Science & Technology Facilities Council
Rutherford Appleton Laboratory

Institute of High Energy Physics
Chinese Academy of Sciences

Carleton University

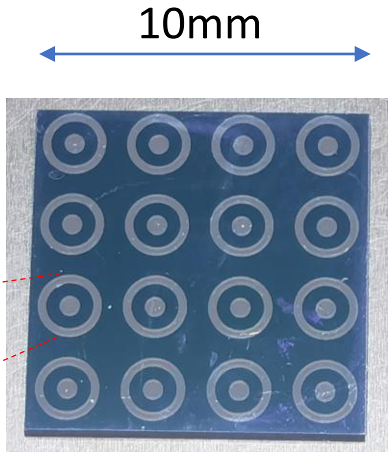
Jožef Stefan Institute
Ljubljana, Slovenia

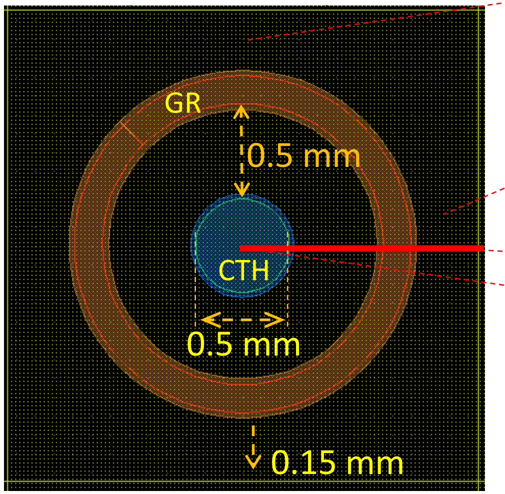
Update on Radiation damage investigation of epitaxial P-type Silicon using Schottky diodes

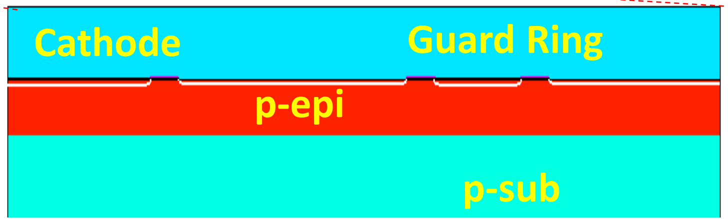
Giulio Villani, Matt Kurth, Yebo Chen, Hongbo Zhu, Peilian Liu
Thomas Koffas, Fergus Wilson, Igor Mandic, Christoph Klein, Garry Tarr, Robert Vandusen

Schottky diode fabrication and model

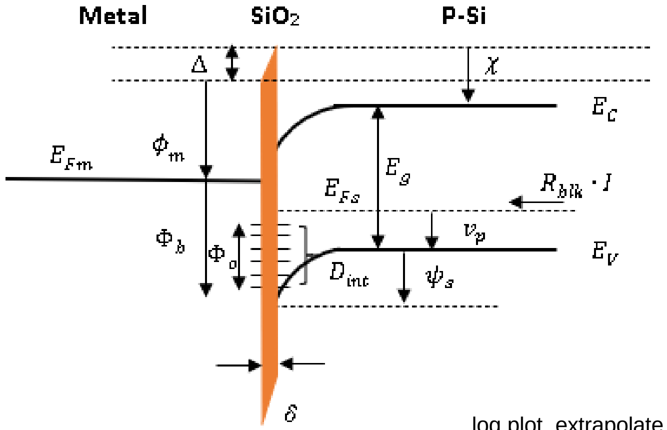
- Geometry of the Schottky diode
  - diameter of Al cathode = 0.5mm
  - epi layer thickness = 50 µm
  - 10mm x 10mm dices
  - high resistivity doping 10^13 p-epi
- Irradiation
  - Neutron irradiation
    - 10^{12}, 10^{13}, 10^{14}, 10^{15}, 10^{16} 1MeV n_{eq}/cm^2
  - Thermal annealing (80/60) to put them all in the same annealed condition
  - Diodes diced from the same wafer as the Irradiated diodes
- TCAD simulation – use cylindrical symmetry to simulate the full device







Schottky diodes barrier



$$1:\ I = SA^*T^2 \exp\left(-\frac{e}{kT}\phi_{b0}\right)\exp\left(\frac{e}{nkT}V\right) = I_0 \exp\left(\frac{e}{nkT}V\right) \xrightarrow{\text{log plot ,extrapolate V = 0}} \phi_{b0} = \frac{kT}{e}\ln\left(\frac{SA^*T^2}{I_{v=0}}\right)$$

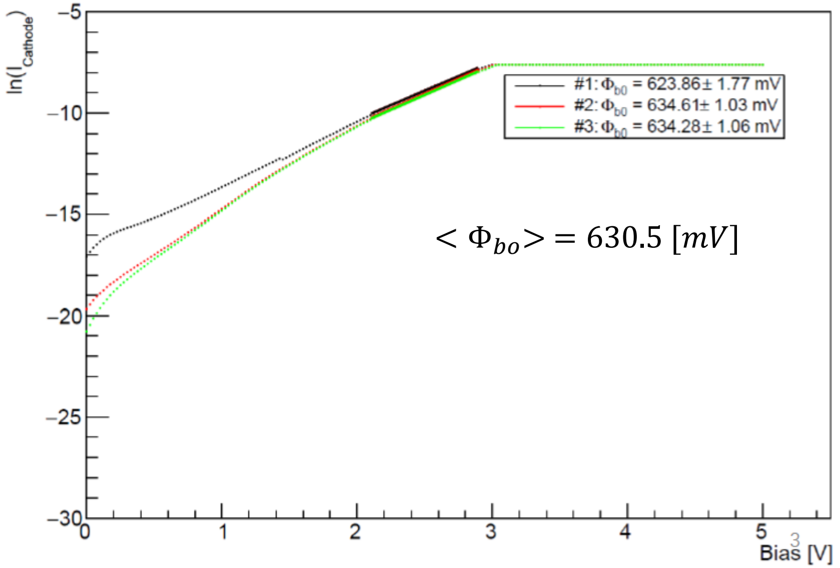
$$2:\ I = SA^*T^2 \exp\left(-\frac{e}{kT}\phi_{b0}\right)\exp\left(\frac{e}{nkT}(V - R_sI)\right) = I_0 \exp\left(\frac{e}{nkT}(V - R_sI)\right) \longrightarrow \frac{dV}{dln(I)} = \frac{nKT}{e} + R_sI$$

S: area of the device [cm^2]   A*: Richardson's constant 32 [for P-type Si, A cm^{-2} T^{-2}]   T: temperature [K]   e: electron charge

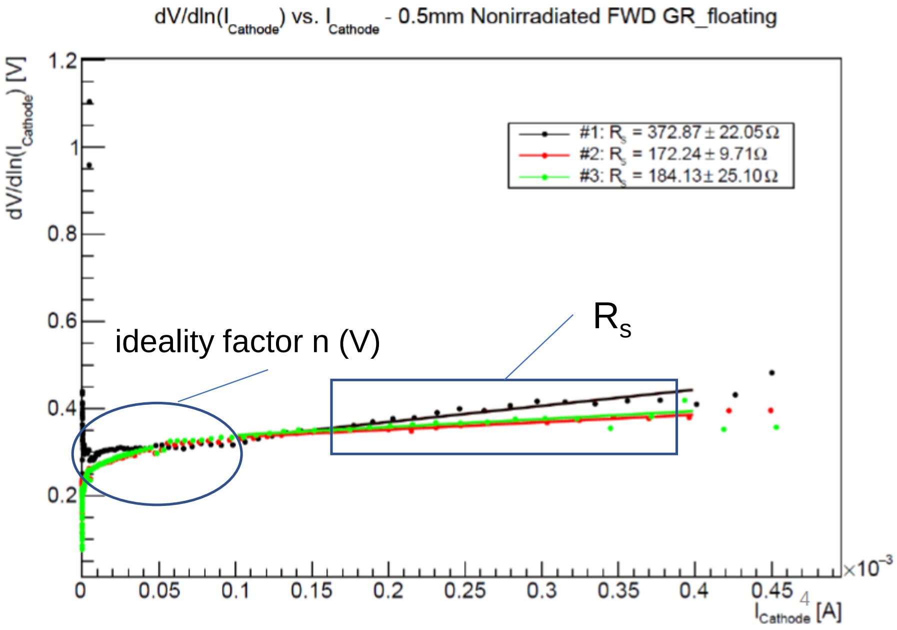
Φ_{b0} : barrier height between semiconductor and Al/SiO2 [eV]   n: ideality factor R_s : bulk resistance

- equation expresses the Schottky diode current assuming thermionic emission
- In a Schottky barrier, effects due to Fermi pinning at ϕo and presence of interface states, Dint, between metal and Si, with proper density and energy distribution, needs taking into account
- Also depending on the fabrication process, thin dielectric layer δ might be present at metal / Si interface
- from I(V) thermionic formula for Schottky diode, including Rs of bulk ,we can determine ϕ_{b0} and infer ideality factor n (V)

IV curve – Barrier height extraction



$$< \Phi_{bo} > = 630.5\ [mV]$$



- Barrier height extracted from IV curve
- From Ideality factor, infer density of interface states vs. energy (H C Card and E H Rhoderick 1971 *J. Phys. D: Appl. Phys.* **4** 1589)
- It should be possible to infer bulk doping from R_s still to be investigated

