Update on Radiation Damage Investigation of Epitaxial P-type Silicon Using Schottky Diodes

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Introduction

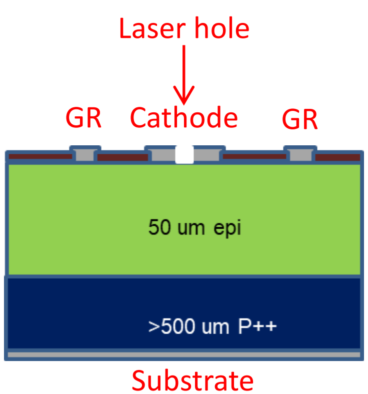
- High luminosity operating environment
  - HL-LHC, CEPC, SppC …
  - N-type silicon sensors
    - Low radiation resistance

- High radiation resistance
  - P-type silicon sensors
    - Sensors with high resistivity silicon substrate
      - ✓ Radiation damage well studied
    - Sensors with epitaxial layer
      - Advantages
        - High spatial resolution
        - High integration
        - Low material
        - High anti-irradiative property
      - ☐ Radiation damage not well studied

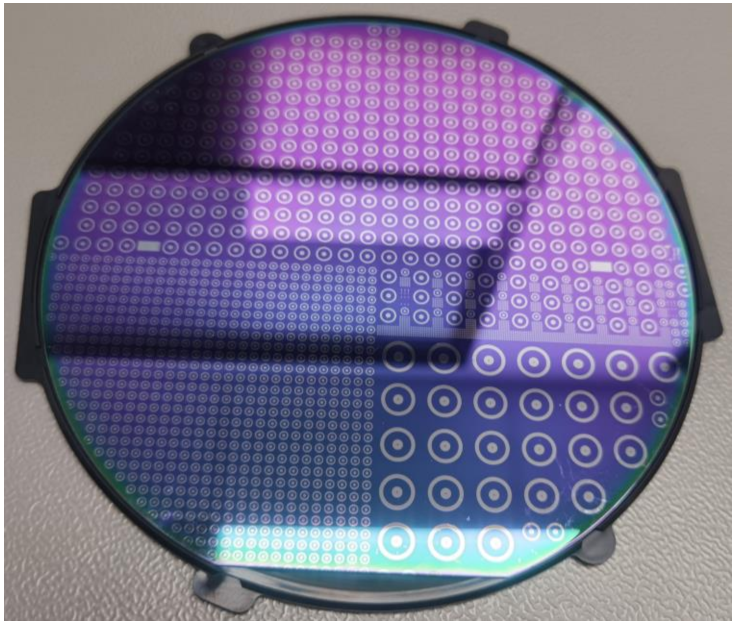
Introduction

- Epitaxial P-type silicon diodes
  - PN-junction diodes studied at Carleton University (*Christoph Klein's talk from the 40th RD50 Workshop*)
  - Schottky diodes studied at RAL and IHEP
    - Metal semiconductor contact -> Simple structure

- Schottky diodes under tests
  - Design and fabrication (*Giulio Villani's talk from the 35th and 36th RD50 Workshop*)
    - 5 type of devices proposed
    - P-type epitaxial layer
      - 10^{13} cm^{-3} doping
      - 50 μm thickness



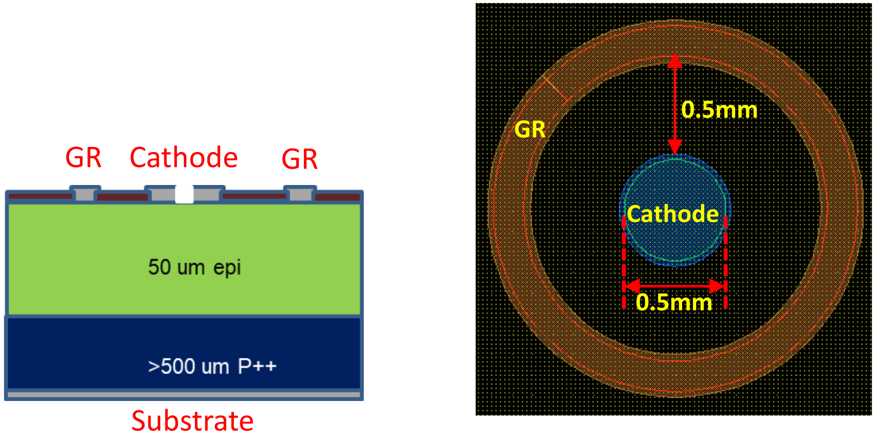
Geometry of Schottky diode


Wafer of Schottky diodes

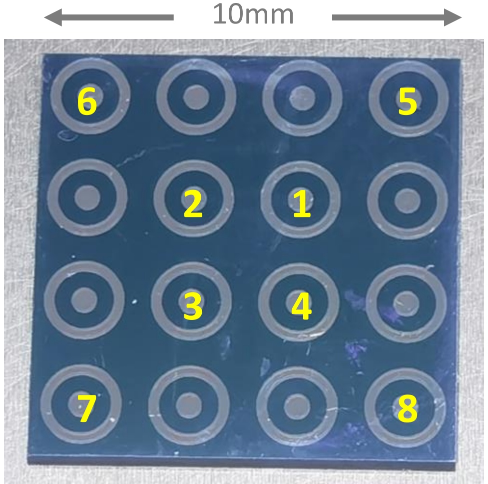
Introduction

- Schottky diodes under tests
  - P-type epitaxial layer
    - 10^{13} doping, 50 μm thickness
  - 10×10 mm diodes diced from the same wafer
    - 0.5mm diameter cathode
    - Irradiation
      - Non-irradiation
      - Neutron irradiation
        - 10^{12}, 10^{13}, 10^{14}, 10^{15}, 10^{16} 1MeV n_{eq}/cm^2
    - Thermal annealing (60℃/80min) -> all in the same annealed condition

Irradiated Schottky diodes



Geometry of Schottky diode



10×10mm diced Schottky diodes

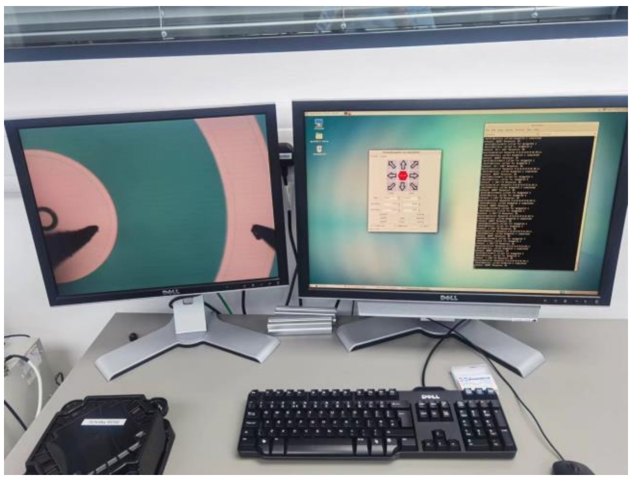
Introduction

- Sentaurus TCAD (Technology Computer Aided Design) simulation
  - Obtain the parameters of properties of epitaxial P-type Schottky before and after radiation
  - Based on these parameters, summarize a new model of bulk damage for epitaxial P-type silicon

