# Study of Gamma Irradiated P-type Silicon Diodes with Different Resistivities


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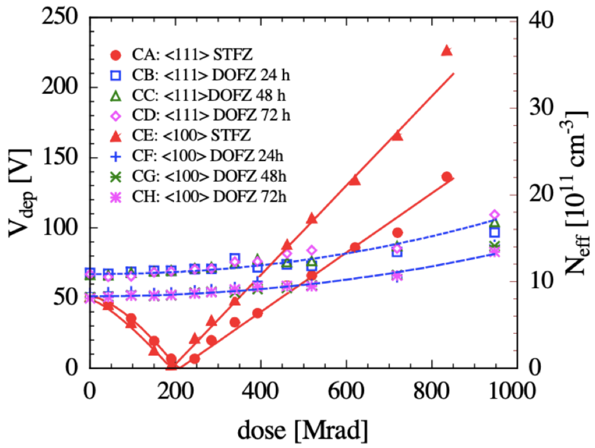
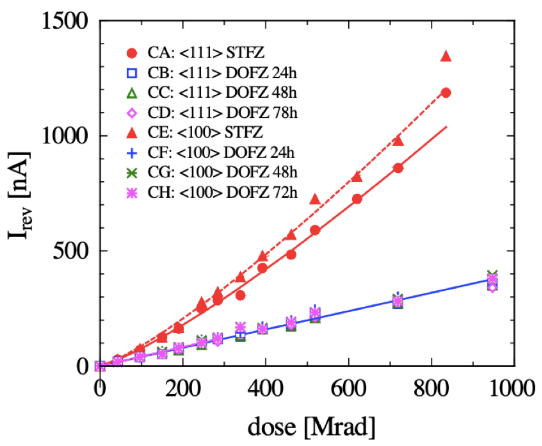
# Motivation

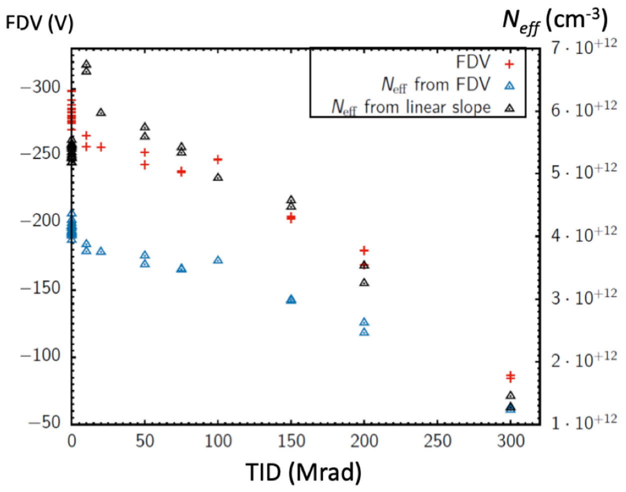
- Most of the previous studies of bulk damage caused by $^{60}$Co gamma in n-type silicon
- A lack of studies of gamma irradiated high resistivity p-type silicon

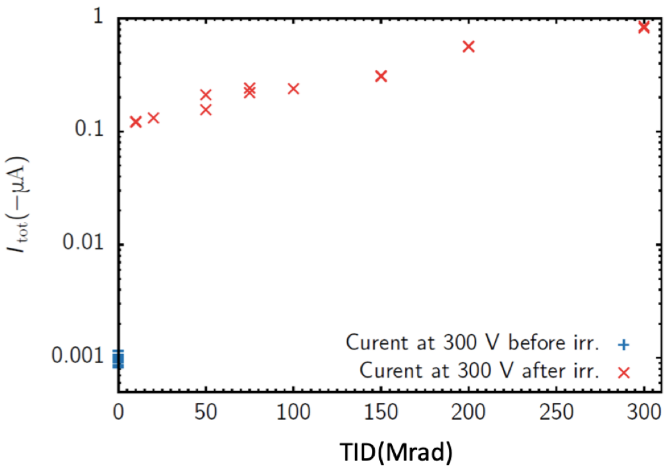
## n-type silicon




## p-type silicon




- STFZ – space charge type inversion at $200$ Mrad
- DOFZ – non-linear increase of the $N_{eff}$

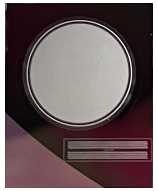
- Irradiation of HPK strip sensors for ATLAS ITk
- Decrease in FDV and $N_{eff}$ observed up to $300$ Mrad

E. Fretwurst et al., NIM A 514 (2003)

M. Mikestikova et al., RD50 meeting Lancaster 2019

# Measured Diodes

- n-in-p standard float zone pad diodes from different manufacturers
- Comparable active areas and thickness but different silicon resistivities
- Contactable guard ring that enables separation of leakage and guard current $I_{tot} = I_{leak} + I_{guard}$
  - **CNM** 7439 – 5 pcs
  - **HPK** ATLAS17-SPL-MINI VPX29549 – 8 pcs
  - **IFX** MD8 & MD8.4 – 5 pcs



| | CNM | HPK | IFX |
|---|---|---|---|
| Active thickness **d** | 285 µm | 290 µm | 285 µm |
| Active area **A** | 50.17 $mm^2$ | 51.55 $mm^2$ | 49.95 $mm^2$ |
| Active volume **V** | 0.0143 $cm^3$ | 0.0149 $cm^3$ | 0.0142 $cm^3$ |
| Measured **FDV** of unirradiated diode | (36.9 ± 8.3) V | (273.4 ± 10.7) V | (283.6 ± 12.0) V |
| Calculated resistivity ρ | (23.975 ± 4.012) kΩ·cm | (3.301 ± 0.001) kΩ·cm | (3.077 ± 0.001) kΩ·cm |
| Wafer oxygen concentration | N/A | $1.5\cdot10^{16} - 6.5\cdot10^{17}$ atoms/$cm^3$* | |

*values from ATLAS ITk requirements document

## Full Depletion Voltage

Determined from interpolation curves of measured CV characteristics

## Resistivity calculation

$$\rho = \frac{d^2}{2\varepsilon_0 \varepsilon_{Si} \mu_p FDV}$$

$\varepsilon_0 = 8.85 \cdot 10^{-12}\ \mathrm{F \cdot m^{-1}}$

$\varepsilon_{Si} = 11.7$

$\mu_p = 450\ \mathrm{cm^2 \cdot V^{-1} \cdot s^{-1}}$

# IV&CV Measurements

- Measurements performed at probestation, diodes contacted by needles
- During all measurements temperature $\mathrm{T} = 21 \pm 2$ °C and $\mathrm{RH} < 10$ %
- Measured currents normalized to $20$ °C
- Diodes measured before irradiation, after irradiation and after irradiation and standard annealing
- After irradiation diodes stored at -$20$ °C to avoid uncontrolled annealing

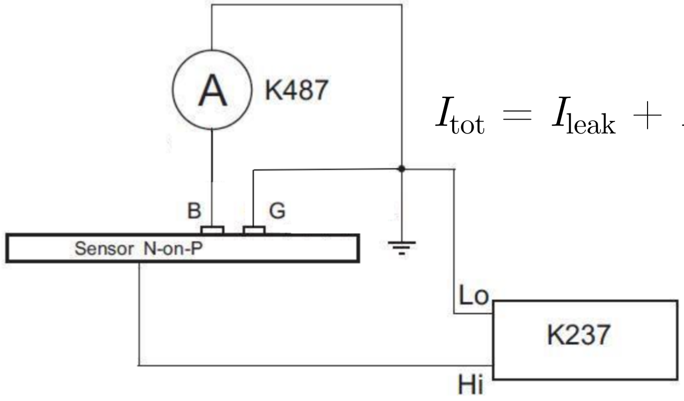
**Standard Annealing**

$60$ °C for 80 minutes

**Full Depletion Voltage**

Determined from interpolation curves of measured CV characteristics

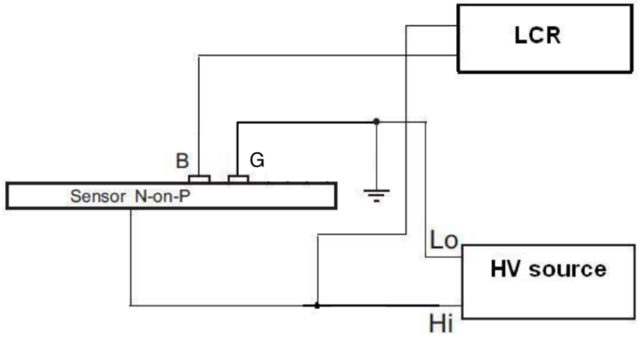
## IV setup




$$I_{\text{tot}} = I_{\text{leak}} + I_{\text{guard}}$$

By contancting guard ring we were able to separate leakage current $I_{\text{leak}}$ from total current $I_{\text{tot}}$

## CV setup




Guard ring grounded during all CV measurements

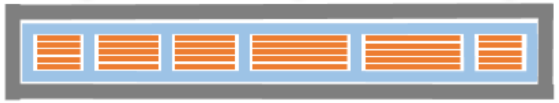
# Irradiation

- Diodes irradiated by $^{60}$Co gamma source in Charge Particle Equilibrium (CPE) box
- Fan used for cooling the irradiation area
    - Dose rate varies in each irradiation campaign $15.73 - 23.02$ krad/min
    - Diameter of irradiation area $9$ cm
    - Temperature up to $35$ °C
- Total ionizing doses from 0.5 up to 5.64 MGy