Measured D_{int}

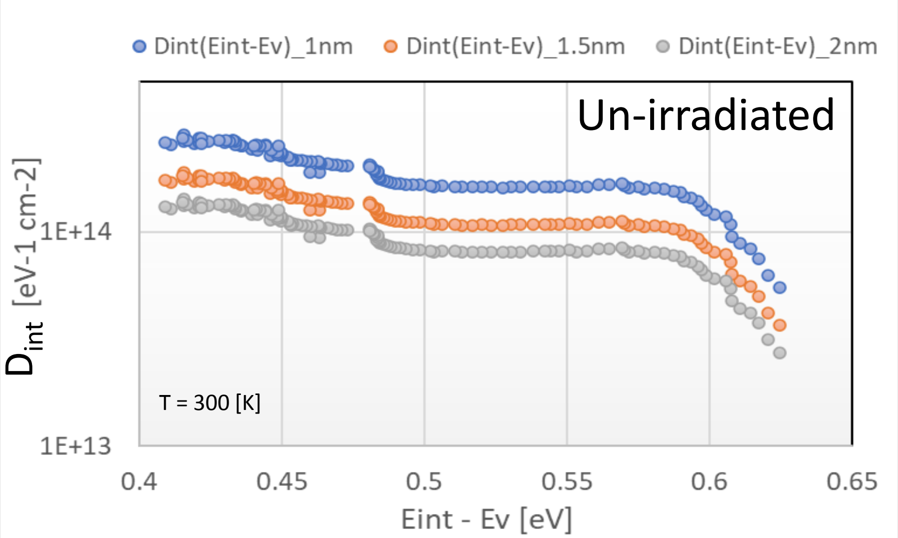
$$D_{int}(V) = \frac{1}{e}\left(\frac{\varepsilon_{ox}}{\delta}(n(V)-1) - \frac{\varepsilon_s}{W(V)}\right)$$

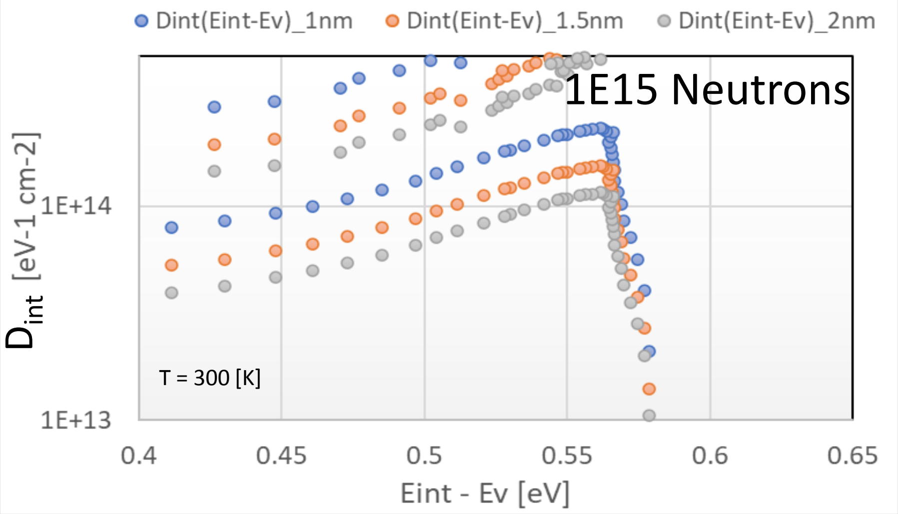
$$W(V) = \sqrt{\frac{2\varepsilon_s}{eN_A}\Psi_s} = \sqrt{\frac{2\varepsilon_s}{eN_A}\left(\Psi_{s0} - \frac{V}{n}\right)}$$

$$E_{int} - E_V = e\left(\Phi_{B0} - \frac{V}{n(V)}\right)$$

e: electron charge
E_{int} : interface states energy
E_V : top of valence band energy
Ψ_{s0} : diffusion potential
Φ_{B0} : barrier height between semiconductor and Al/SiO2
n: ideality factor
ε_s / ε_{ox} : Si /SiO2 permittivity
δ: interface layer thickness
N_A :doping concentration
W :depletion width

- Energy distribution profile of interface state densities Dint from ideality factor
- 0.5 mm Al/p-Si non-irradiated and 1e15 n-irradiated Schottky diodes
- Assumed native oxide layer (SiO2) δ thickness 1, 1.5 and 2 nm
- wafers were left exposed in air after etching and prior to Al sputtering
- neglect extension of W in forward region
- Expected decrease of density of states for higher energy - pinning located > 600 meV
- Irradiated data noisy





Density of interface states

$$\varphi_{B0} = \gamma \cdot \left(E_g + \chi_{si} - \phi_m\right) + (1-\gamma) \cdot \phi_o$$

$$\gamma = \frac{\varepsilon_{ox}}{\varepsilon_{ox} + q^2 \cdot \delta \cdot D_{int}}$$

E_g : band gap
χ_{Si} : electron affinity of Si
ϕ_m : metal workfunction
Φ_0 : neutral level
ε_{ox} : SiO2 permittivity
δ: interface layer thickness

$$\overline{D_{int}} = 1.95\ e14\ \delta = 1nm$$
$$\overline{D_{int}} = 1.3\ e14\ \delta = 1.5nm$$
$$D_{int} = 9.775\ e13\ \delta = 2nm$$
$$\phi_{BO} \sim 0.63\ [eV]$$
$$\phi_o \sim 0.65\ [eV]$$

non-irrad

$$\overline{D_{int}} = 6.57\ e14\ \delta = 1nm$$
$$\overline{D_{int}} = 4.38\ e14\ \delta = 1.5nm$$
$$\overline{D_{int}} = 3.28\ e14\ \delta = 2nm$$
$$\phi_{BO} \sim 0.604\ [eV]$$
$$\phi_o \sim 0.622\ [eV]$$

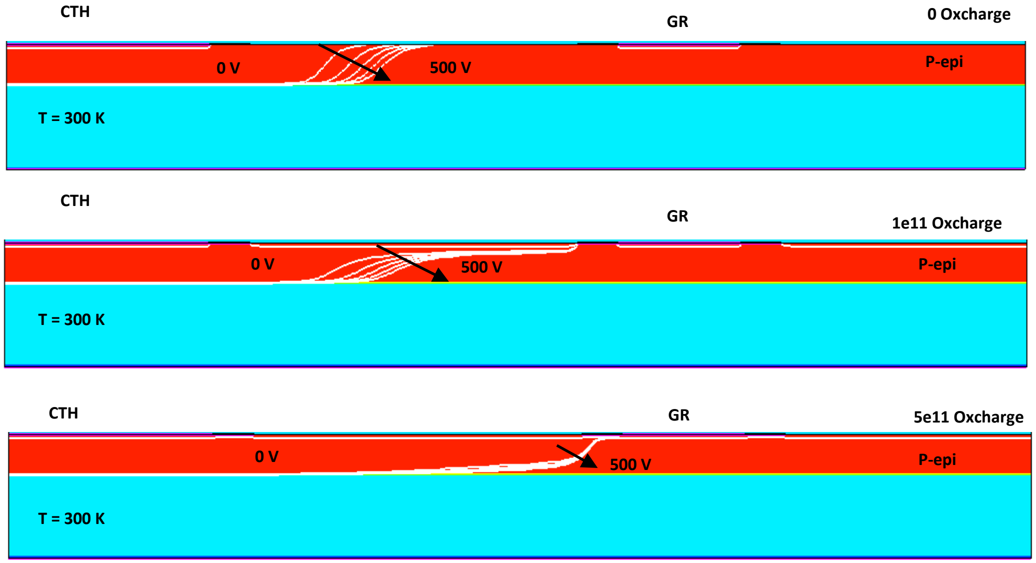
1e15 n-irrad

```
Electrode = "CathodeR"  {
Schottky {
###Fermi pinnning params

Pinning_d =@dint_thick@
Pinning_CNL =@CNL@
Pinning_Nint =@Nint@

###Barrier lowering params
InsBL_tox = 1e-7
      }
            }
```

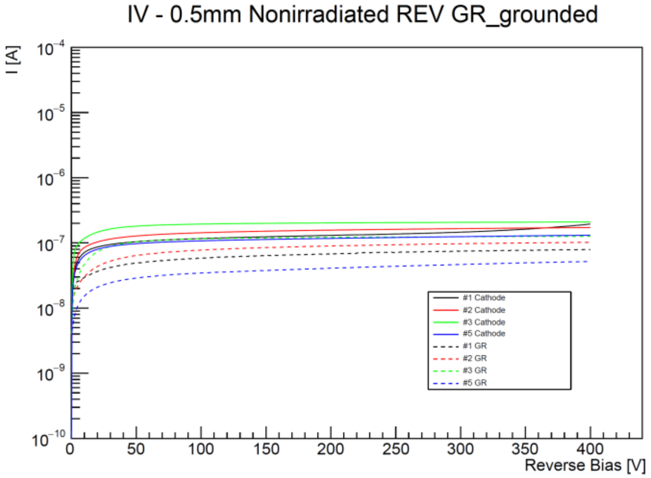
- For simulations take an average of D_{int} for non-irradiated and irradiated vs. δ and infer neutral level ϕ_0
  - TCAD expect CNL (i.e. $E_g + \chi_{si} + \psi_{s0} - \phi_0$) w.r.t. vacuum level, not E_v
  - It seems only single value, not spectrum are allowed in electrode parameter

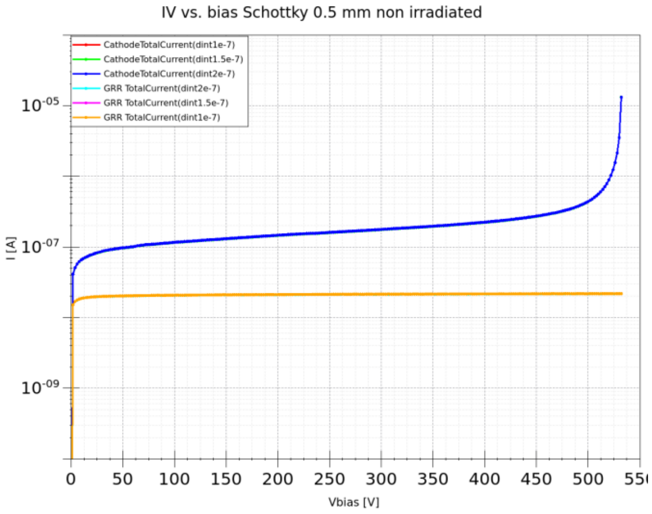
- Include Schottky barrier lowering, full band to band h^+ tunnelling from cathode, Si-SiO2 interface states