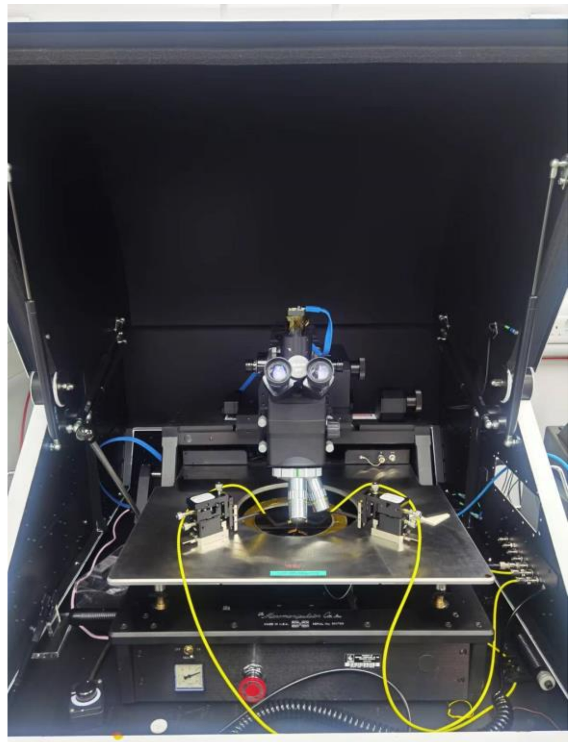
- The purpose of this study is to investigate and gain a deeper understanding of radiation bulk damage in epitaxial P-type silicon

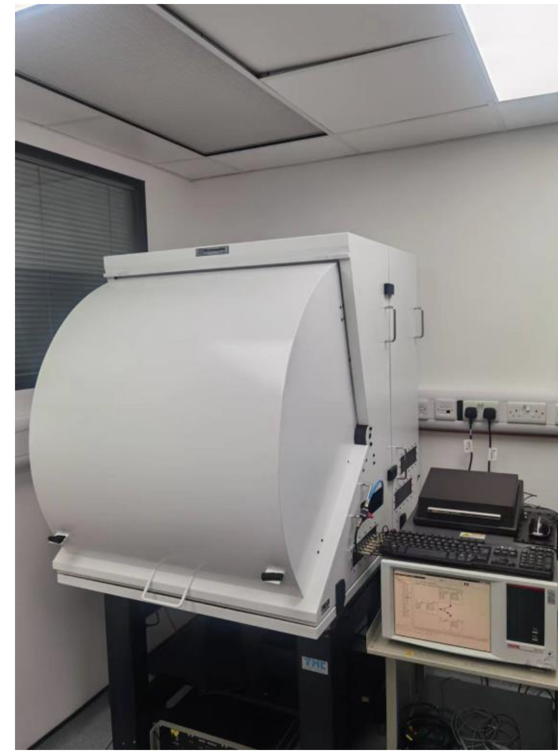
IV and CV Tests

➤ Set up of IV and CV tests



Monitors of probe station

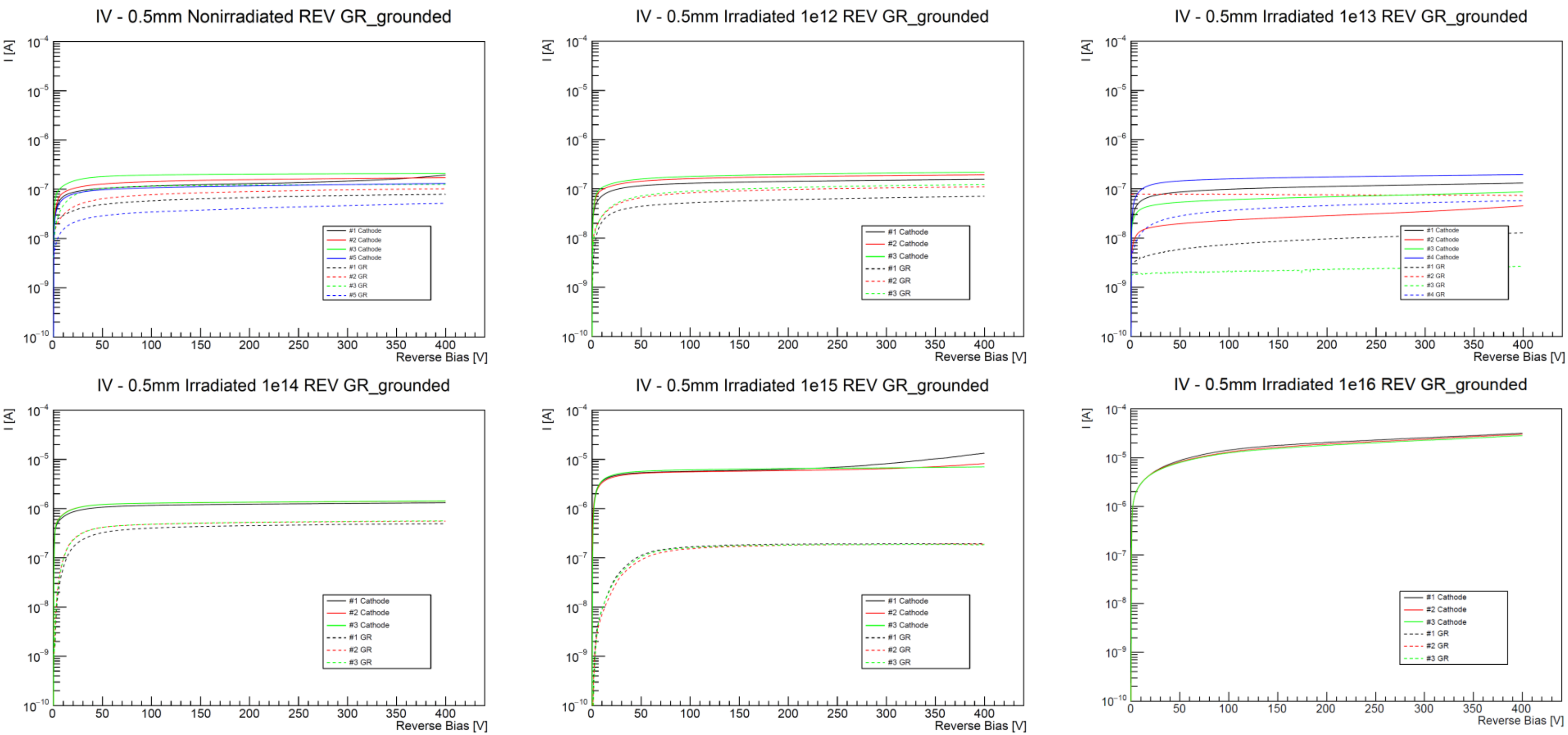




Probe station used in IV and CV tests

IV and CV Tests

- Reverse current (Reverse bias: 0 – 400V)
  - 3 different conditions of GR: floating, grounded or at the same potential as cathode