$^{60}$Co

$^{60}$Co Terabalt, ÚJP Praha

**CPE box**



5 layers of diodes

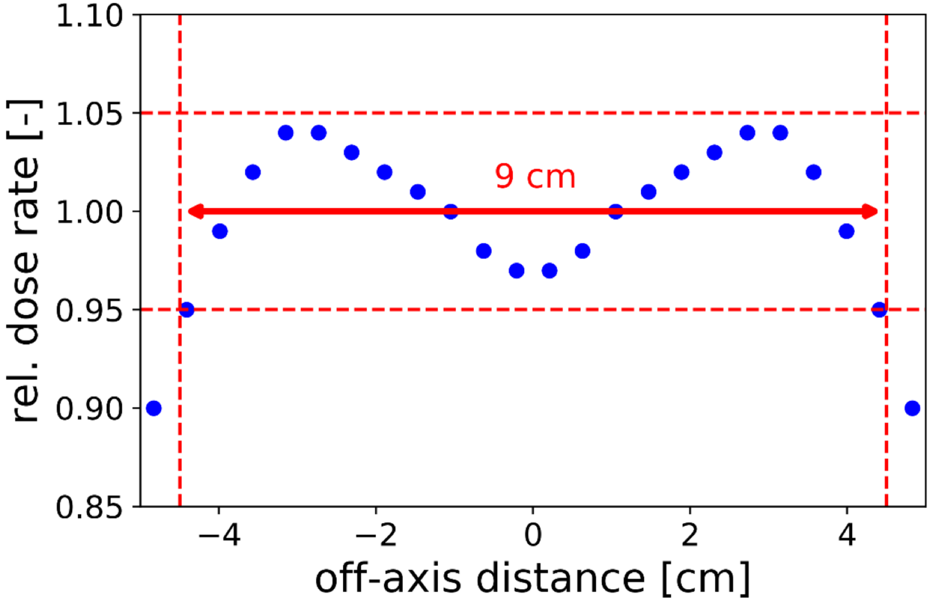
Al 1 mm holder

Pb 1.5 mm

} minimizes dose enhancement from low-energy scattered radiation by producing charged-particle equilibrium

**Dose profile**

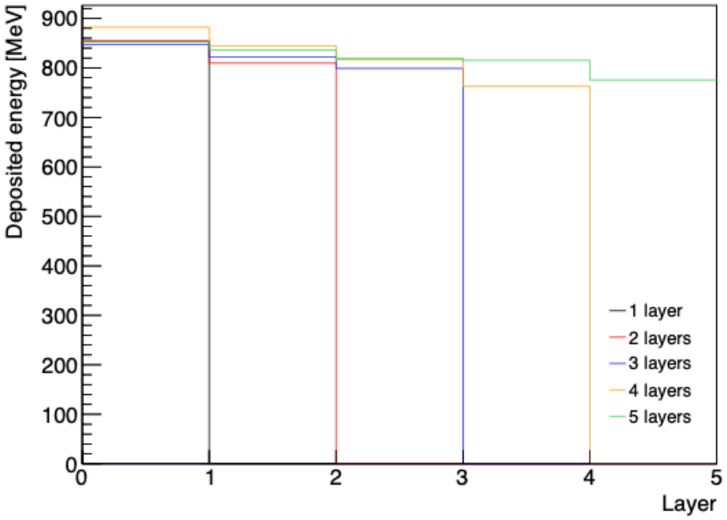
**$^{60}$Co-source to sample distance 3-4 cm**

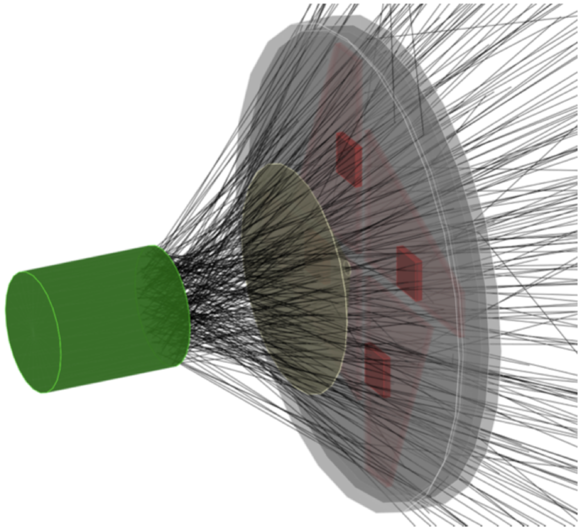



# Irradiation

- Geant4 irradiation simulations
- Isotropic emission of $50 \cdot 10^6$ photons of energy $1.25$ MeV

⇒ CPE box provides almost equal distribution of total deposited energy through all the layers of samples

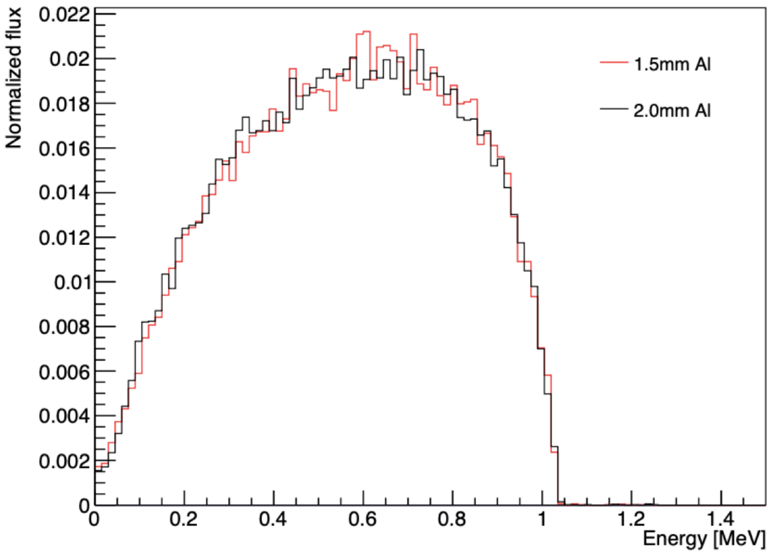


**Displacement damage caused by $^{60}$Co gamma** is primarily caused by the interaction of Compton electrons with the maximum energy $1.2$ MeV

- The minimum energy for production of clusters is $\approx 8$ MeV
- The maximum recoil energy for the primary knock on Si atoms by Compton electron is $\approx 140$ MeV
- The minimum electron energy neeed for a single displacement resulting in Freknel pair is $\approx 260$ keV

⇒ Damage caused by $^{60}$Co gamma is exclusively caused by point defects.



# CV Measurements of Unirradiated Diodes

- CNM diodes measured up to $250\ \mathrm{V}$, HPK and IFX diodes measured up to $500\ \mathrm{V}$, using frequency $1\ \mathrm{kHz}$
- Assuming homogeneous space charge distribution, we can calculate resistivity $\varrho$ and effective doping concentration $N_{\mathrm{eff}}$ from measured $\mathrm{FDV}$

**Resistivity**

$$\boldsymbol{\rho = \frac{d^2}{2\varepsilon_0\varepsilon_{\mathrm{Si}}\mu_{\mathrm{p}}FDV}}$$

**Effective doping concetration**

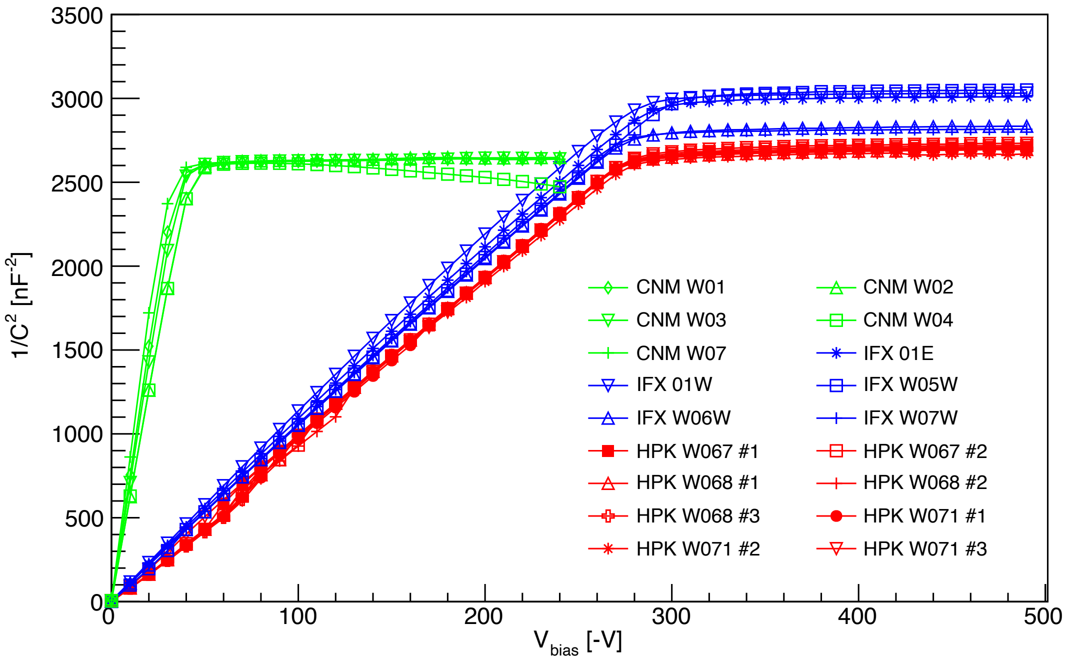
$$\boldsymbol{|N_{\mathrm{eff}}| = \frac{2\epsilon_0\epsilon_{\mathrm{Si}}FDV}{qd^2}}$$