TCAD modeling



Depletion regions vs. bias voltage for different levels of OxIntCharge, non-irradiated


IV - 0.5mm Nonirradiated REV GR_grounded

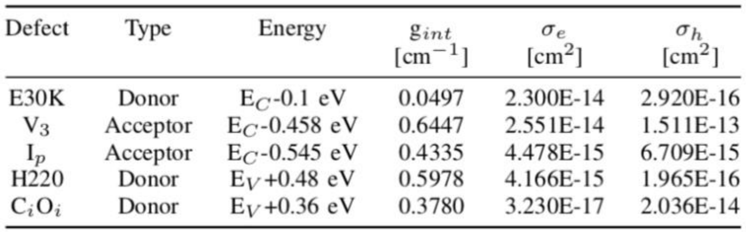

IV vs. bias Schottky 0.5 mm non irradiated

Interface Defect	Level	Concentration	σ
Acceptor	E_C-0.4 eV	40% of acceptor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV
Acceptor	E_C-0.6 eV	60% of acceptor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV
Donor	E_V+0.7 eV	100% of donor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV

***** ***Effects of Interface Donor Trap States on Isolation Properties of Detectors Operating at High-Luminosity LHC***, *DOI:* 10.1109/TNS.2017.2709815

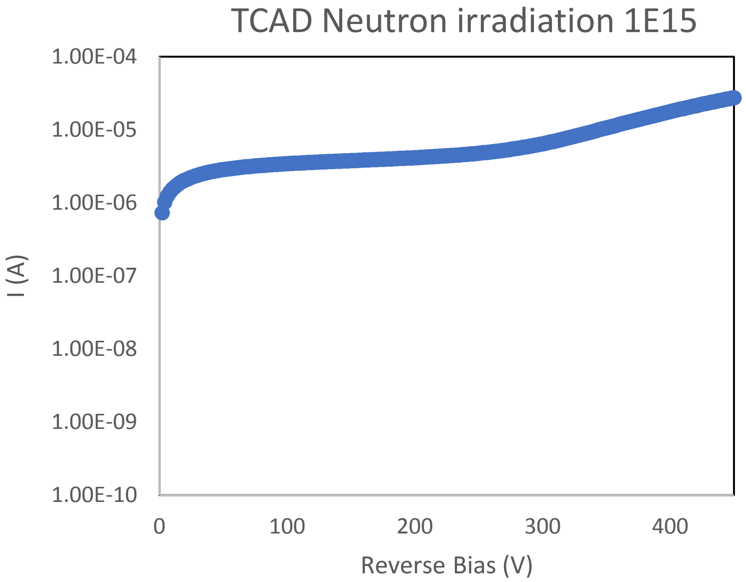
- Non-irradiated, depletion region vs. bias voltage with GR grounded
- Extension of depletion region ~ GR before BV (unrealistic, with OxIntcharge 5e11) , up to ~ 150 µm with 0 OxIntcharge

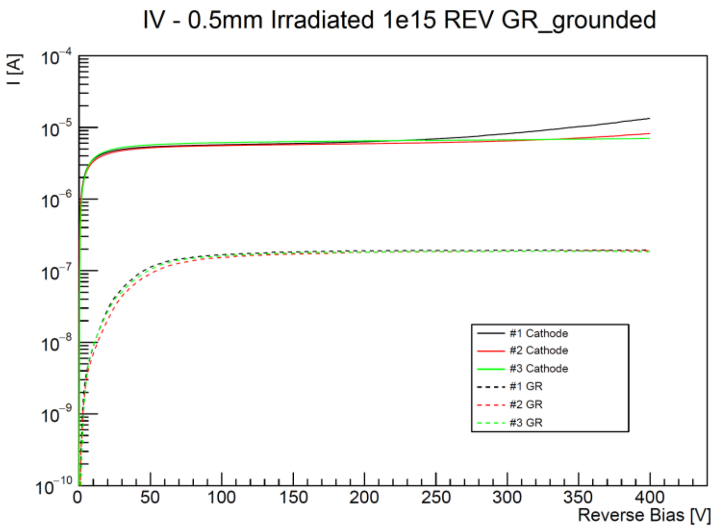
TCAD neutron irradiation



Defect	Type	Energy	g_{int} [cm^{-1}]	σ_e [cm^2]	σ_h [cm^2]
E30K	Donor	E_C-0.1 eV	0.0497	2.300E-14	2.920E-16
V_3	Acceptor	E_C-0.458 eV	0.6447	2.551E-14	1.511E-13
I_p	Acceptor	E_C-0.545 eV	0.4335	4.478E-15	6.709E-15
H220	Donor	E_V+0.48 eV	0.5978	4.166E-15	1.965E-16
C_iO_i	Donor	E_V+0.36 eV	0.3780	3.230E-17	2.036E-14

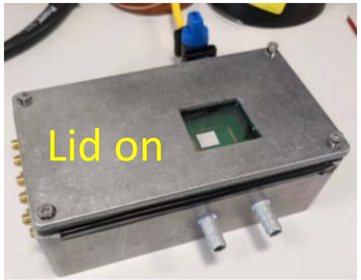
- Trap concentration of defects: $\mathbf{N = g_{int} \cdot \Phi_{neq}}$

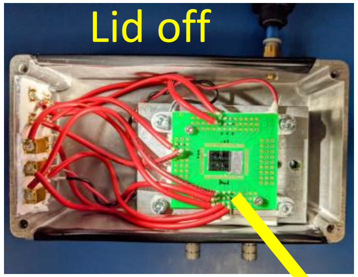


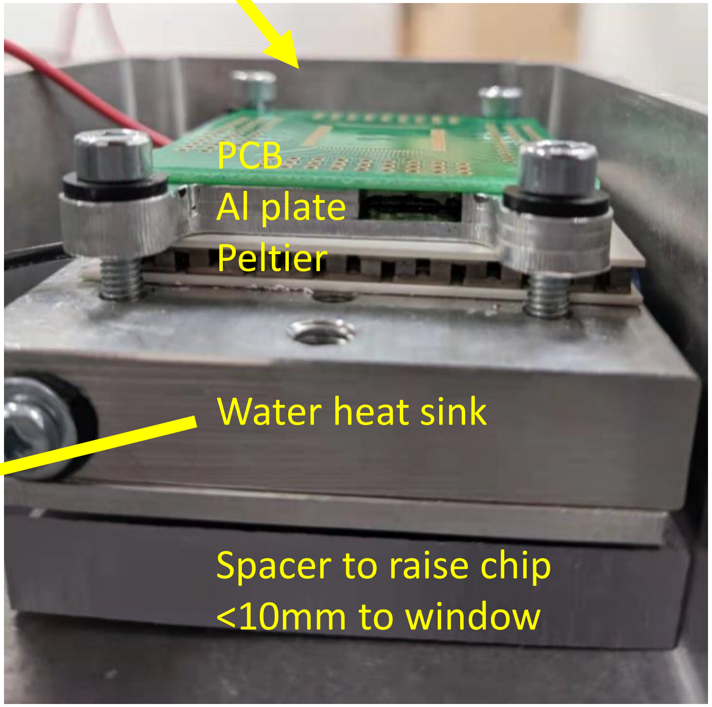


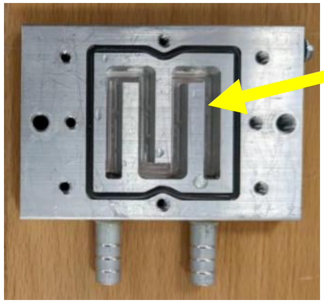
- Implementing the HPT (Hamburg Pentatrap model)
- A factor 1.66 applied to g_{int} to account for n-irradiation

Dry/Cold box for charge collection





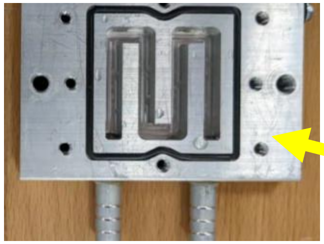


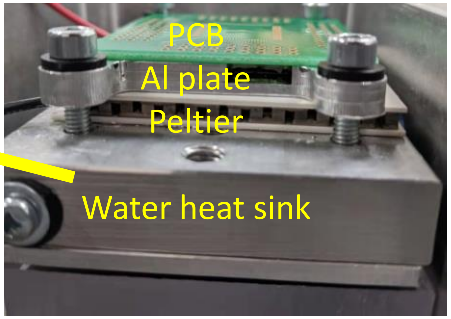


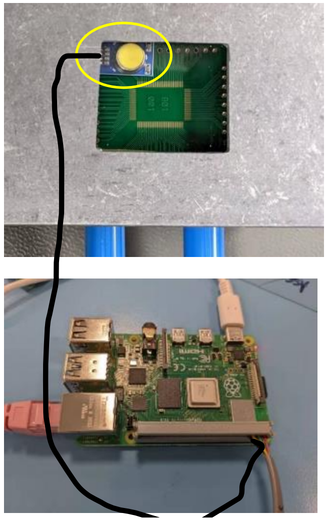
- Box designed to achieve these goals:
    - Temperature control down to -20 C
    - Keep the environment dry to 5% RH
    - Shield signal from laser’s EMP
    - Small enough to fit on laser stage
    - Temp/humidity readout
    - Window IR transparent/homogeneous
    - Limit to < 1 cm from diode to window to allow optical focus