Reverse IV with GR grounded

IV and CV Tests

- Reverse current
  - $I(\Phi_{eq}) - I(\Phi_0) = \Delta I = \alpha\Phi_{eq}V$
    - $I(\Phi_0)$: reverse current before irradiation
    - $I(\Phi_{eq})$: reverse current after irradiation with fluence Φ_{eq}
    - V: depleted detector volume
    - α: current related damage rate

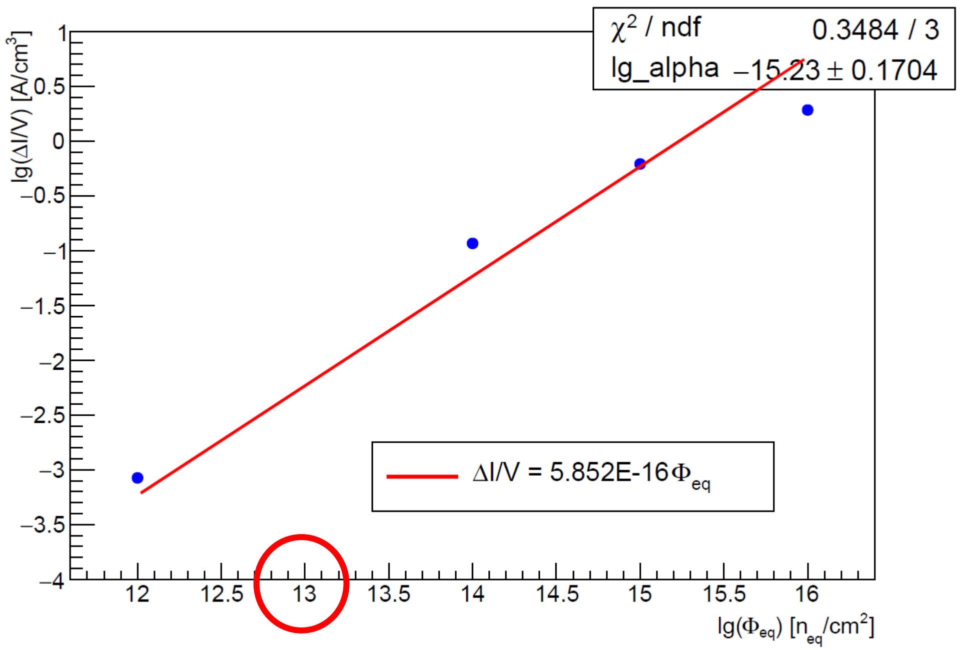
  - Sensors irradiated to very high fluences cannot be fully depleted
    - TCT measurements are required to verify it
    - $I(\Phi_{eq}) - I(\Phi_0) = \Delta I = \alpha^*\Phi_{eq}V$
      - α^*: geometric current related damage rate
      - For a fully depleted sensor α and α^* are the same

  - $I(\Phi_{eq}) - I(\Phi_0) = \Delta I = \alpha^*\Phi_{eq}V$
    - $V = \pi(\frac{D_{cathode}}{2})^2 \cdot 50\mu m$

  - $\frac{\Delta I}{V} = \alpha^*\Phi_{eq} \Rightarrow \lg\left(\frac{\Delta I}{V}\right) = \lg(\alpha^*) + \lg(\Phi_{eq})$

IV and CV Tests

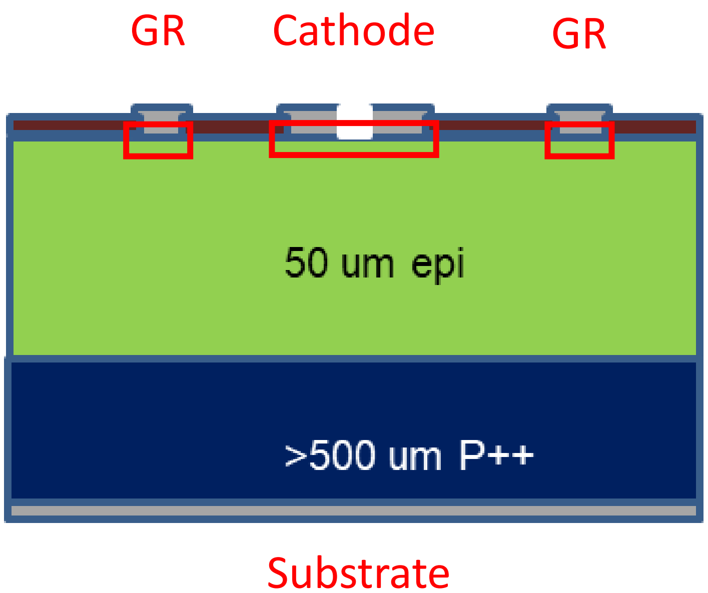
- Reverse current
  - $\frac{\Delta I}{V} = \alpha^* \Phi_{eq} \Rightarrow \lg\left(\frac{\Delta I}{V}\right) = \lg(\alpha^*) + \lg(\Phi_{eq})$
    - Reverse bias 200V with GR grounded
    - $\Delta I_{\Phi_{eq}=10^{13}} < 0$
      - Problematic diodes
      - Or other mechanisms



Geometric current related damage rate fitting

IV and CV Tests

- Reverse current
  - The breakdown voltage is much higher than expected from TCAD simulation
    - Wafers were left exposed in air after etching and prior to Al sputtering
    - The silicon surface is oxidized to form an additional silicon dioxide layer