$\varepsilon_0 = 8.85 \cdot 10^{-12}\ \mathrm{F}\cdot\mathrm{m}^{-1}$

$\varepsilon_{\mathrm{Si}} = 11.7$

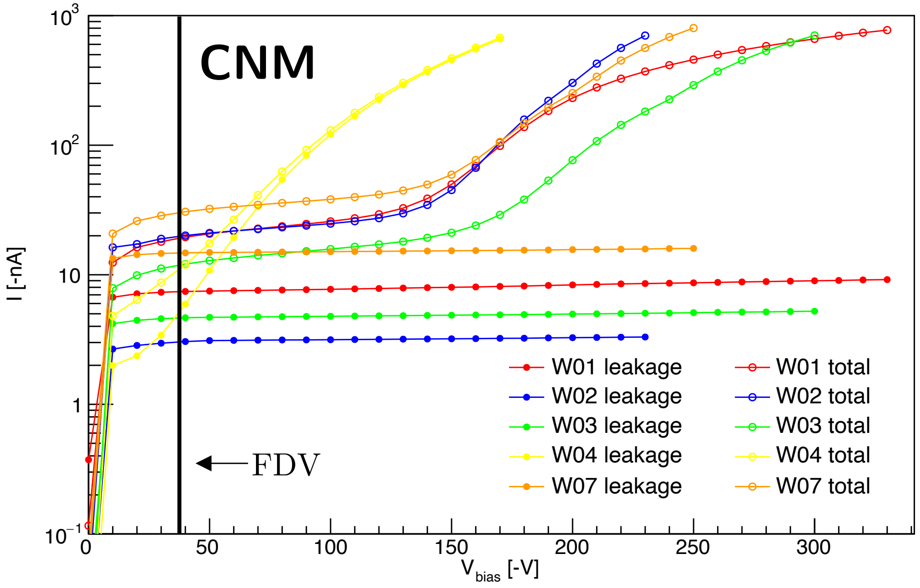
$\mu_{\mathrm{p}} = 450\ \mathrm{cm}^2\cdot\mathrm{V}^{-1}\cdot\mathrm{s}^{-1}$

$q = 1.602\ \cdot 10^{-19}\ \mathrm{C}$



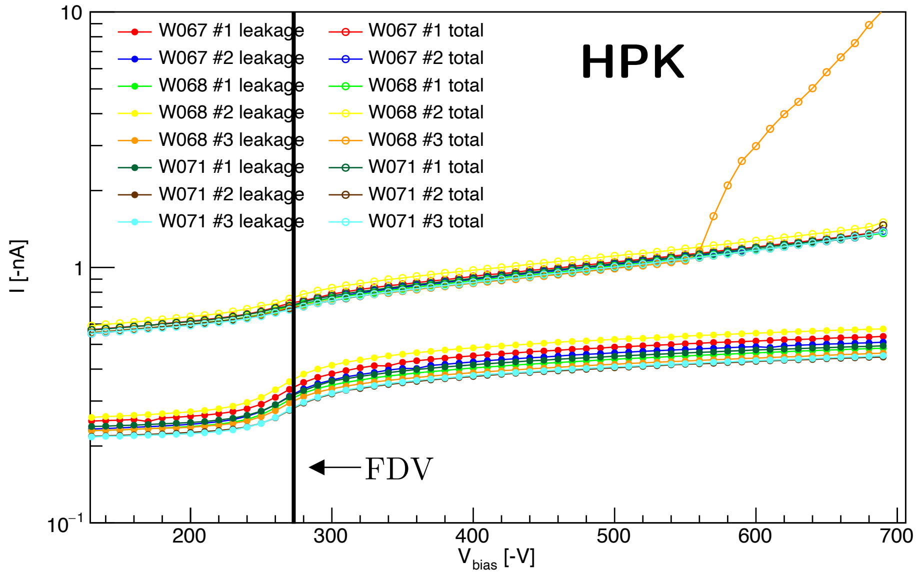

| | CNM | HPK | IFX |
|---|---|---|---|
| Active thickness **d** | 285 µm | 290 µm | 285 µm |
| Measured **FDV** | $(36.9 \pm 8.3)$ V | $(273.4 \pm 10.7)$ V | $(283.6 \pm 12.0)$ V |
| Resistivity ρ | $(23.975 \pm 4.012)$ kΩ·cm | $(3.301 \pm 0.001)$ kΩ·cm | $(3.077 \pm 0.001)$ kΩ·cm |
| Effective doping concentration $\lvert N_{\mathrm{eff}}\rvert$ | $(0.59 \pm 0.13) \cdot 10^{12}\ \mathrm{cm}^{-3}$ | $(4.20 \pm 0.16) \cdot 10^{12}\ \mathrm{cm}^{-3}$ | $(4.52 \pm 0.19) \cdot 10^{12}\ \mathrm{cm}^{-3}$ |

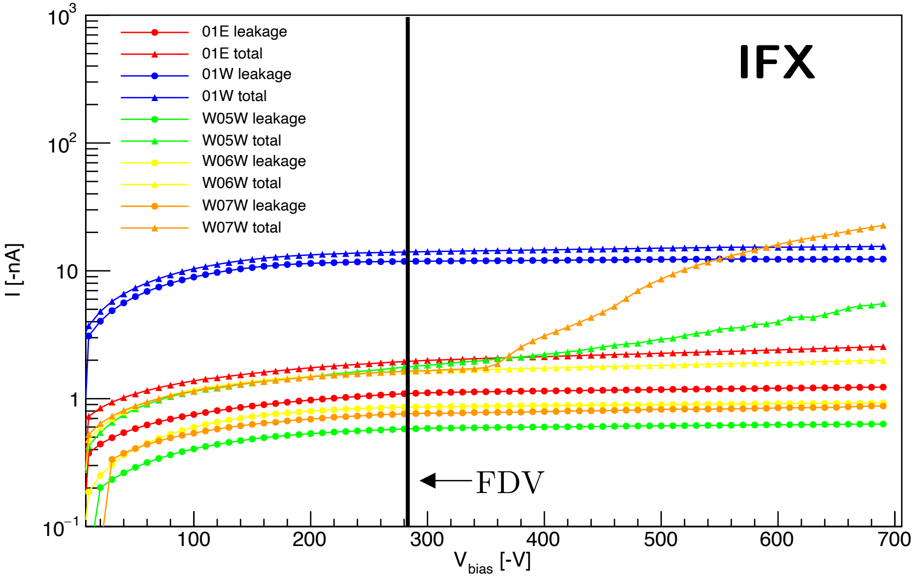
# IV Measurements of Unirradiated Diodes



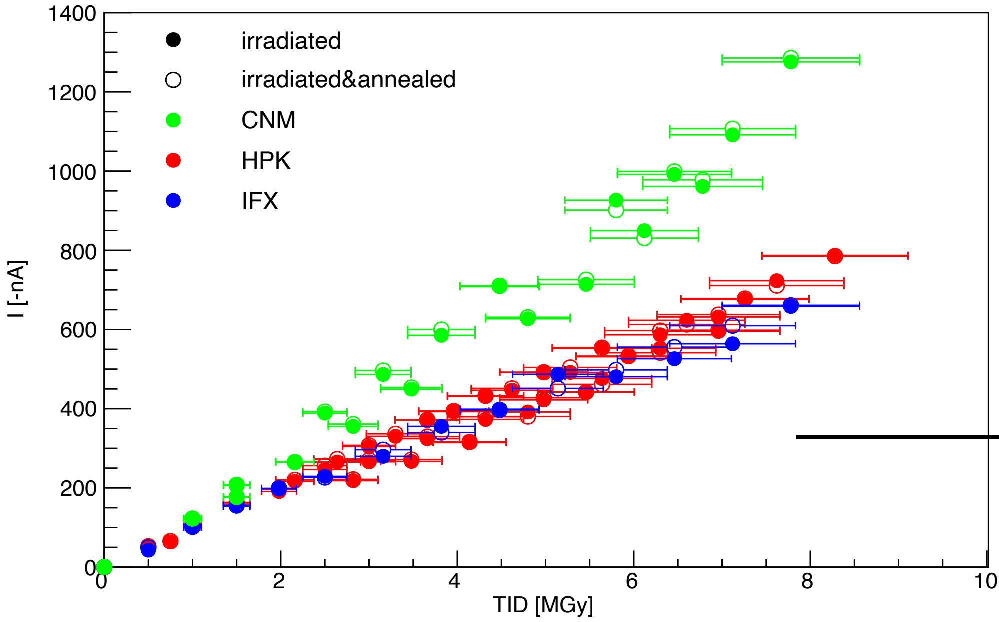

| | CNM at 60 V | HPK at 300 V | IFX at 300 V |
|---|---|---|---|
| Leakage current $I_{\text{leak}}$ | 3-15 nA | 0.3-0.5 nA | 0.6-0.9 nA |
| Total current $I_{\text{tot}}$ | 10-30 nA | 0.85-1.00 nA | 1.6-2.0 nA |

- Early breakdown of CNM W04
- IFX 01W higher values of current than other IFX diodes
- HPK diodes have lowest values of leakage current



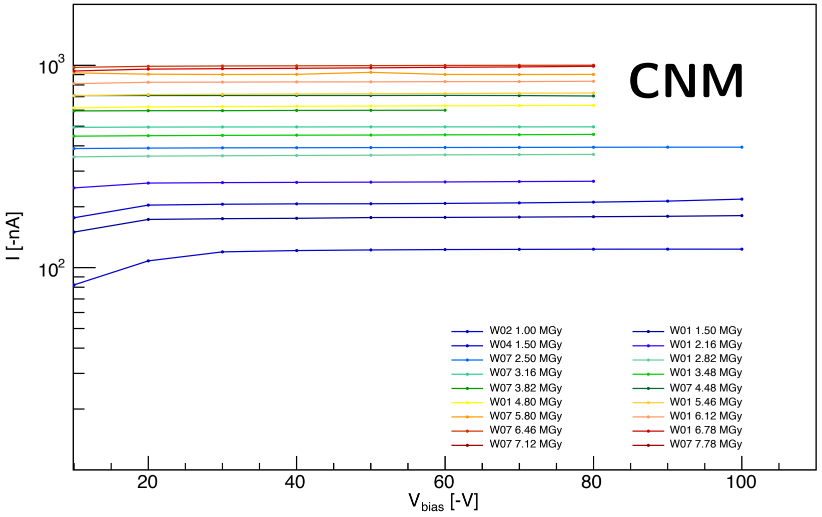



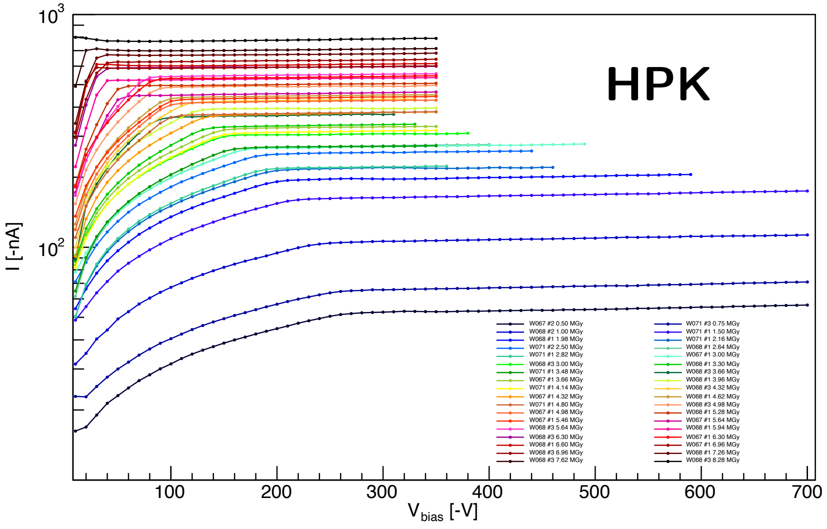
# Leakage Current of Irradiated&Annealed Diodes