Temp control and monitoring

- A Grant water chiller is plumbed into the water heat sink
- Water chiller run with DI water at 5 C
- The Peltier is powered with variable power supply up to 6A to achieve -20 C
- 4 layers are bolted together with thermal paste for heat transfer
- Humidity and temp measured with HYT221
  - Accurate for low humidity and temp
- HYT221 placed on surface of PCB with thermal paste to obtain same temp as diodes
- The humidity and temp read out with raspberry pi





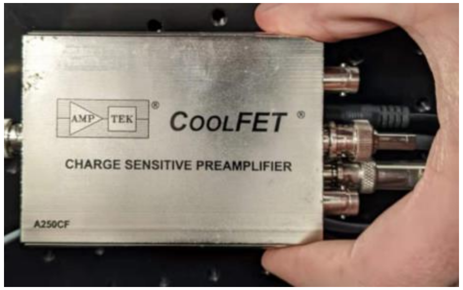


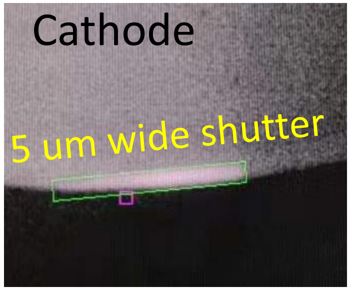
ET -127-20-15 Peltier Module	
Max current	13.1 A
Δ T max	74

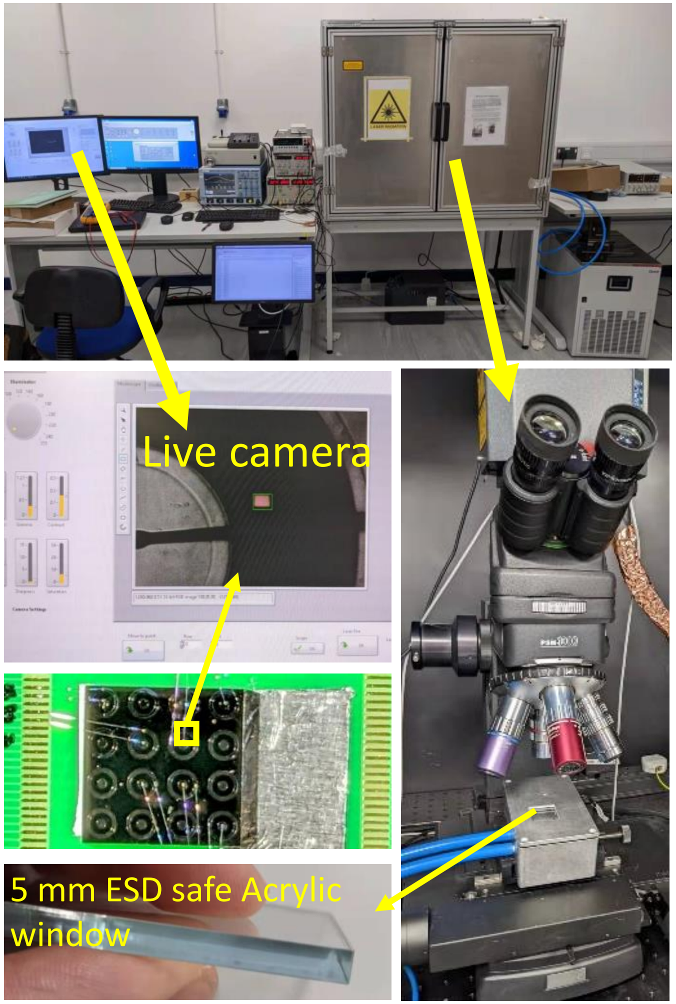
HYT221 sensor	Temperature	Humidity
Operating Range	- 40 C to 125 C	0 % RH to 100 % RH
Accuracy	0.2 C	1.8 % (0 – 90 %)

Lab Setup

- The laser has a built-in camera that allows the illumination of shutter with red light
- Shutter can close to a gap of 5um for charge collection measurements between cathode and guard ring
- The cold/dry box is moved with a stage that can move with 1 um increments
- The laser output is calibrated with the acrylic window to 50 pJ
- Signal is fed into a charge amplifier (CoolFET A250CF Amptek) and readout on oscilloscope

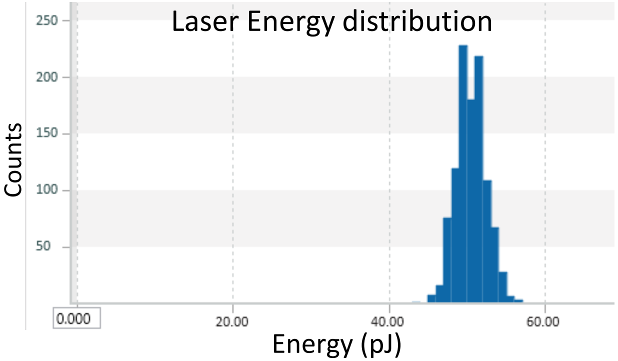






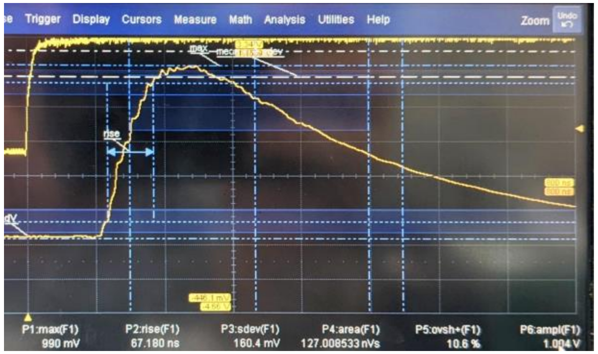
Laser and signal

- QuikLaze Trilite was repurposed
  - Designed for microelectronics machining
  - Filters to significantly reduce the power
  - 1064 nm wavelength used
- Calibrated to 50 pJ with a Sd = 1.9 pJ
  - Calibrated with PD10-pJ-v2 through Acrylic window
  - 50pJ chosen as a low energy reliably could be measured with PD10-pJ-v2
  - Tested Acrylic homogeneity and variation across window wasn't seen
  - Fan blows over top of window to prevent condensation when held at -20 C
- Oscilloscope used to measure amplitude from charge sensitive pre-amp
  - The laser was set as the trigger
  - The EMP from laser was consistent and noise subtracted to see smooth distribution
  - ~100 ns delay of signal from trigger
  - ~70 ns rise time

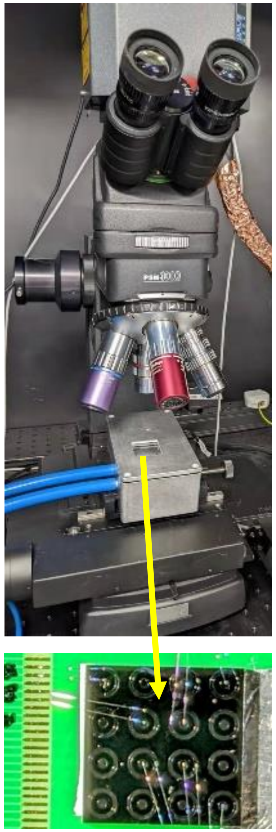



5 mm ESD safe Acrylic window

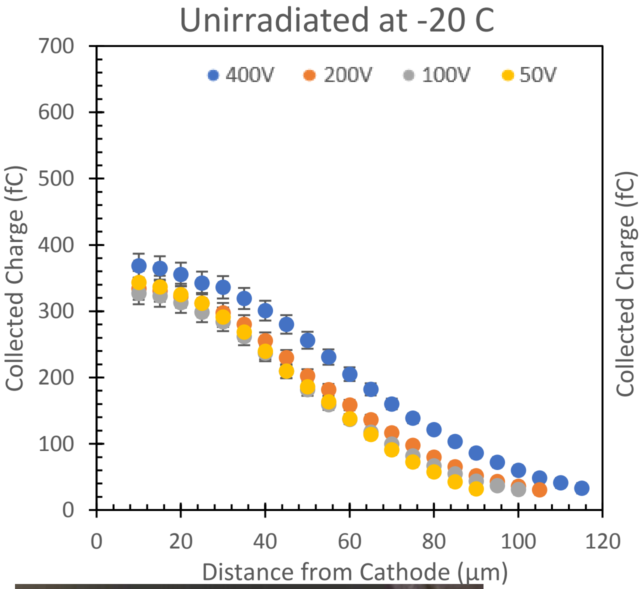
Thickness assists in reduction of condensation on outer surface