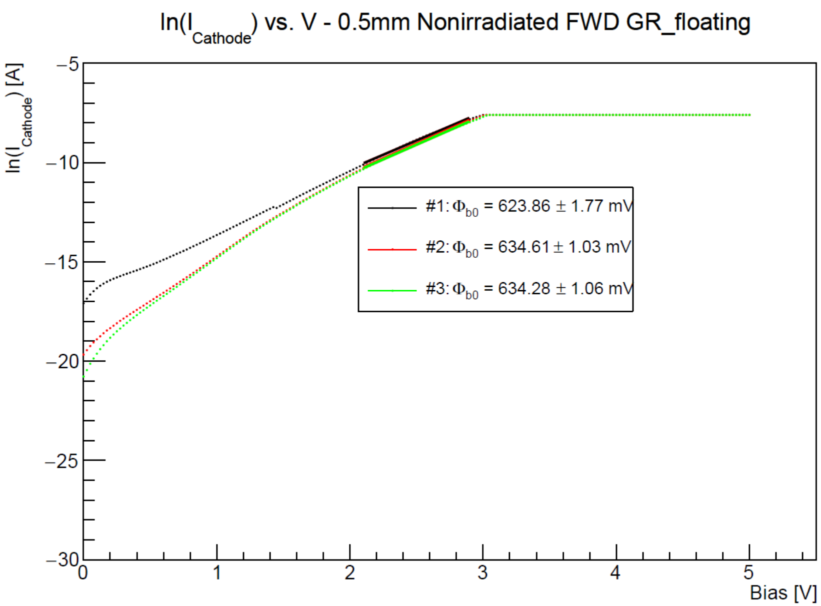
Additional silicon dioxide layer at interface

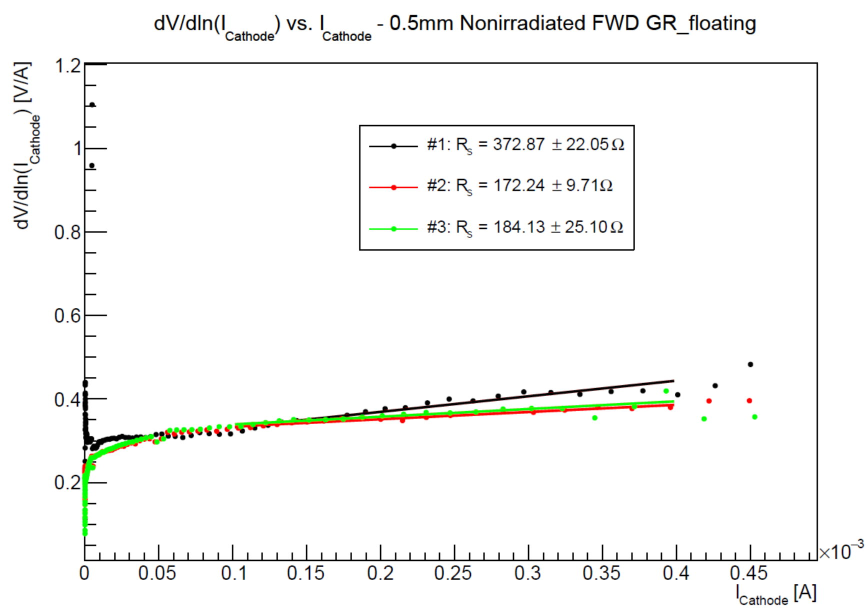
IV and CV Tests

- Forward current (Forward bias: 0 – 5V with GR floating)
  - Thermionic emission theory
    - Barrier height $\Phi_{b0}[eV]$
      - $I = SA^*T^2 \exp\left(-\frac{e}{k_BT}\Phi_{b0}\right)\exp\left(\frac{e}{nk_BT}V\right) = I_0 \exp\left(\frac{e}{nk_BT}V\right)$
        - S: Area of the device $[cm^2]$
        - A^*: Richardson's constant 32 $[Acm^{-2}K^{-2}]$
        - n: Ideality factor
      - $\Rightarrow \ln(I) = \ln(I_0) + \frac{e}{nk_BT}V$
      - $\Rightarrow \Phi_{b0} = \frac{k_BT}{e}\ln\left(\frac{SA^*T^2}{I_{V=0}}\right)$
  - Taking into account the resistance R_s of the substrate
    - $I = SA^*T^2 \exp\left(-\frac{e}{kT}\Phi_{b0}\right)\exp\left(\frac{e}{nkT}(V - R_sI)\right) = I_0 \exp\left(\frac{e}{nkT}(V - R_sI)\right)$
    - $\Rightarrow \frac{dV}{dln(I)} = \frac{nkT}{e} + R_sI$
      - $R_s \sim \rho\frac{L}{S} = \frac{1}{eN_A\mu_p}\frac{L}{S}$
    - $\Rightarrow n(V)$

IV and CV Tests

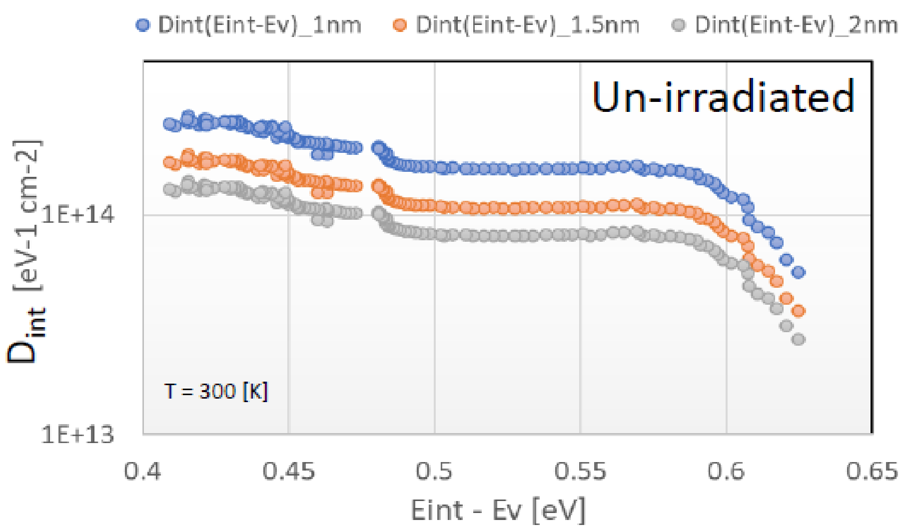
- Forward current
  - Φ_{b0} and $n(V)$ extracted
  - The calculation of resistivity still needs further investigation





IV and CV Tests

- Forward current
  - Density of interface states extracted from ideality factor (Card H C, Rhoderick E H. Studies of tunnel MOS diodes I. Interface effects in silicon Schottky diodes[J]. Journal of Physics D: Applied Physics, 1971, 4(10): 1589.)
  - Implementing the HPT (Hamburg Penta Trap Model) into TCAD