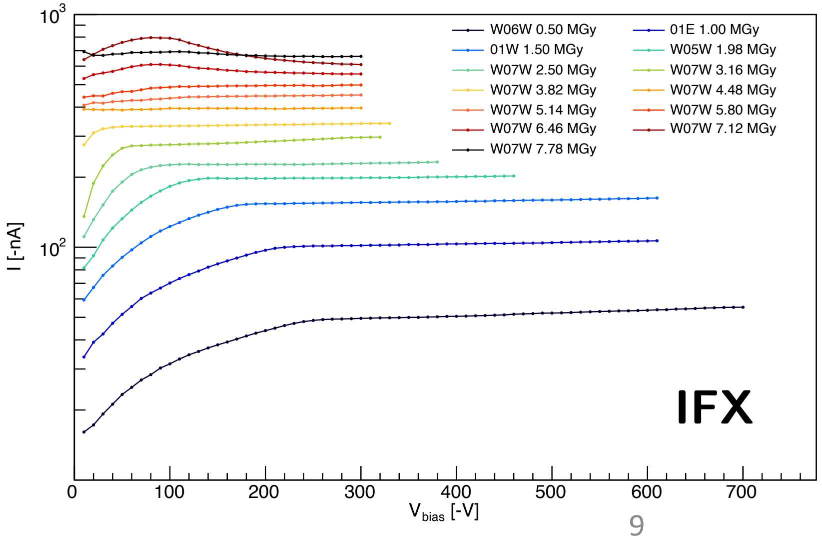



- Measured currents normalized to $20\ ^\circ\mathrm{C}$
- Constant values of $I_{\mathrm{leak}}$ measured after $\mathrm{V}_{\mathrm{bias}}$ reaches FDV
- Increasing values of $I_{\mathrm{leak}}$ with increasing TID

**Change of $I_{\mathrm{leak}}$ after standard annealing was not observed.**
⇒ Leakage current after gamma irradiation does not change after standard annealing.

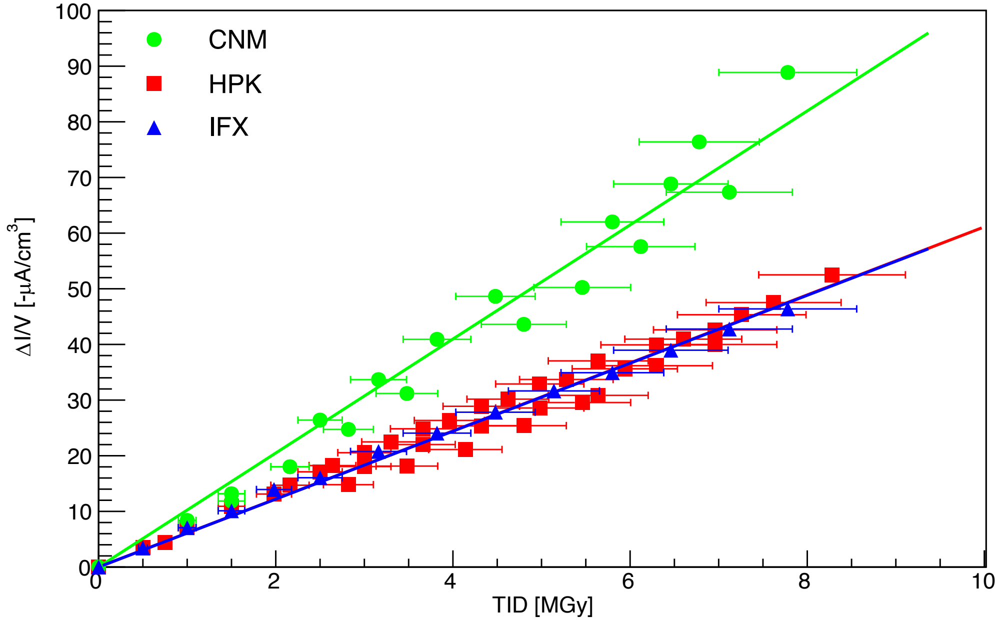


# Leakage Current $\Delta I/V$ Dependence on TID after Annealing

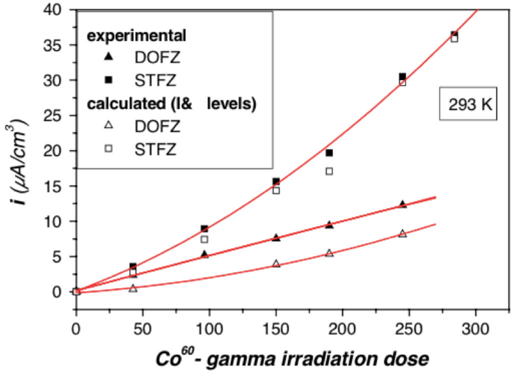
- Leakage current increases up to the maximum TID
- From the relation between $\Delta I/V$ and TID, we can determine the damage coefficient $\boldsymbol{a}$




$$\frac{\Delta \boldsymbol{I}}{\boldsymbol{V}} = \boldsymbol{a} \cdot \boldsymbol{TID}$$

| | $a$ [A·cm$^{-3}$·MGy$^{-1}$] |
|---|---|
| CNM | $(10.25 \pm 0.22)\cdot 10^{-6}$ |
| HPK | $(6.11 \pm 0.07)\cdot 10^{-6}$ |
| IFX | $(6.10 \pm 0.06)\cdot 10^{-6}$ |

Diodes with the similar initial resistivity and therefore effective doping concentration – HPK&IFX,
show the same degree of damage.
CNM with higher initial resistivity and different effective doping concentration has higher damage coefficient.



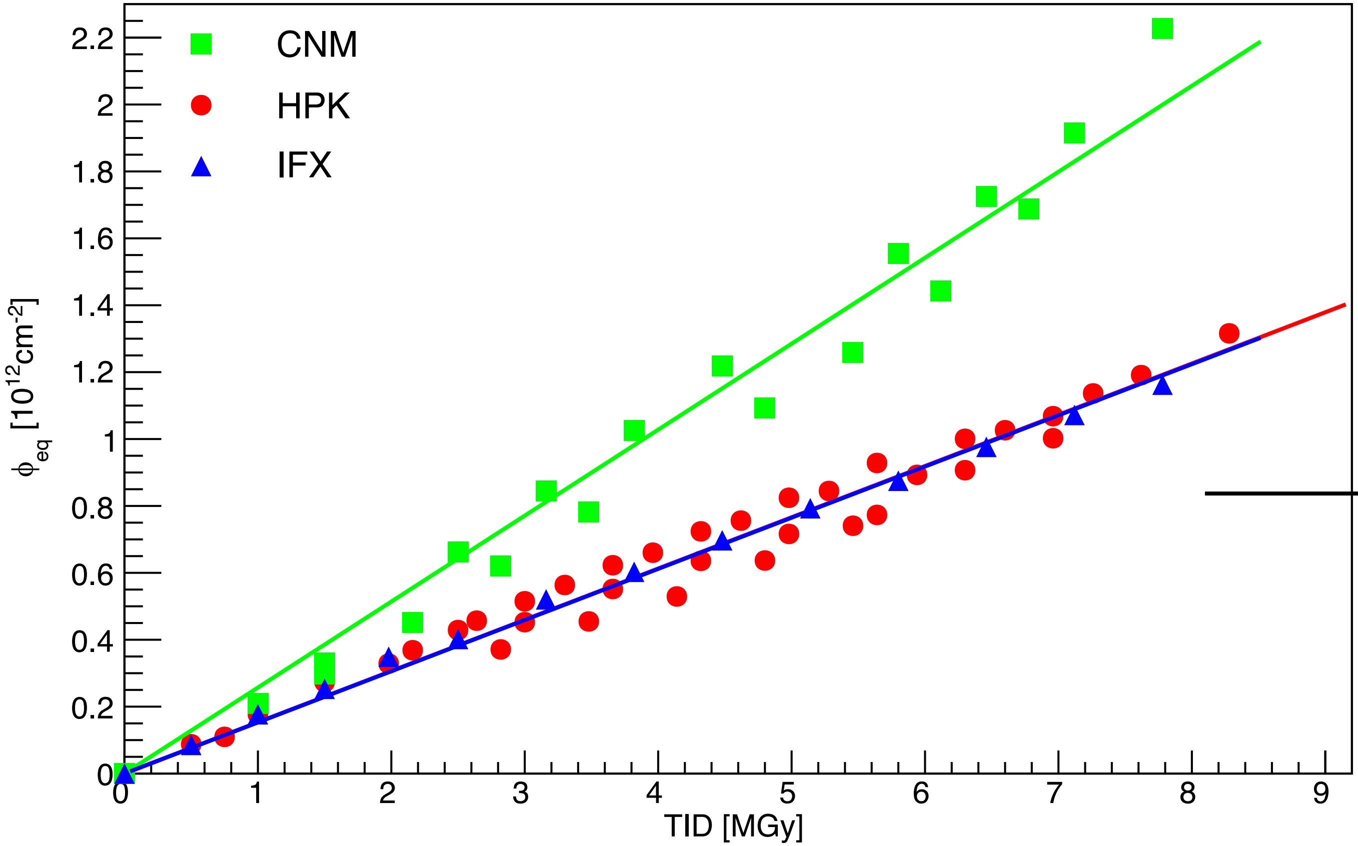

The results are in agreement with previous measurements of n-type standard float zone diodes.

