71E+15	4.81E+15	3.41E+15
37	4.00E+15	10	7.51E+15	5.33E+15	9.45E+15	6.71E+15
39	5.00E+15	9	1.02E+16	7.24E+15	1.28E+16	9.11E+15
41	8.00E+15	9	1.43E+16	1.02E+16	1.80E+16	1.28E+16

Error Calculation

Cap:	1 pF	2pF	5pF	10pF	20pF	50pF
Cap:	1.00E-12	2.00E-12	5.00E-12	1.00E-11	2.00E-11	5.00E-11
LCR meter error	3.00E-15	6.00E-15	1.50E-14	3.00E-14	6.00E-14	1.50E-13
LCR correction error	1.20E-13	1.20E-13	1.20E-13	1.20E-13	1.20E-13	1.20E-13
Temperature error	2.00E-14	4.00E-14	1.00E-13	2.00E-13	4.00E-13	1.00E-12
LCR statistical error	5.00E-14	5.00E-14	5.00E-14	5.00E-14	5.00E-14	5.00E-14
capacitance error (fF) =	1.3.E-13	1.4.E-13	1.6.E-13	2.4.E-13	4.2.E-13	1.0.E-12
1/c^2 error =	2.63E+23	3.40E+22	2.64E+21	4.81E+20	1.06E+20	1.63E+19
percent error:	26%	14%	7%	5%	4%	4%

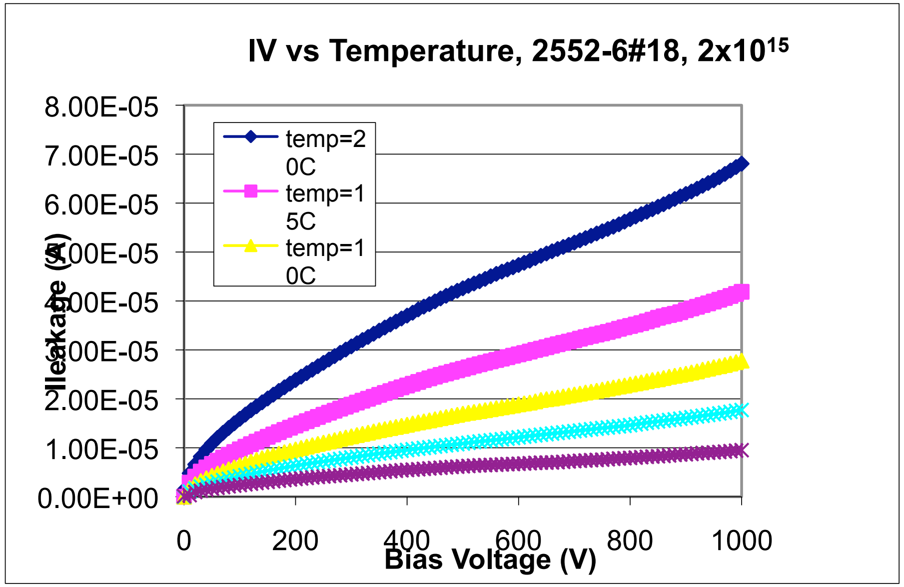
$$\sigma_{a-\alpha}(Cap) = \sqrt{(0.05a)^2 + (0.07\alpha)^2}$$

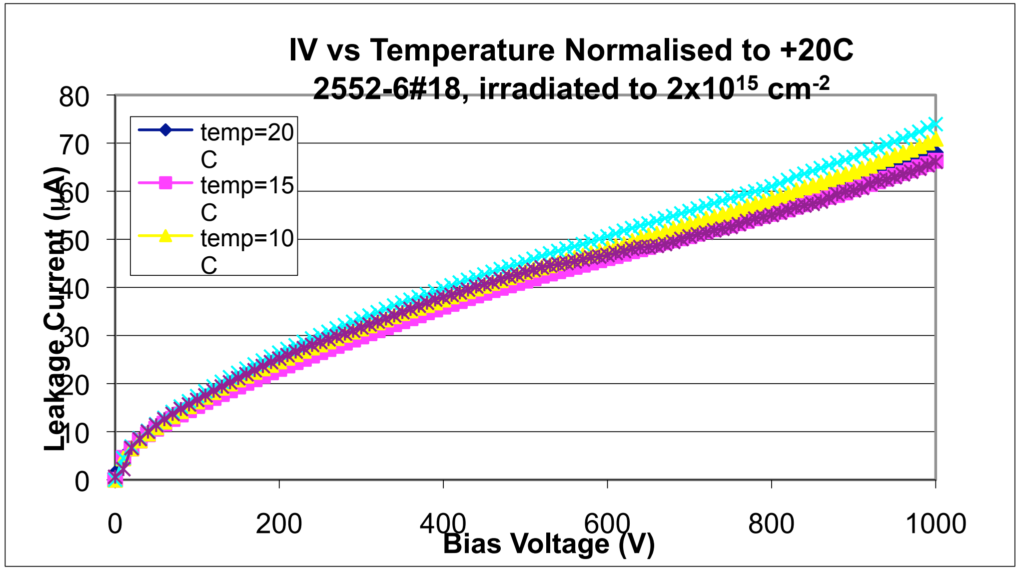
$$\sigma_{\beta-b}(Cap) = \sqrt{(0.05b)^2 + (0.07\beta)^2}$$