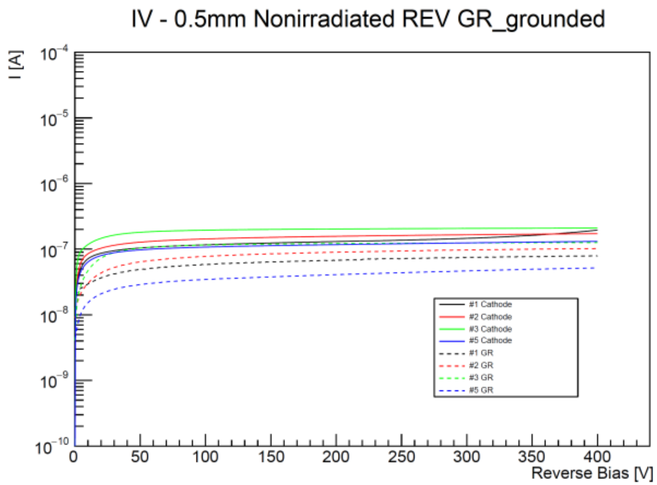
Density of interface states

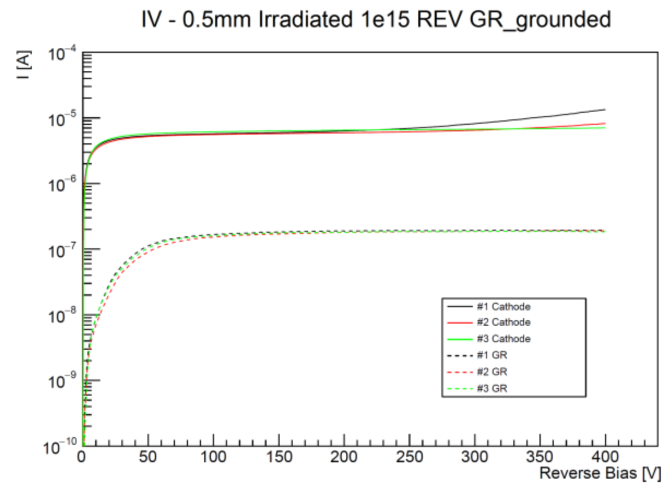
Defect	Type	Energy	g_{int} [cm^{-1}]	σ_e [cm^2]	σ_h [cm^2]
E30K	Donor	E_C-0.1 eV	0.0497	2.300E-14	2.920E-16
V_3	Acceptor	E_C-0.458 eV	0.6447	2.551E-14	1.511E-13
I_p	Acceptor	E_C-0.545 eV	0.4335	4.478E-15	6.709E-15
H220	Donor	E_V+0.48 eV	0.5978	4.166E-15	1.965E-16
C_iO_i	Donor	E_V+0.36 eV	0.3780	3.230E-17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