I. Pintilie et al., NIM A 514 (2003)

| | CNM unirradiated | HPK unirradiated | IFX unirradiated |
|---|---|---|---|
| Resistivity ρ | $(23.975 \pm 4.012)$ kΩ·cm | $(3.301 \pm 0.001)$ kΩ·cm | $(3.077 \pm 0.001)$ kΩ·cm |

# TID vs. $\Phi_{eq}$ after Annealing

Assuming increasing leakage current with TID that is caused by displacement damage, we can estimate equivalent fluence $\Phi_{eq}$ from damage parameter α Moll 2018




$$\frac{\Delta I}{V} = \alpha \cdot \phi_{eq}$$

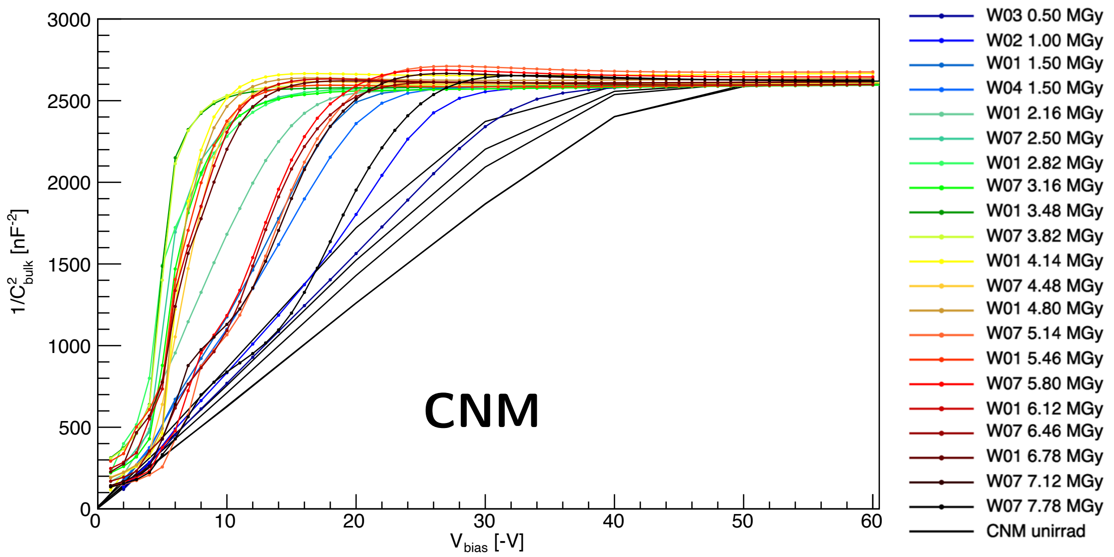
$\alpha = (3.99 \pm 0.03) \cdot 10^{-17}\ \mathrm{A \cdot cm^{-1}}$

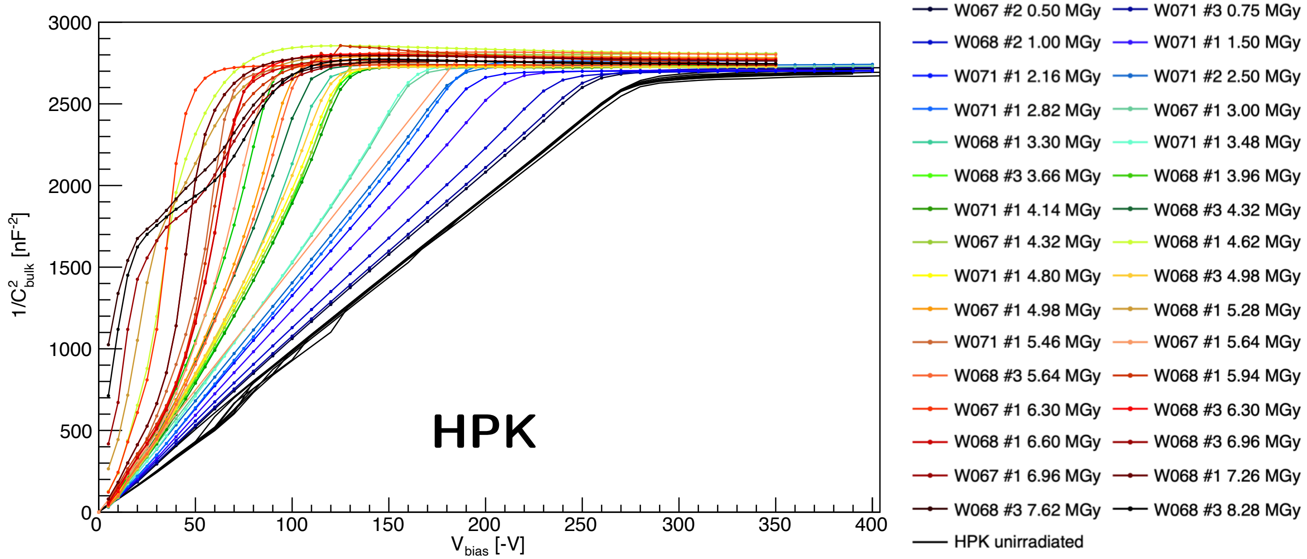
for currents measured at 20 °C after annealing (80 min for 60 °C)

1 MGy = $2.5 \cdot 10^{11}\ \mathrm{cm^{-2}}$ for CNM diodes

1 MGy = $1.5 \cdot 10^{11}\ \mathrm{cm^{-2}}$ for HPK&IFX diodes

# CV Measurements of Irradiated&Annealed Diodes

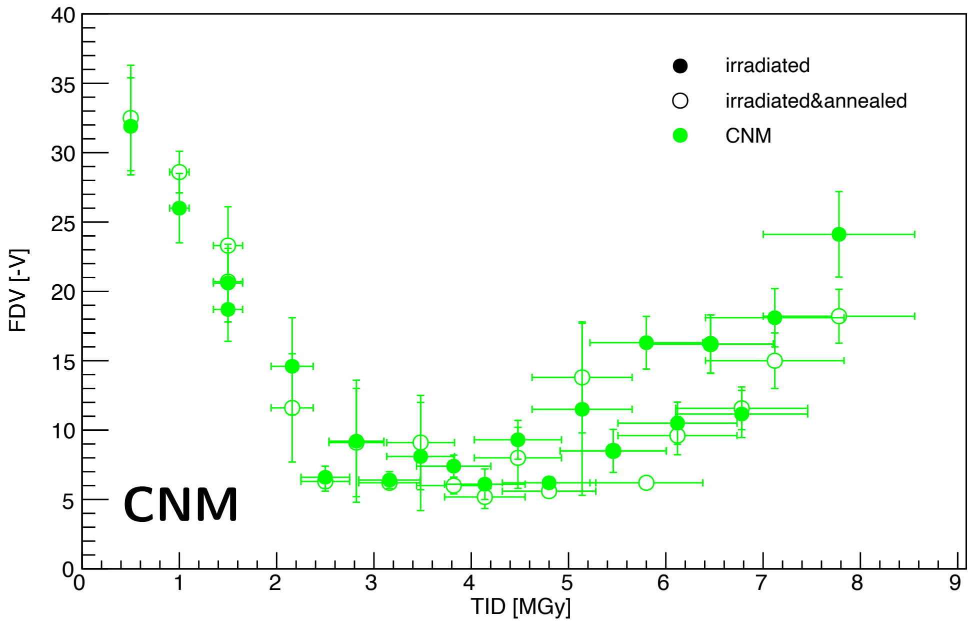


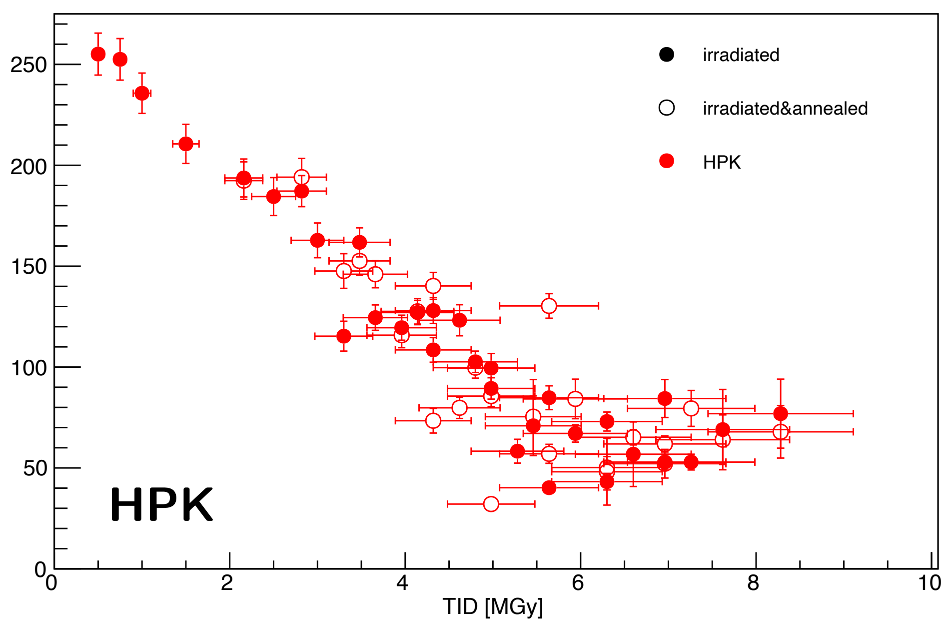




Observed change in CV characteristics with increasing TID.
⇒ Significant change of effective doping concentration $N_{\mathrm{eff}}$ with TID.