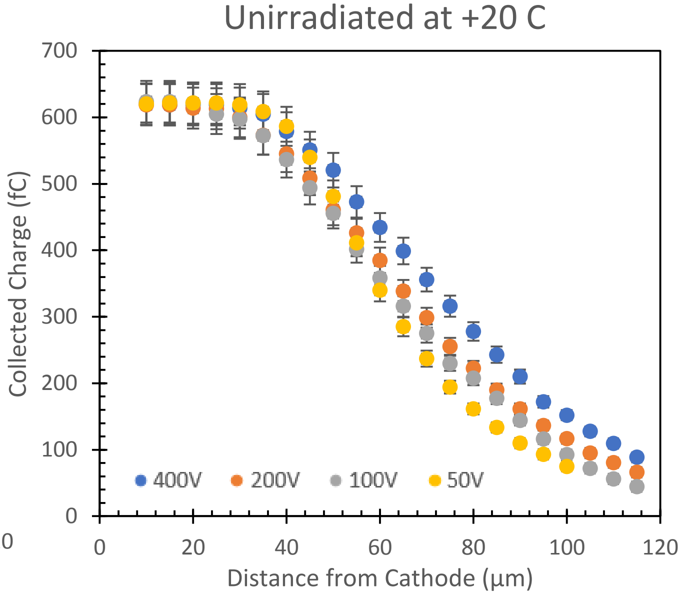


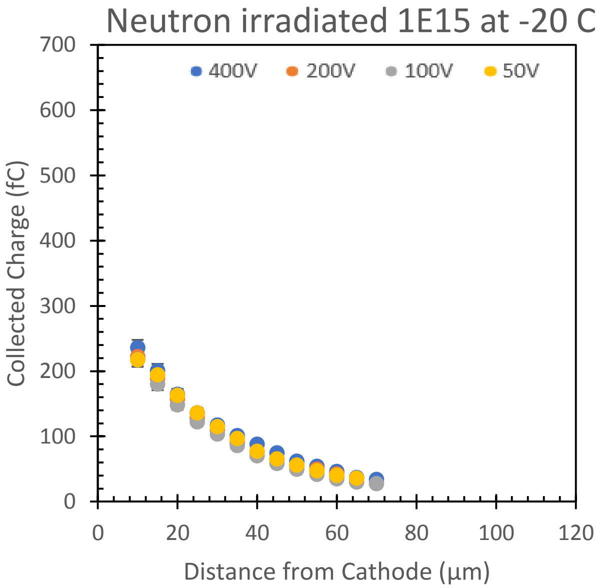
P1:max(F1)	P2:rise(F1)	P3:sdev(F1)	P4:area(F1)	P5:ovsh+(F1)	P6:ampl(F1)
990 mV	67.180 ns	160.4 mV	127.008533 nVs	10.6 %	1.004 V

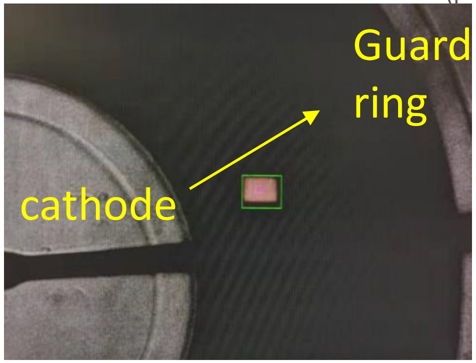


Charge Collection Measurements


Unirradiated at -20 C

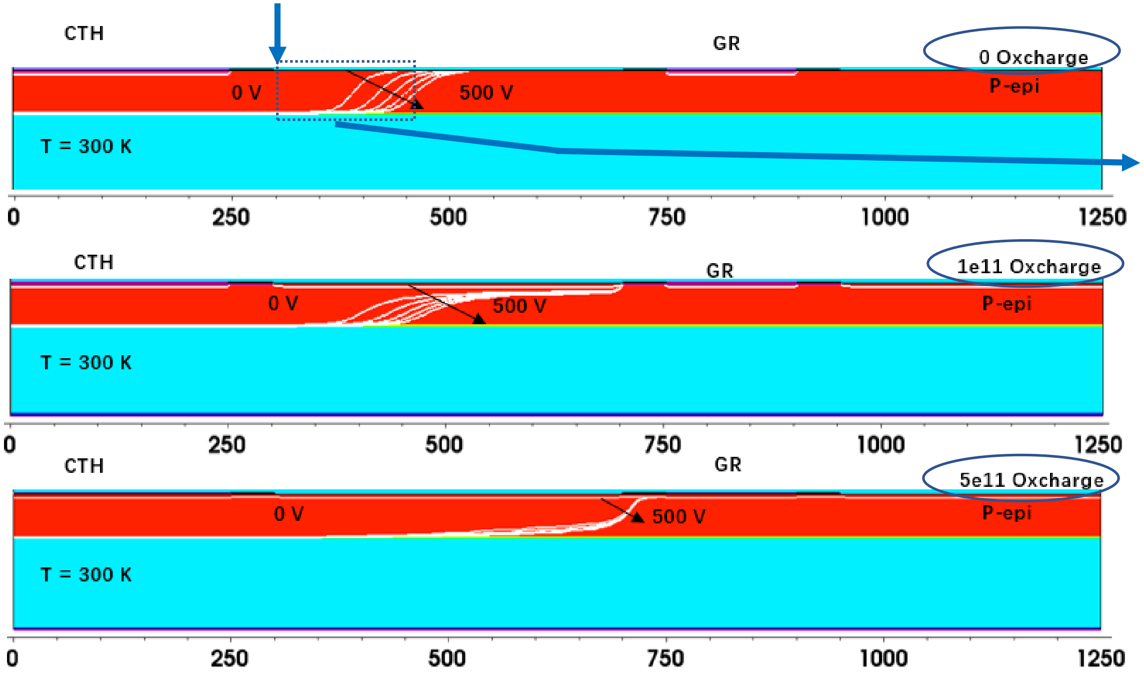

Unirradiated at +20 C


Neutron irradiated 1E15 at -20 C



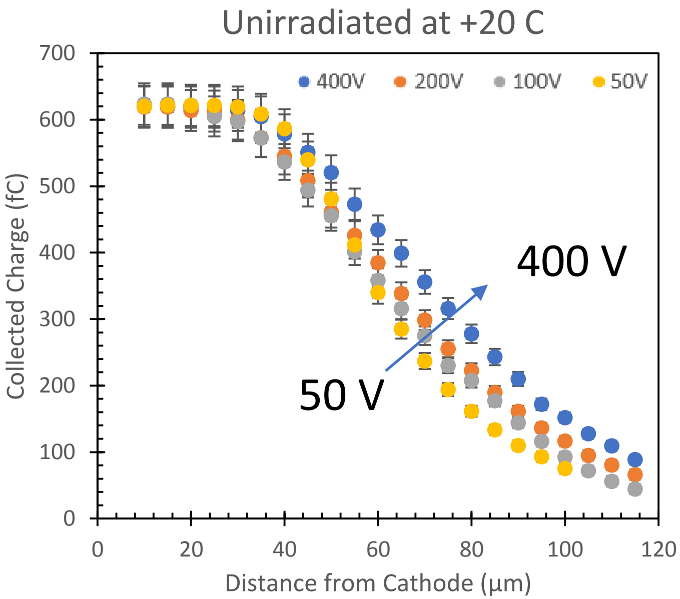
- depletion region is within 100 um of the cathode as the charge detection decays
- Increase of temp will increase the charge collection
- Irradiated diode decreases the charge collection and shrinks the depletion region
- Leakage current too high to make measurement at room temp for irradiated chip which current charge amplifier

TCAD simulation comparison to data



Edge of cathode and start of charge collection measurements

Depletion regions vs. bias voltage for different levels of OxIntCharge, non-irradiated

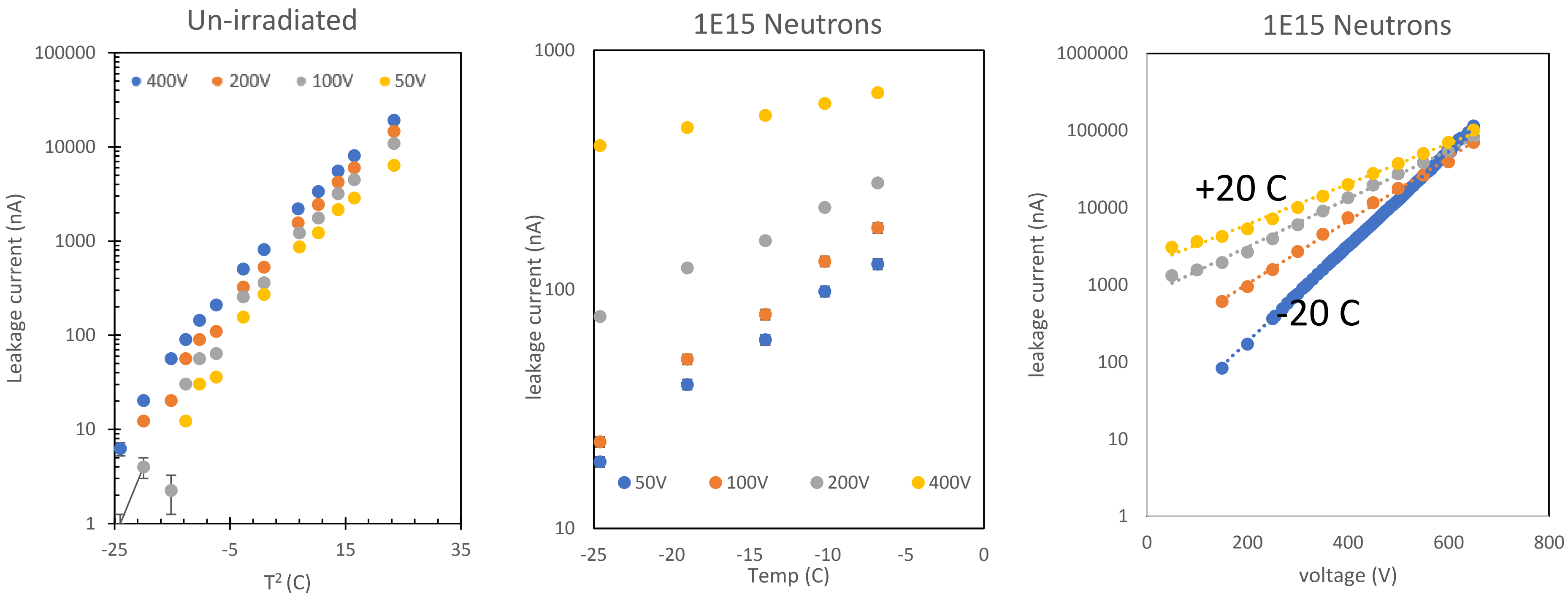


Interface Defect	Level	Concentration	σ
Acceptor	E_C-0.4 eV	40% of acceptor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV
Acceptor	E_C-0.6 eV	60% of acceptor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV
Donor	E_V+0.7 eV	100% of donor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV

* ***Effects of Interface Donor Trap States on Isolation Properties of Detectors Operating at High-Luminosity LHC***, *DOI:* 10.1109/TNS.2017.2709815