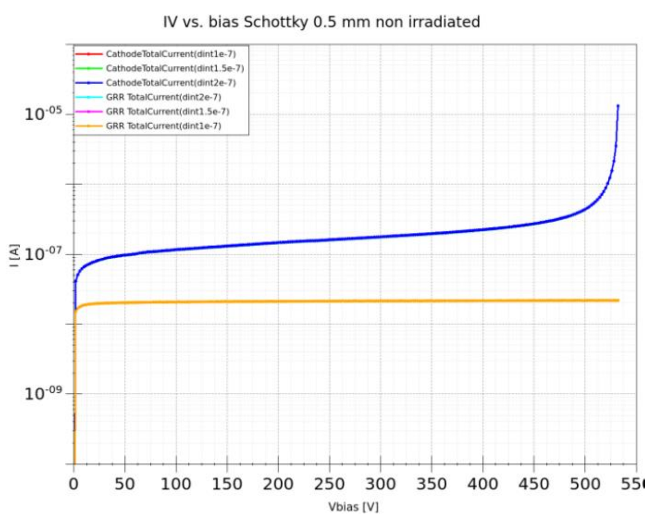
HPT Model

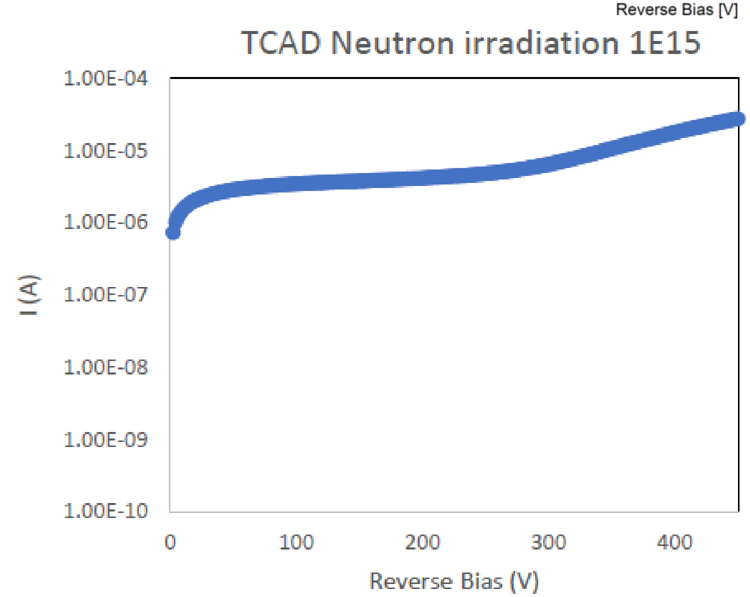
IV and CV Tests

➢ Comparison between IV tests and TCAD simulation



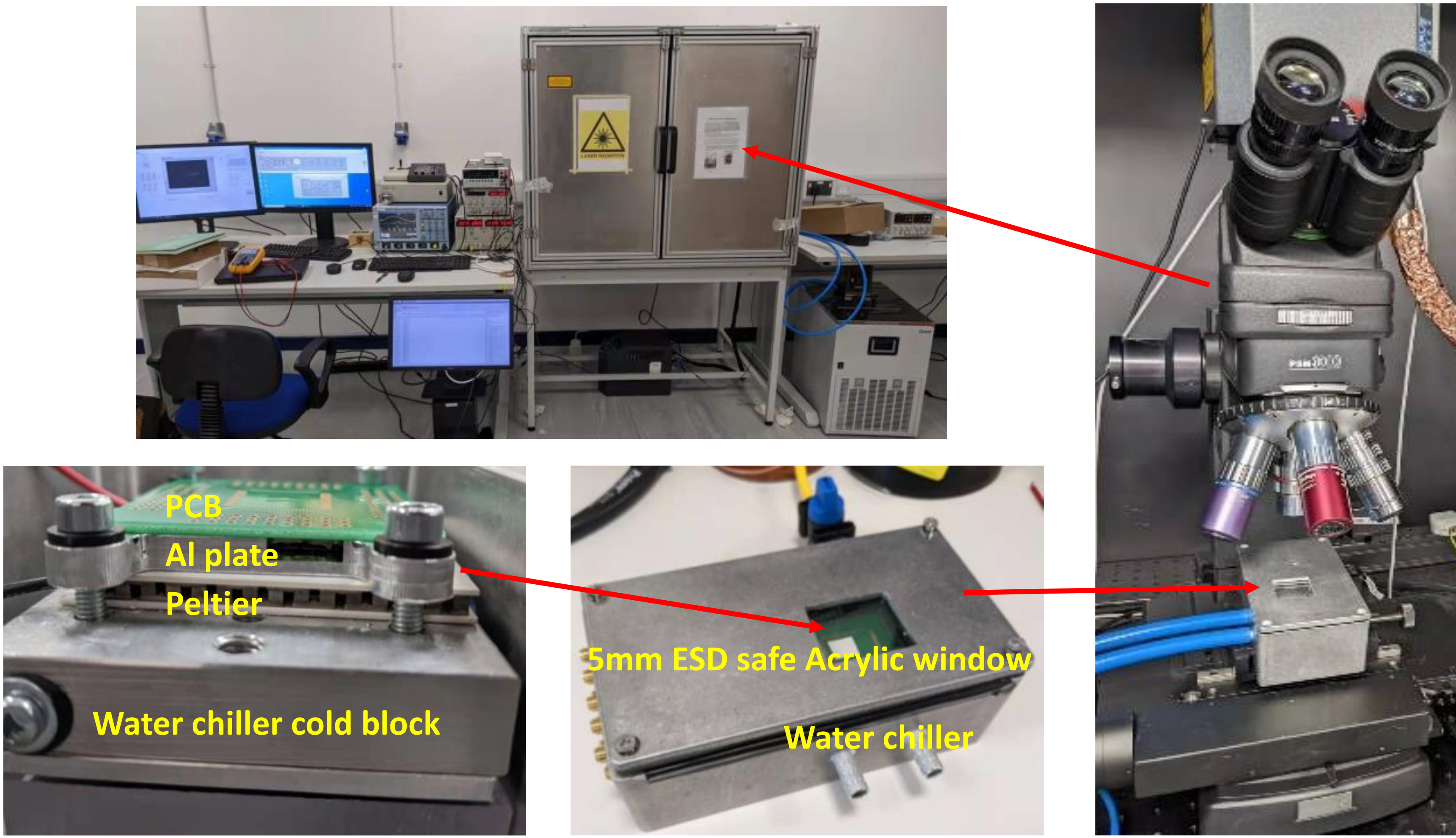






Charge Collection Tests

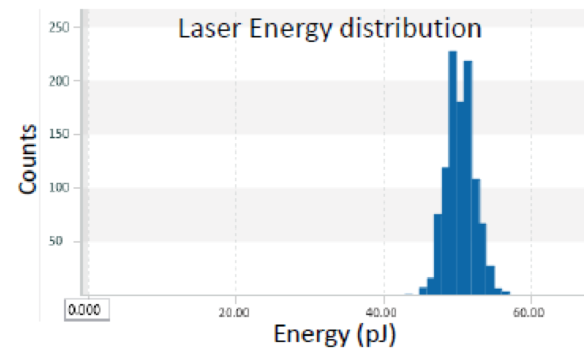
- Set up of charge collection tests



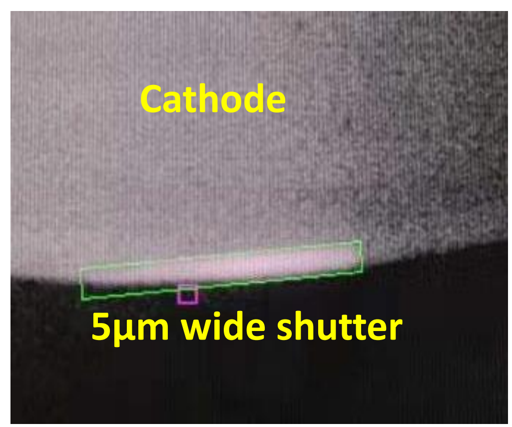
Laser system and cold & dry box

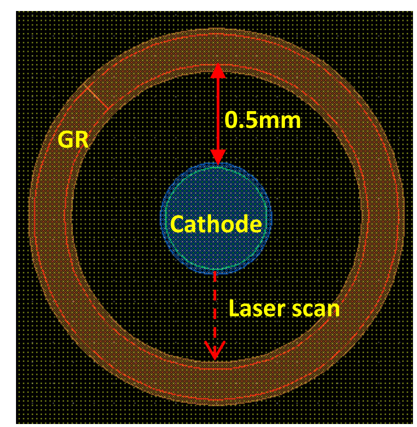
Charge Collection Tests

- Set up of charge collection tests
  - Laser (wavelength 1064nm) calibrated to 50pJ with Std = 1.9pJ
  - Signal is fed into a charge amplifier and readout on oscilloscope
    - The trigger is given by the laser
    - ~100ns delay of signal from trigger
    - ~70ns rise time
  - Laser scan step 5μm