Test frequency 100 kHz determined from measured dependencies of capacitance on test frequency.

# CV Measurements of Irradiated&Annealed Diodes

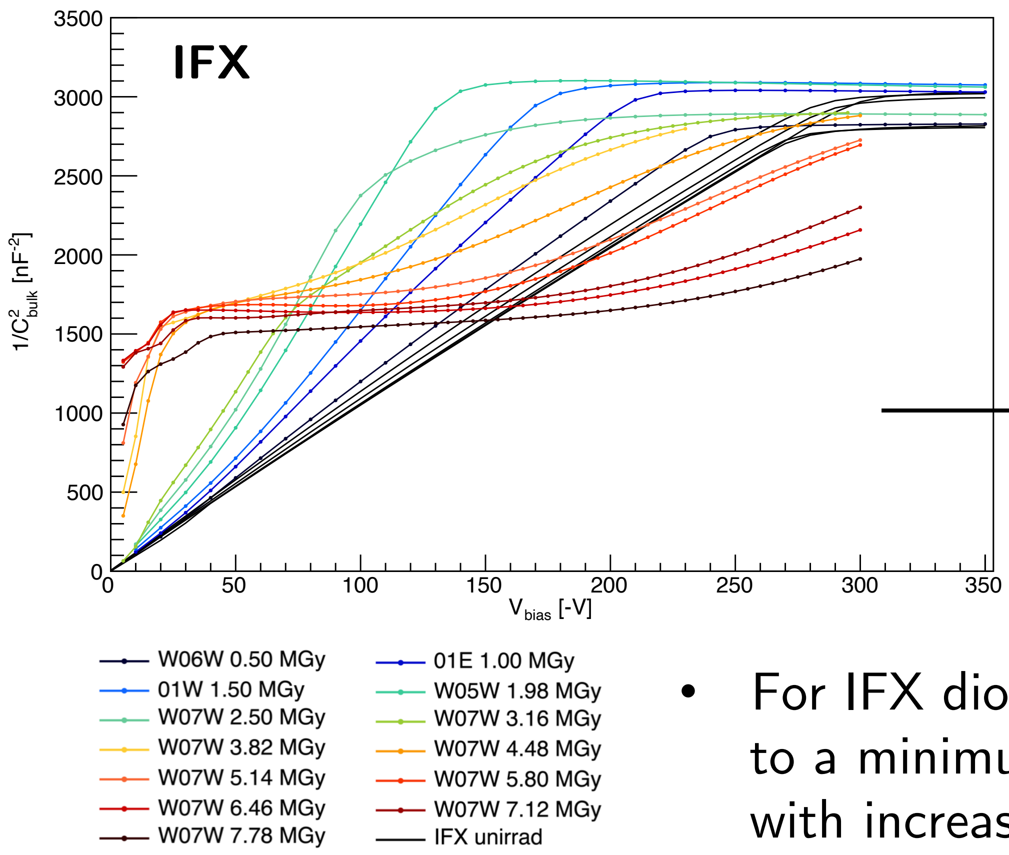


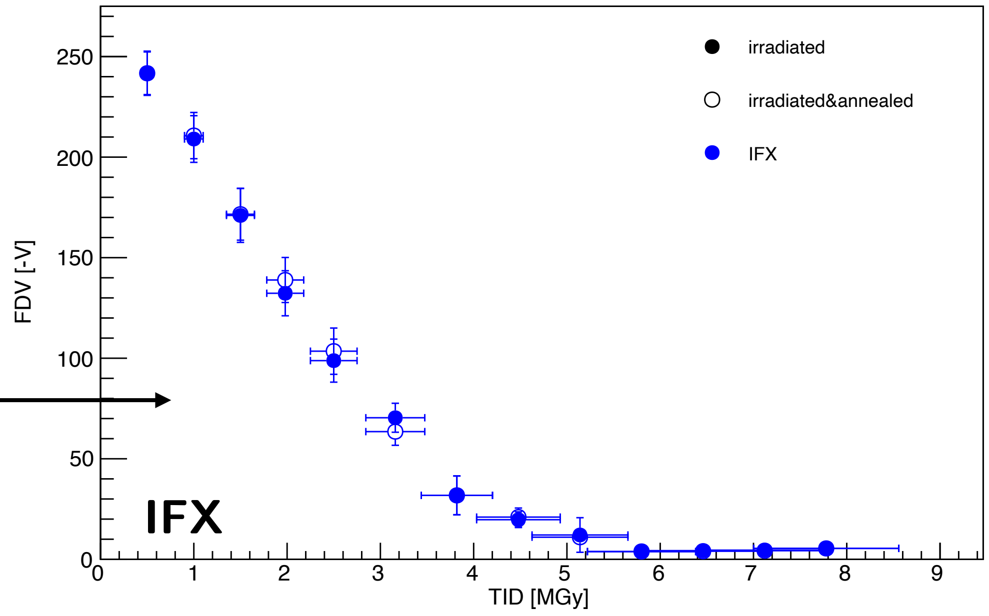




- For CNM and HPK diodes, full depletion voltage drops to a minimum at a specific dose and then it increases with increasing dose again.
- Observed effect can be linked to type inversion of p-type diodes to n-type

| Minimum of FDV at dose | |
|---|---|
| CNM | 4.14 MGy |
| HPK | 5.64 MGy |

# CV Measurements of Irradiated&Annealed Diodes




- For IFX diodes, full depletion voltage drops to a minimum at $5.80\ \mathrm{MGy}$ and the increase with increasing dose is not observed yet again.
- Change in measured CV curves at higher $\mathrm{TIDs}$ needs to be investigated.

# FDV Dependence on TID

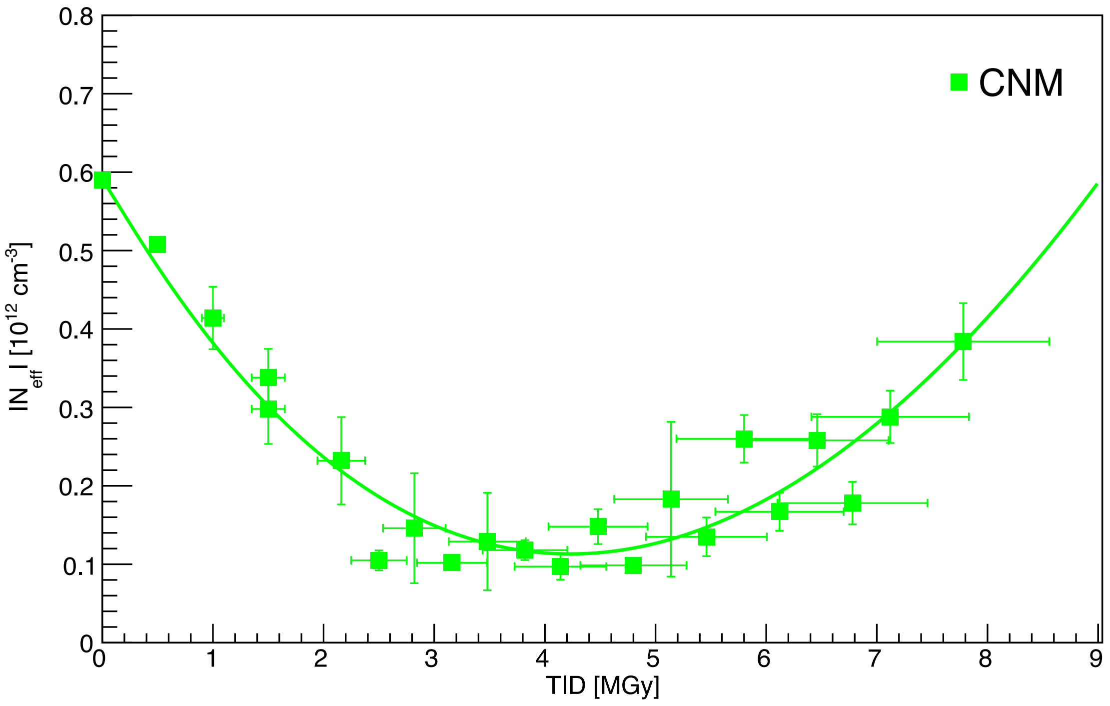
- Used fitting function was previously determined for n-type silicon
- Very good agreement for p-type silicon but some modifications will be needed