- Non-irradiated, depletion region vs. bias voltage with GR grounded
- Extension of depletion region ~ GR before BV (unrealistic, with OxIntcharge 5e11) , up to ~ 150 µm with 0 OxIntcharge
- Substrate and GR grounded with bias supplied to the cathode

Dry/Cold box for charge collection



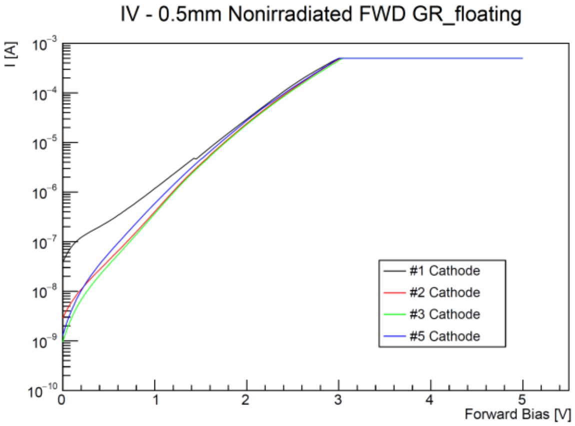
- The leakage current exponentially increases with temp – second method to calc the barrier height
- Irradiated diode has an increases leakage current by a factor >50

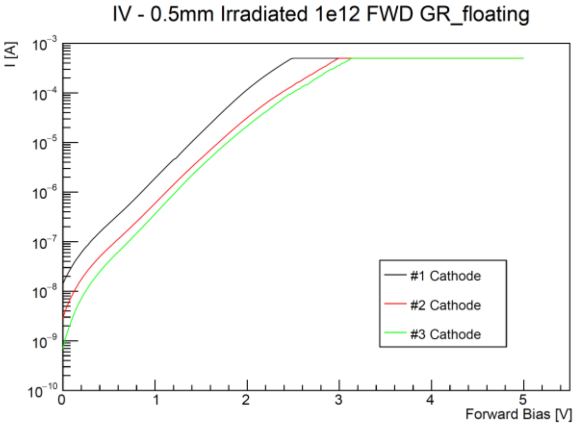
Conclusions and Outlook

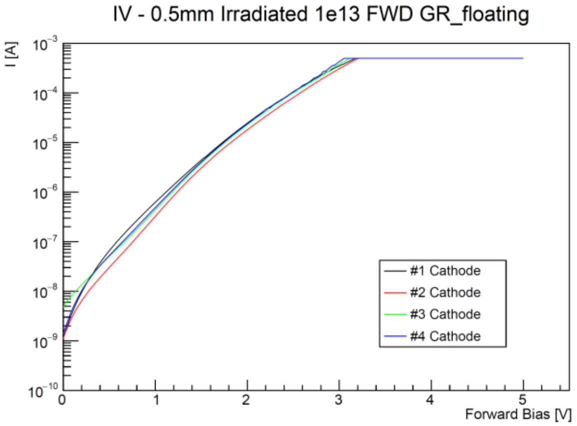
- Fabricated Schottky diodes on 5 6-inch p-type wafers (3 high resistivity 10^13 epi doping and 2 medium 10^14/10^15)
- High resistivity wafer works well, no early breakdown [breakdown >600V]
- Tested 500µm devices for IV/CV and charge collection with neutron irradiated up to 10^16
- Plan to test with protons and different device flavors (1 and 2mm sizes)
- Continue TCAD parameter optimization to agree with charge collection and AC/DC measurements for irradiated and non-irradiated devices