Signal in oscilloscope

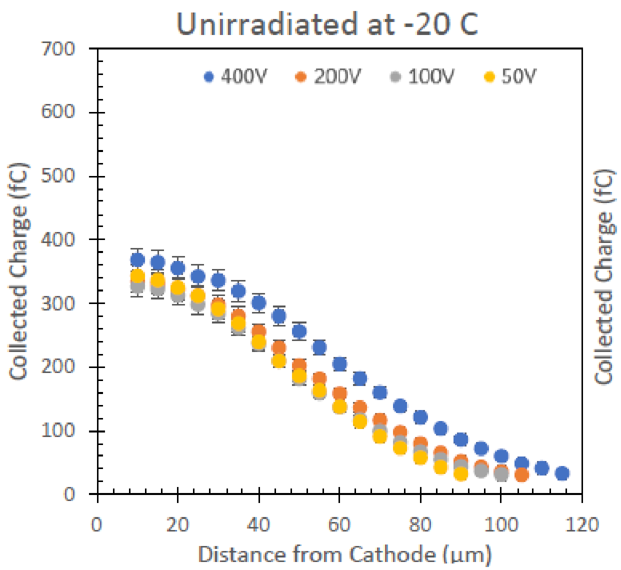


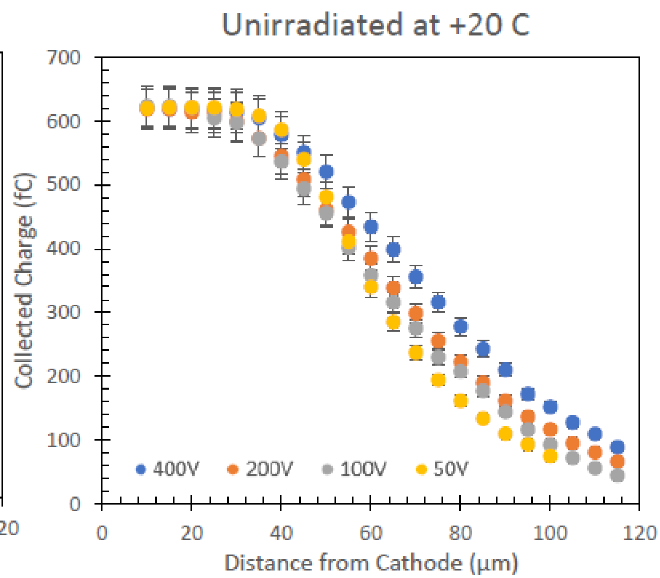


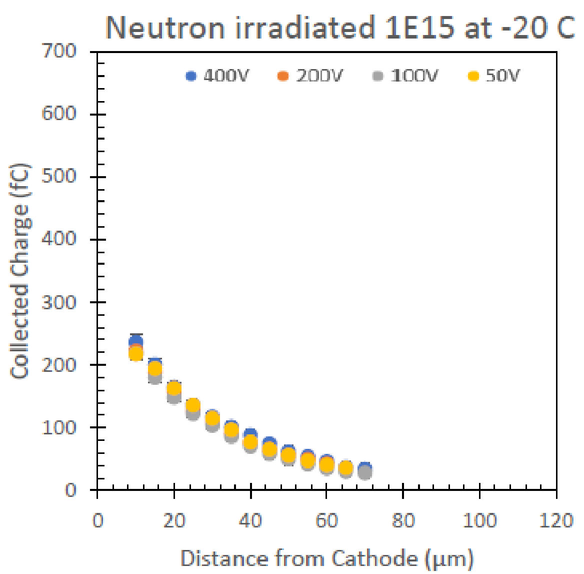
Laser scan

Charge Collection Tests

- Results of charge collection tests
  - Diodes unirradiated and diodes neutron irradiated to 10^{15} 1MeV n_{eq}/cm^2
    - Leakage current too high to make measurement at room temperature for irradiated diodes
    - Lower charge collection and shrunk depletion region of irradiated diodes

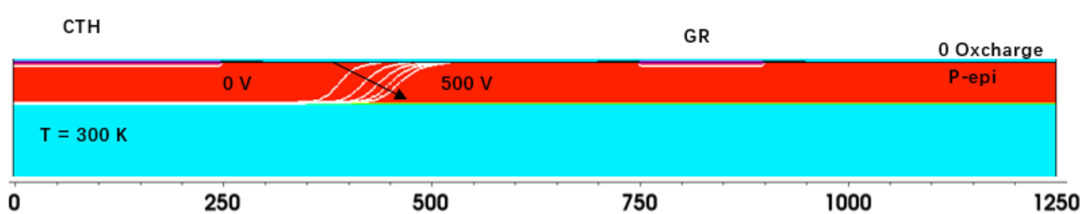




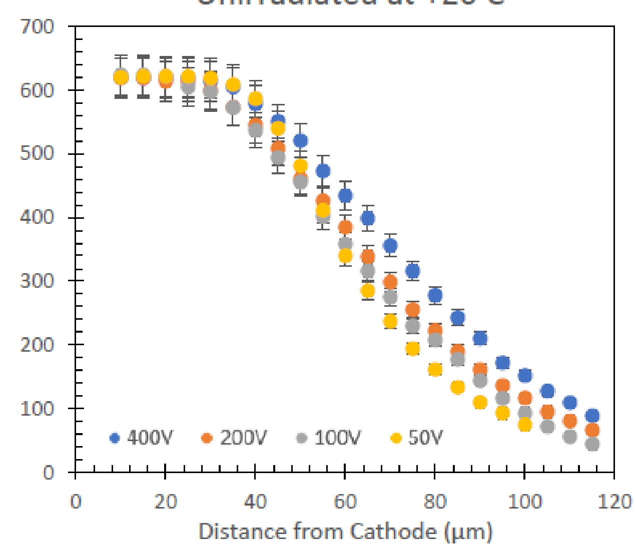


Charge Collection Tests

- Results of charge collection tests
  - Diodes unirradiated and diodes neutron irradiated to 10^{15} 1MeV n_{eq}/cm^2
    - Leakage current too high to make measurement at room temperature for irradiated diodes
    - Lower charge collection and shrunk depletion region of irradiated diodes
    - Depletion region is within around 100µm of the cathode as the charge collection decays