$$\sigma_{V_fd}(Cap) = V_{fd}\sqrt{\frac{\sigma^2_{\beta-b}}{\beta-b} + \frac{\sigma^2_{a-\alpha}}{a-\alpha}}$$

Error calculated for each V_{fd} point

Errors



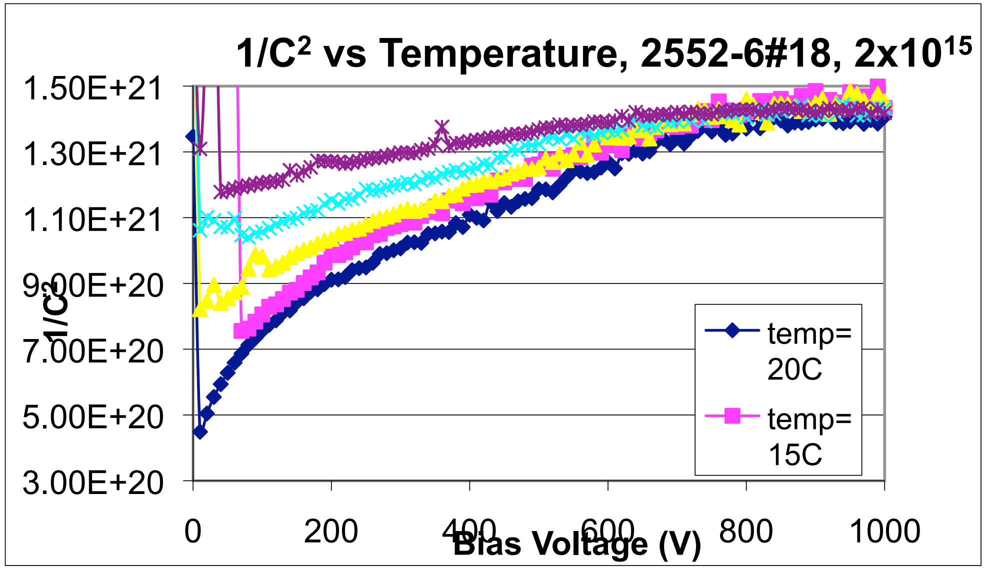


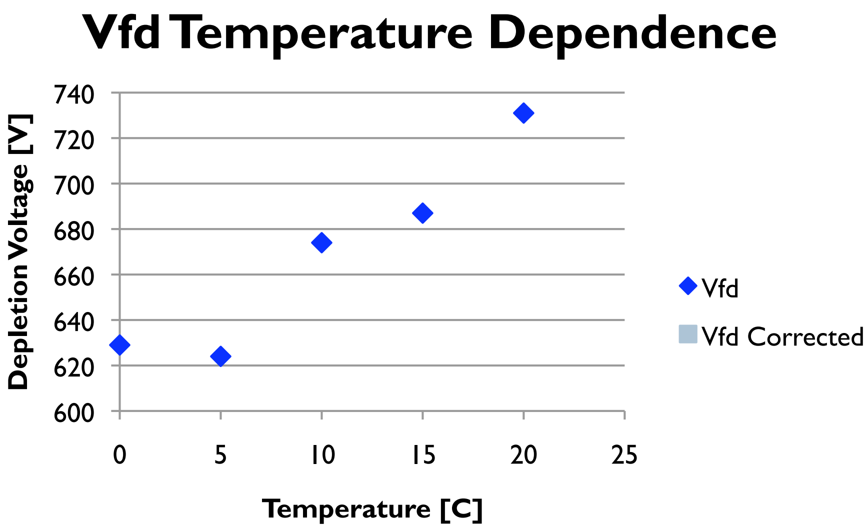
Temperature Correction:

$$J(T) = AT^2 e^{\frac{-E}{2k_B T}}$$

T = temperature, A = some constant, k_B = Boltzman's constant, E = 1.24 eV

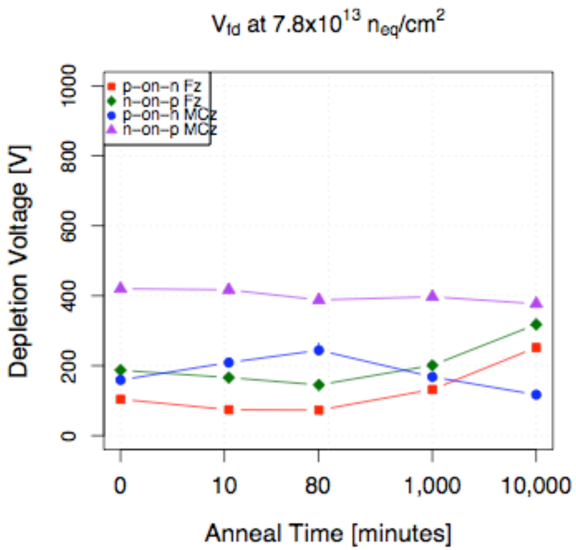
Errors

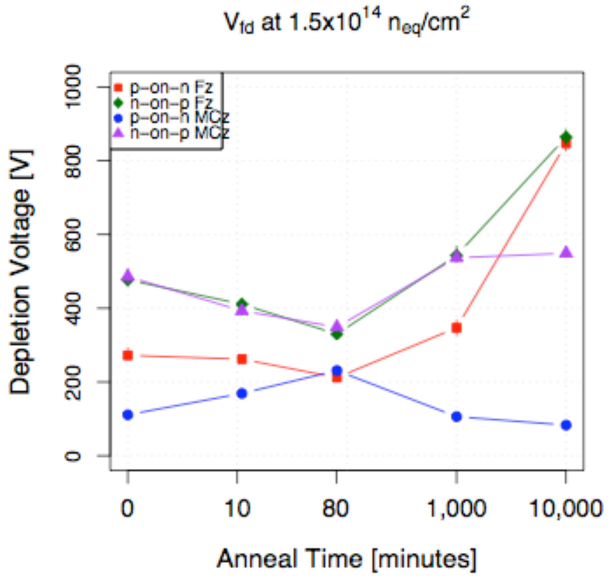


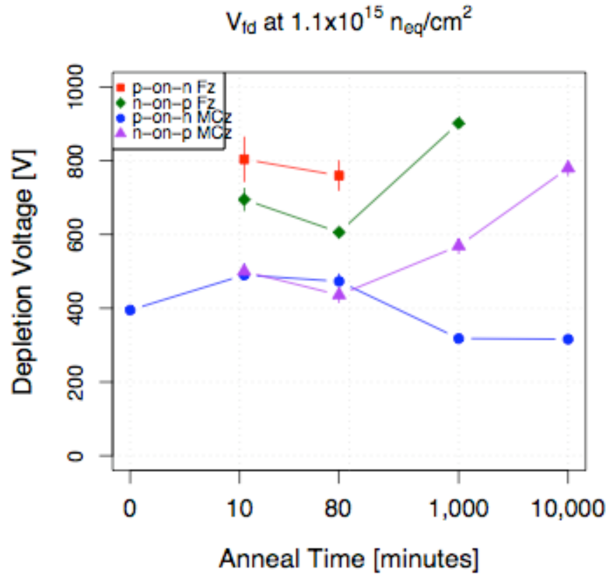


The slope between 5 and 10 °C (largest temperature dependence) has a slope of 7 V, => ±2% conservatively

V_{fd} Evolution







In the first part of the the annealing curve you introduce positive space charge, then it switches to negative.

Fz n-type, p-on-n Before: + After: - (after proton irradiation)