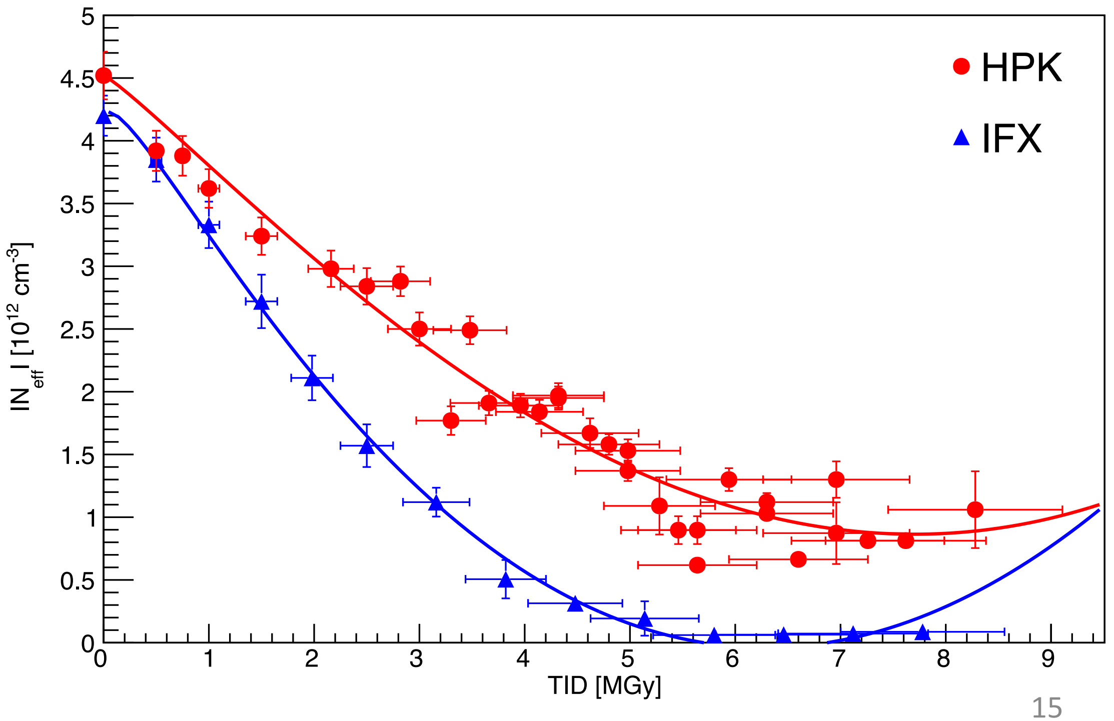
$$N_{\text{eff}}(D) = N_{\text{eff},0} + N_{\text{SD}}(D) - N_{\text{A}}(D)$$

$$N_{\text{SD}}(D) = g_{\text{SD}} \times D^{\gamma_{\text{SD}}}$$

$$N_{\text{A}}(D) = g_{\text{DA-I}} \times D^{\gamma_{\text{DA-I}}} + g_{\text{DA-}\Gamma} \times D$$

*E. Fretwurst et al. / Nuclear Instruments and Methods in Physics Research A 514 (2003) 1–8*



# Conclusions

- The effects of gamma irradiation on p-type silicon diodes were studied.
- The diodes had comparable active areas and thickness but different initial silicon resistivities and oxygen concentrations. Thanks to the contactable guard ring we were able to separate $I_{\mathrm{leak}}$
- Diodes were irradiated up to $8.28\ \mathrm{MGy}$ by $^{60}$Co and then annealed at $60\ ^{\circ}\mathrm{C}$ for 80 minutes.
- Annealing effect in gamma irradiated diodes was not observed in IV&CV measurements results.
- Leakage current increases with increasing TID by $6.1{\cdot}10^{-6}\ \mathrm{A/cm^3/MGy}$

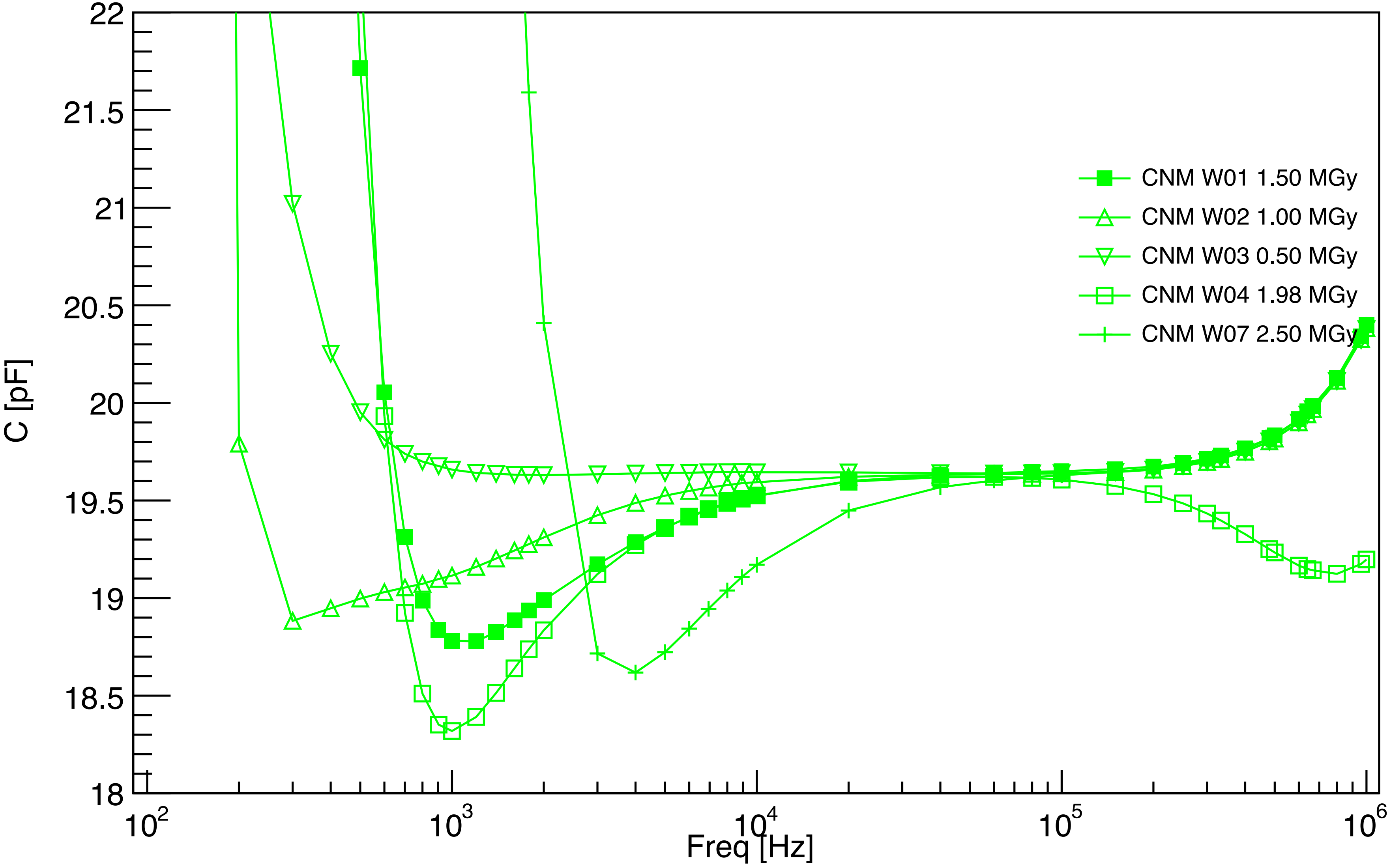
  for HPK&IFX diodes and by $10.3{\cdot}10^{-6}\ \mathrm{A/cm^3/MGy}$ for CNM diodes.
- $N_{\mathrm{eff}}$ and therefore $\mathrm{FDV}$ significantly decreases with increasing TID and then it starts to increase again at specific dose. We assume at the decrease is caused by the effect of acceptor removal.

**Future plans**

- Further studies of field distribution and charge collection by TCT method required.
- Measurements of oxygen concentration in studied samples in progress.