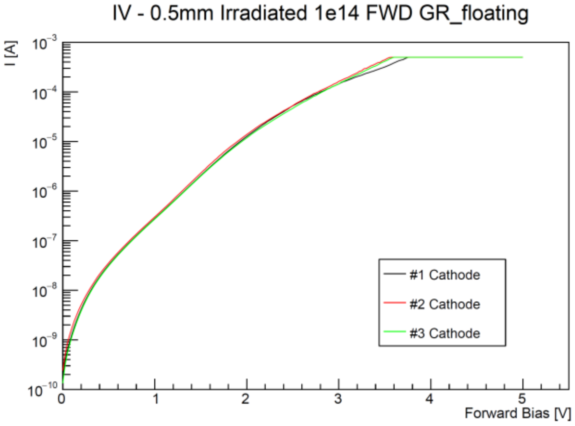
Backup

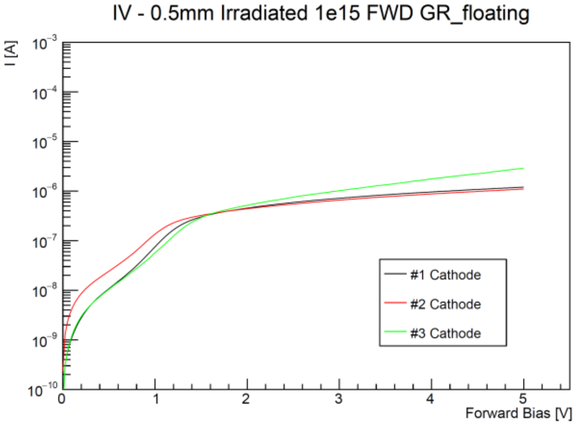
FWD IV – GR floating

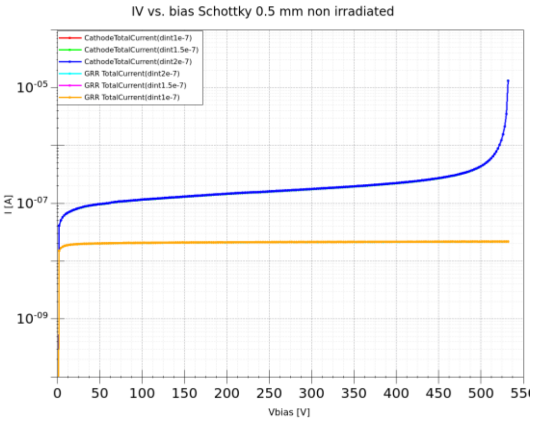

IV - 0.5mm Nonirradiated FWD GR_floating


IV - 0.5mm Irradiated 1e12 FWD GR_floating

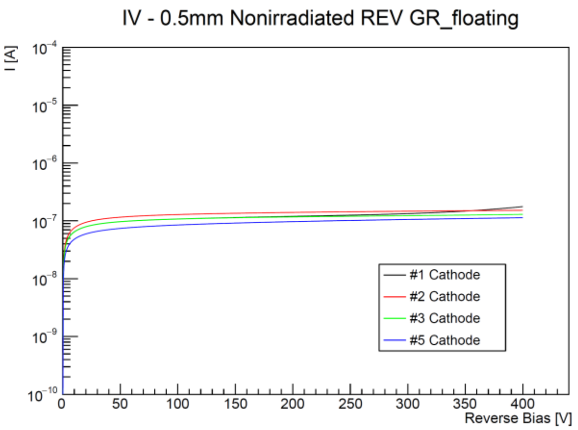

IV - 0.5mm Irradiated 1e13 FWD GR_floating

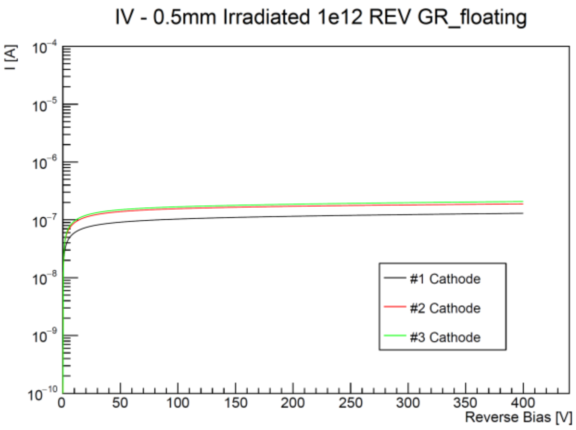

IV - 0.5mm Irradiated 1e14 FWD GR_floating

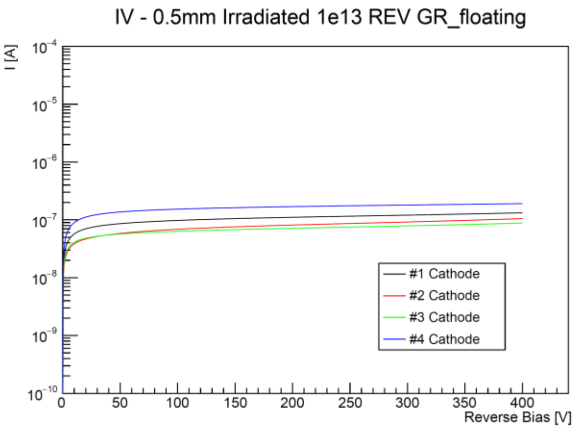

IV - 0.5mm Irradiated 1e15 FWD GR_floating

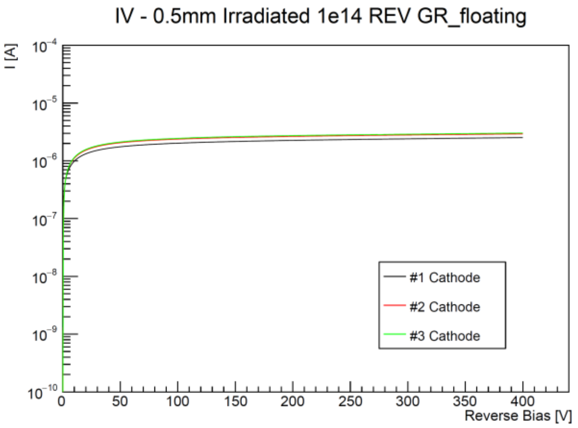

IV vs. bias Schottky 0.5 mm non irradiated

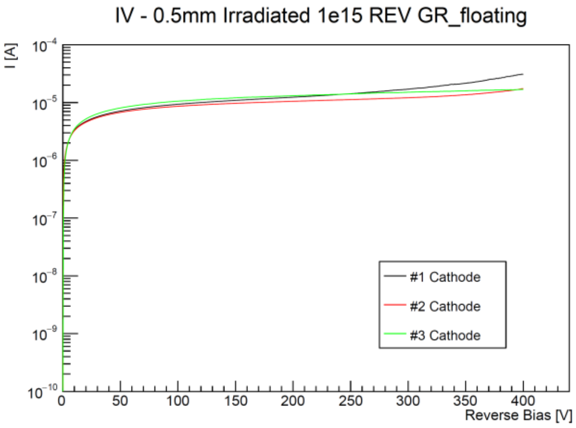
REV IV – GR floating


IV - 0.5mm Nonirradiated REV GR_floating

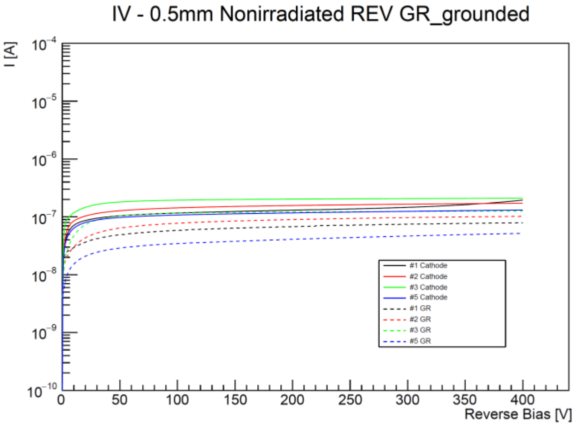

IV - 0.5mm Irradiated 1e12 REV GR_floating

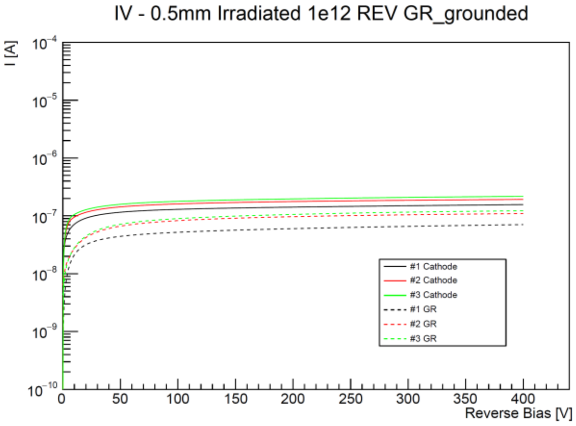

IV - 0.5mm Irradiated 1e13 REV GR_floating

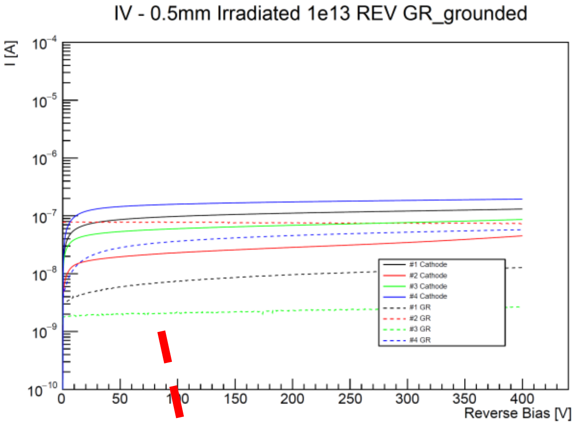

IV - 0.5mm Irradiated 1e14 REV GR_floating


IV - 0.5mm Irradiated 1e15 REV GR_floating

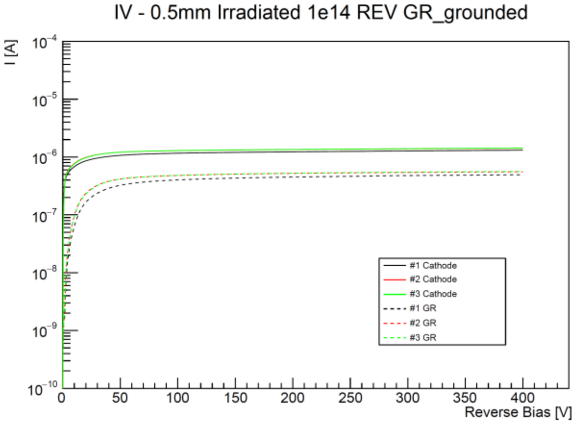
REV IV – GR grounded

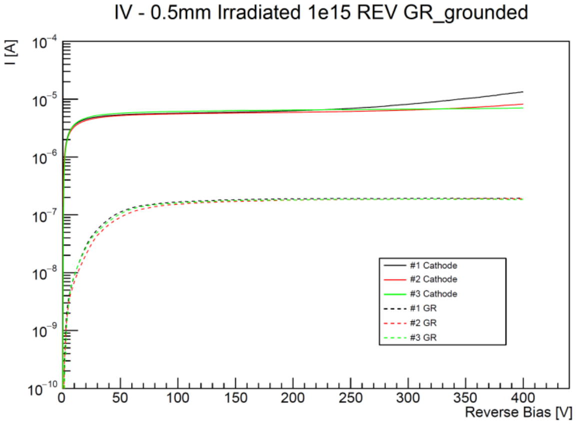

IV - 0.5mm Nonirradiated REV GR_grounded


IV - 0.5mm Irradiated 1e12 REV GR_grounded


IV - 0.5mm Irradiated 1e13 REV GR_grounded

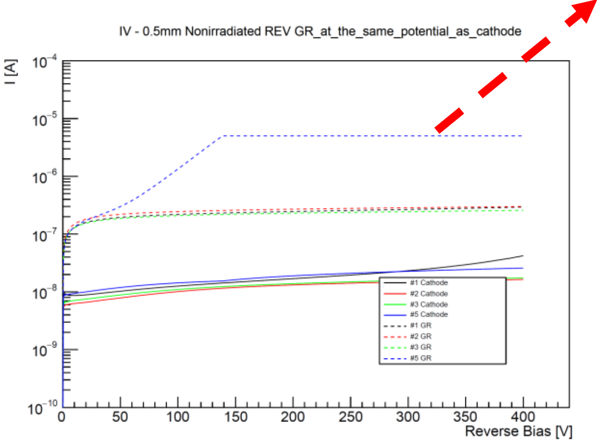
different from each other

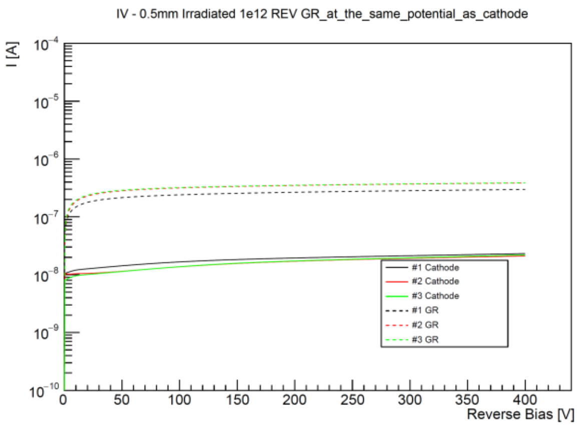

IV - 0.5mm Irradiated 1e14 REV GR_grounded

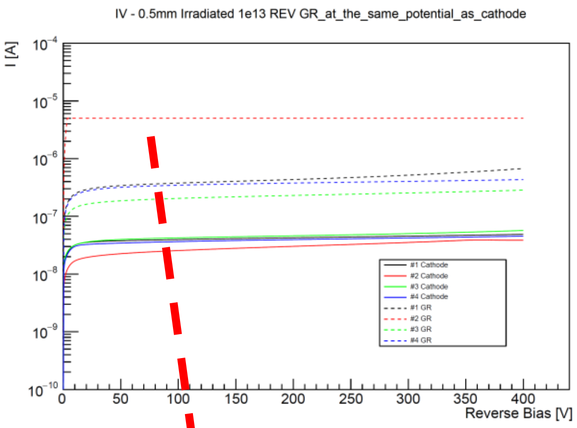

IV - 0.5mm Irradiated 1e15 REV GR_grounded

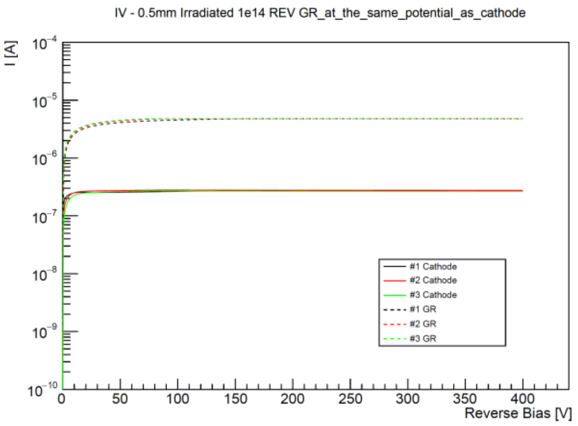
REV IV – GR at the same potential as cathode