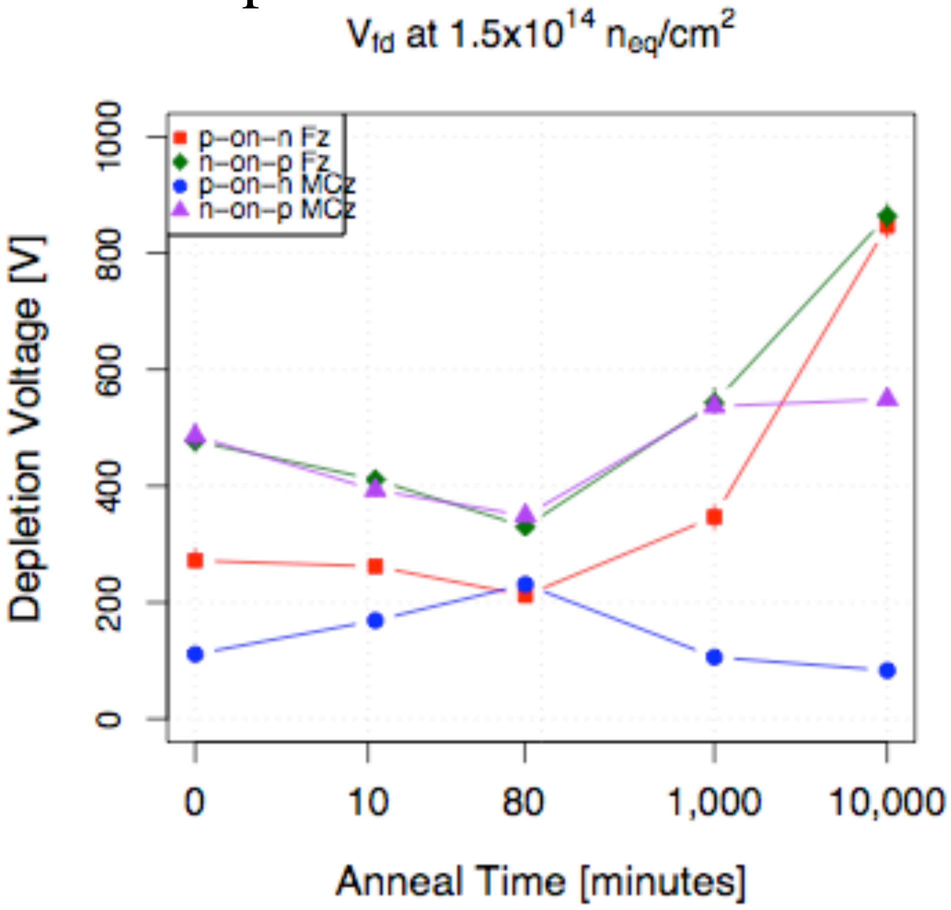
Fz p-type, n-on-p Before: - After: -

MCz n-type, p-on-n Before: + After: +

MCz p-type, n-on-p Before: - After: -

V_{fd} at $1.5x10^{14}$ n_{eq}/cm^2

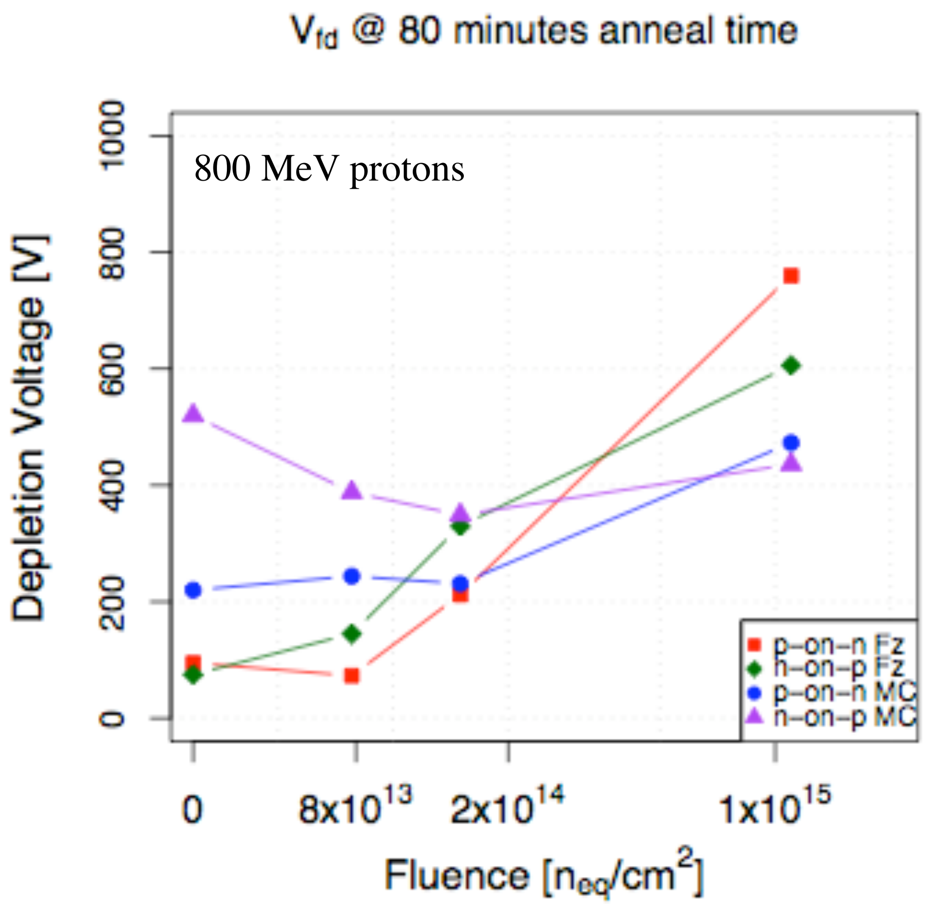
800 MeV protons



Observations:

- both Fz devices have strong reverse annealing at 10,000 minutes
- n-on-p MCz appears to have saturated

Comparison @80 minutes



Observations:

- Note: 80 minutes was where the minimum value of V_{fd} was reached--shows the most beneficial annealing for "p-type" samples (all but p-on-n MCz)
- Fz show greatest increase of V_{fd} with increasing fluence
- n-on-p MCz shows little change