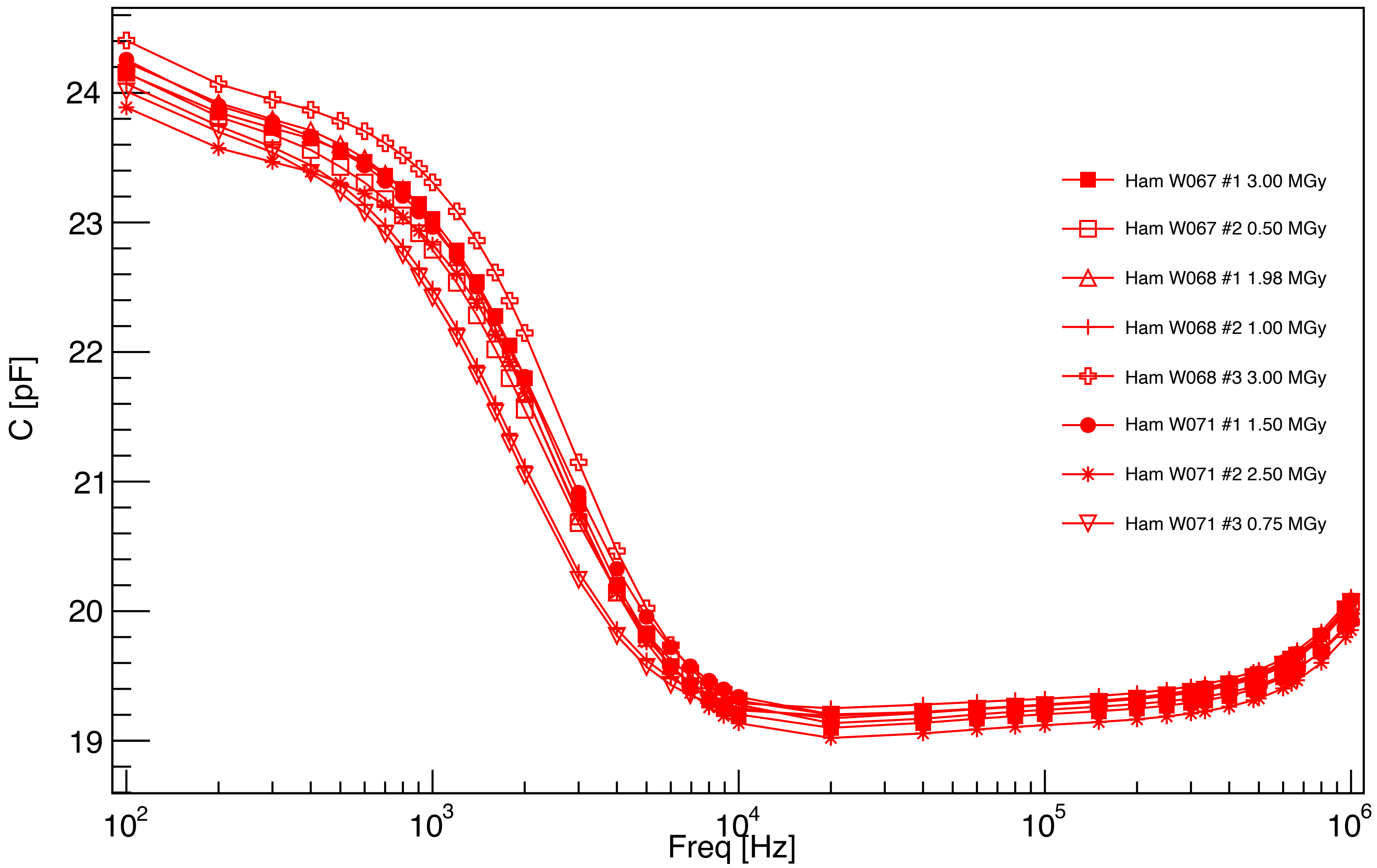
# Back up

# Capacitance Dependence on Measuring Frequency of CNM Irradiated and Annealed Diodes @ $60\ \mathrm{V}$



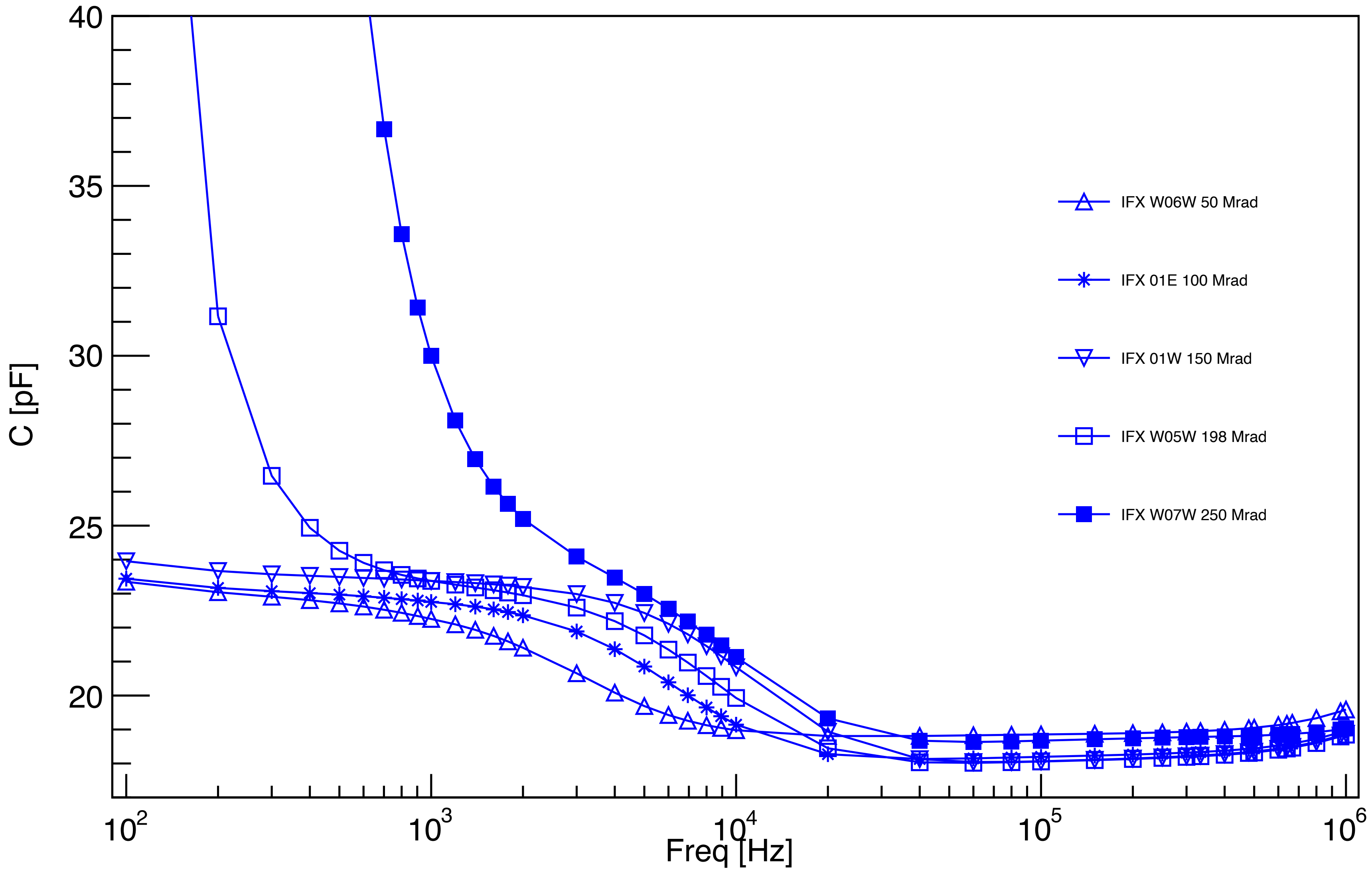

- Chosen measuring frequency $100\ \mathrm{kHz}$

# Capacitance Dependence on Measuring Frequency of HPK Irradiated and Annealed Diodes @ 300 V




- Chosen measuring frequency $100\ \mathrm{kHz}$

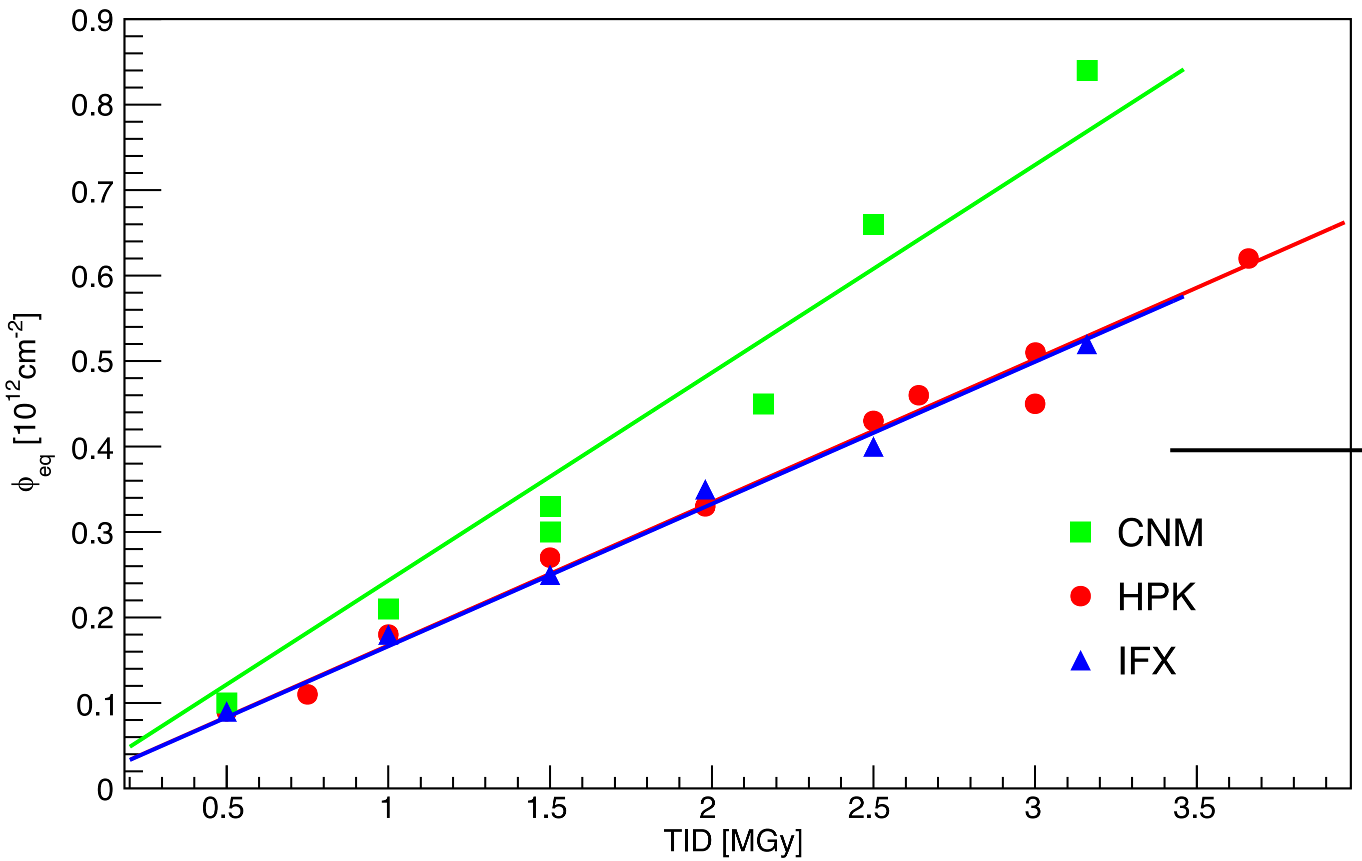
# Capacitance Dependence on Measuring Frequency of IFX Irradiated and Annealed Diodes @ $300\ \mathrm{V}$




- Chosen measuring frequency $100\ \mathrm{kHz}$

# TID vs. $\Phi_{eq}$ after Annealing

Assuming increasing leakage current with TID that is caused by displacement damage, we can estimate equivalent fluence $\Phi_{eq}$ from damage parameter α Moll 2018




$$\frac{\Delta I}{V} = \alpha \cdot \phi_{eq}$$

$\alpha = (3.99 \pm 0.03) \cdot 10^{-17}\ \mathrm{A \cdot cm^{-1}}$

for currents measured at 20 °C after annealing (80 min for 60 °C)

1 MGy = $2.4 \cdot 10^{11}\ \mathrm{cm^{-2}}$ for CNM diodes

1 MGy = $1.7 \cdot 10^{11}\ \mathrm{cm^{-2}}$ for HPK&IFX diodes

**1 MGy = $9.3 \cdot 10^{12}\ \mathrm{cm^{-2}}$** G. Lindstroem et al., Journal of Optoelectronics Vol.4 (2004)

**1 MGy = $4.8 \cdot 10^{11}\ \mathrm{cm^{-2}}$** Z. Li et al., IEEE Transactions on Nuclear Science Vol. 44 (1997)