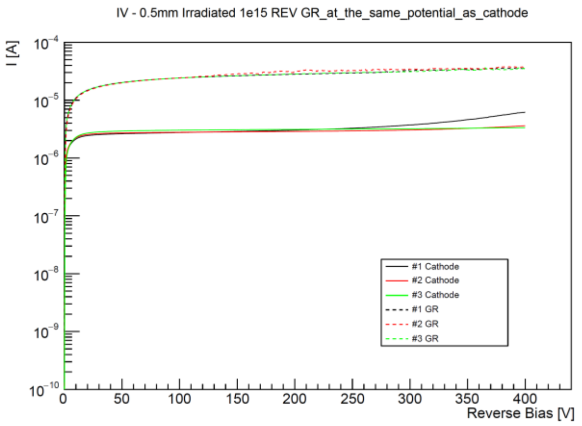
diode at the corner


IV - 0.5mm Nonirradiated REV GR_at_the_same_potential_as_cathode


IV - 0.5mm Irradiated 1e12 REV GR_at_the_same_potential_as_cathode


IV - 0.5mm Irradiated 1e13 REV GR_at_the_same_potential_as_cathode

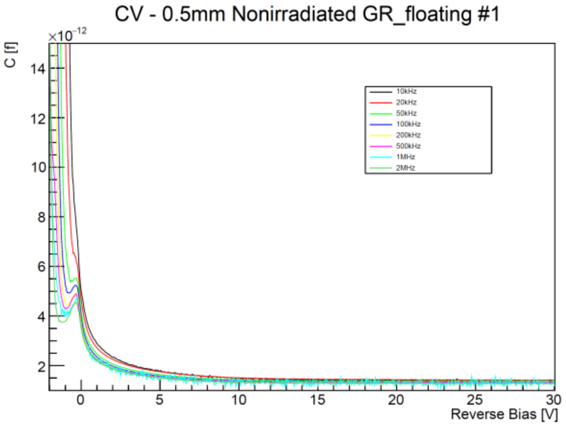

IV - 0.5mm Irradiated 1e14 REV GR_at_the_same_potential_as_cathode

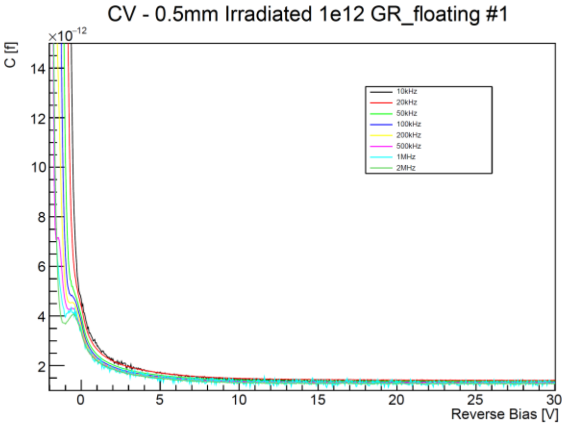

IV - 0.5mm Irradiated 1e15 REV GR_at_the_same_potential_as_cathode

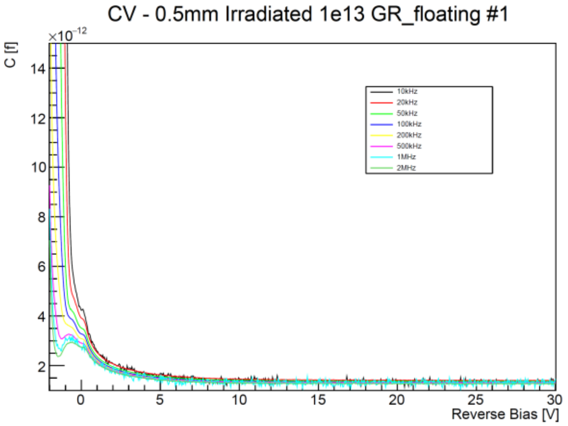
diode #2: different from others
its CV not measured
diode measured #4 instead

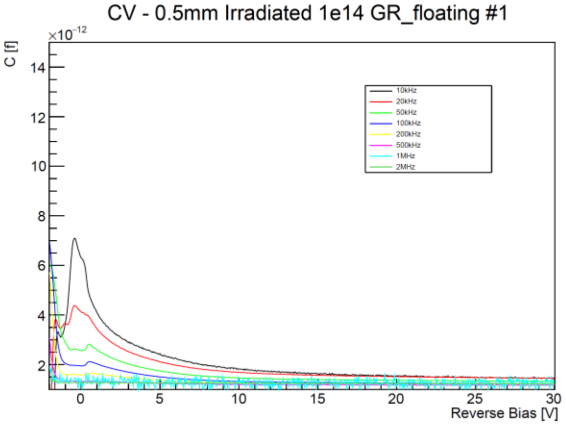
CV – GR floating

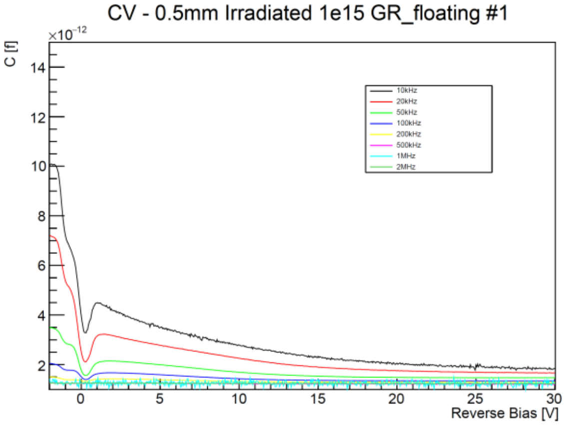
Plot of each diode looks similar
Just diodes #1 shown here


CV - 0.5mm Nonirradiated GR_floating #1


CV - 0.5mm Irradiated 1e12 GR_floating #1

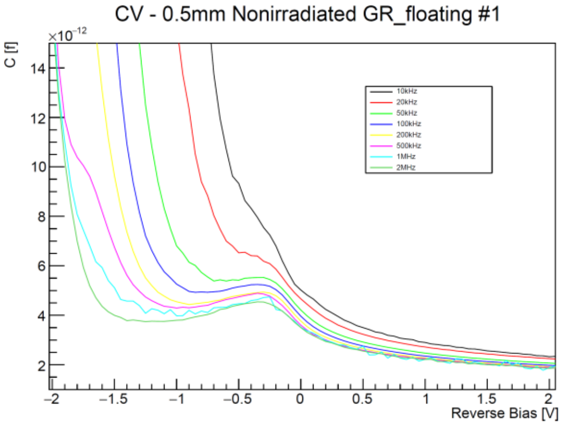

CV - 0.5mm Irradiated 1e13 GR_floating #1

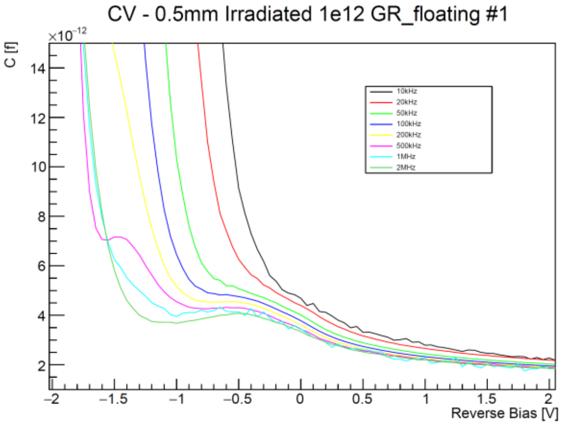

CV - 0.5mm Irradiated 1e14 GR_floating #1

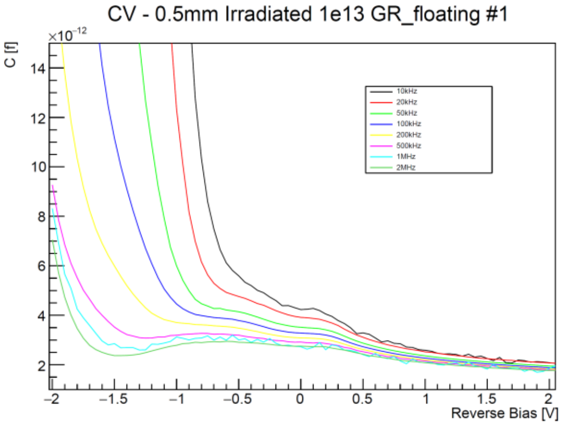

CV - 0.5mm Irradiated 1e15 GR_floating #1

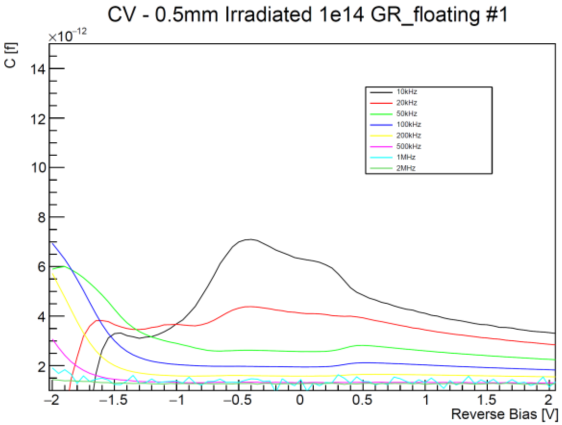
CV – GR floating

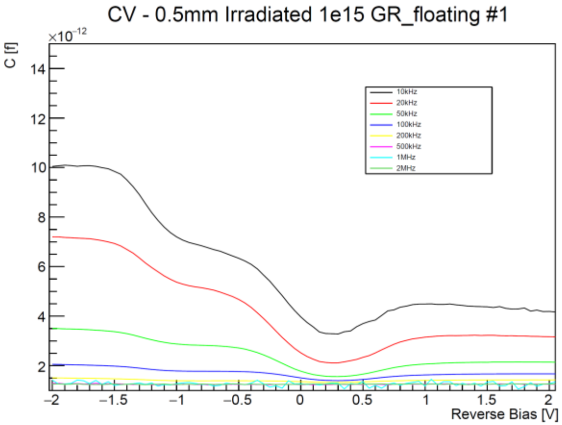
Zoom in


CV - 0.5mm Nonirradiated GR_floating #1


CV - 0.5mm Irradiated 1e12 GR_floating #1


CV - 0.5mm Irradiated 1e13 GR_floating #1


CV - 0.5mm Irradiated 1e14 GR_floating #1


CV - 0.5mm Irradiated 1e15 GR_floating #1