TCAD simulation



Summary and Next

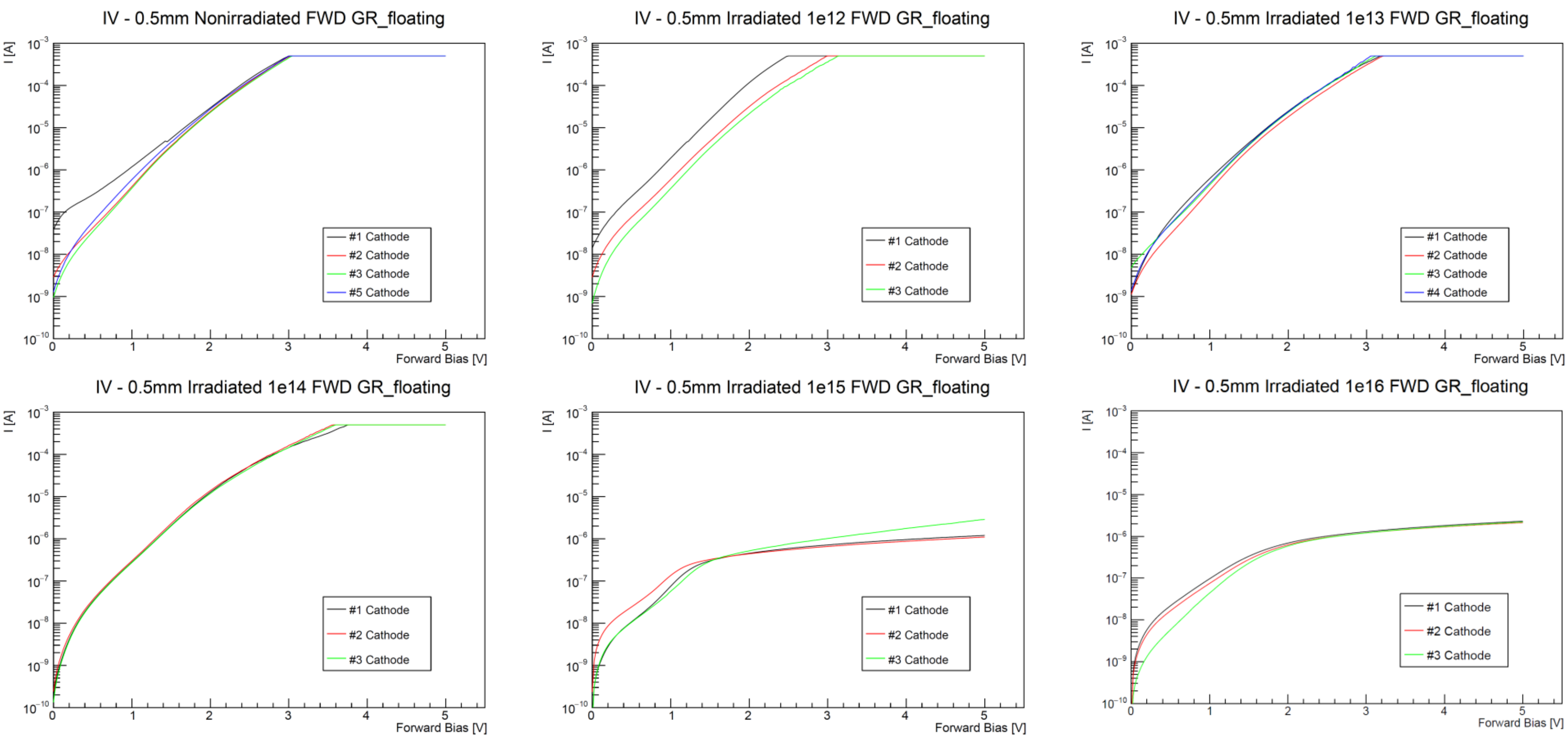
- Summary
  - ✓ Epitaxial P-type Schottky diodes with interface SiO_2 layer have breakdown voltage higher than 400V
  - ✓ Tests were carried out on the diodes nonirradiated and irradiated up to 10^{16} 1MeV n_{eq}/cm^2
  - ✓ Parameters are extracted from the tests and input into the TCAD simulation. The simulation results are consistent with the tests to a certain extent

- Next
  - ☐ Validation and optimization of analysis methods
  - ☐ More diced diodes will be irradiated by neutron and proton and then tested
  - ☐ Continue TCAD parameter optimization to more agree with tests for irradiated and nonirradiated diodes

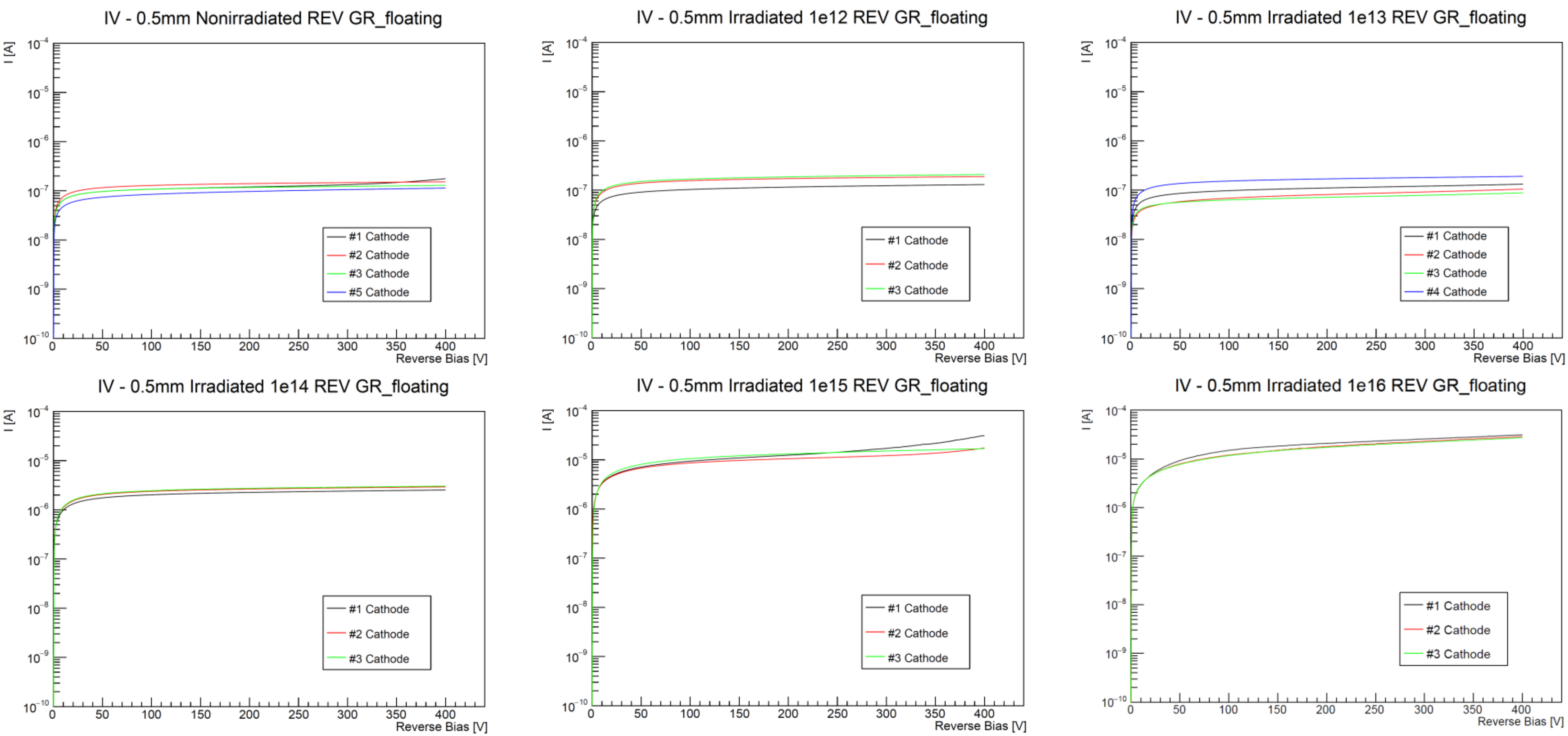
Thanks!

BACKUP

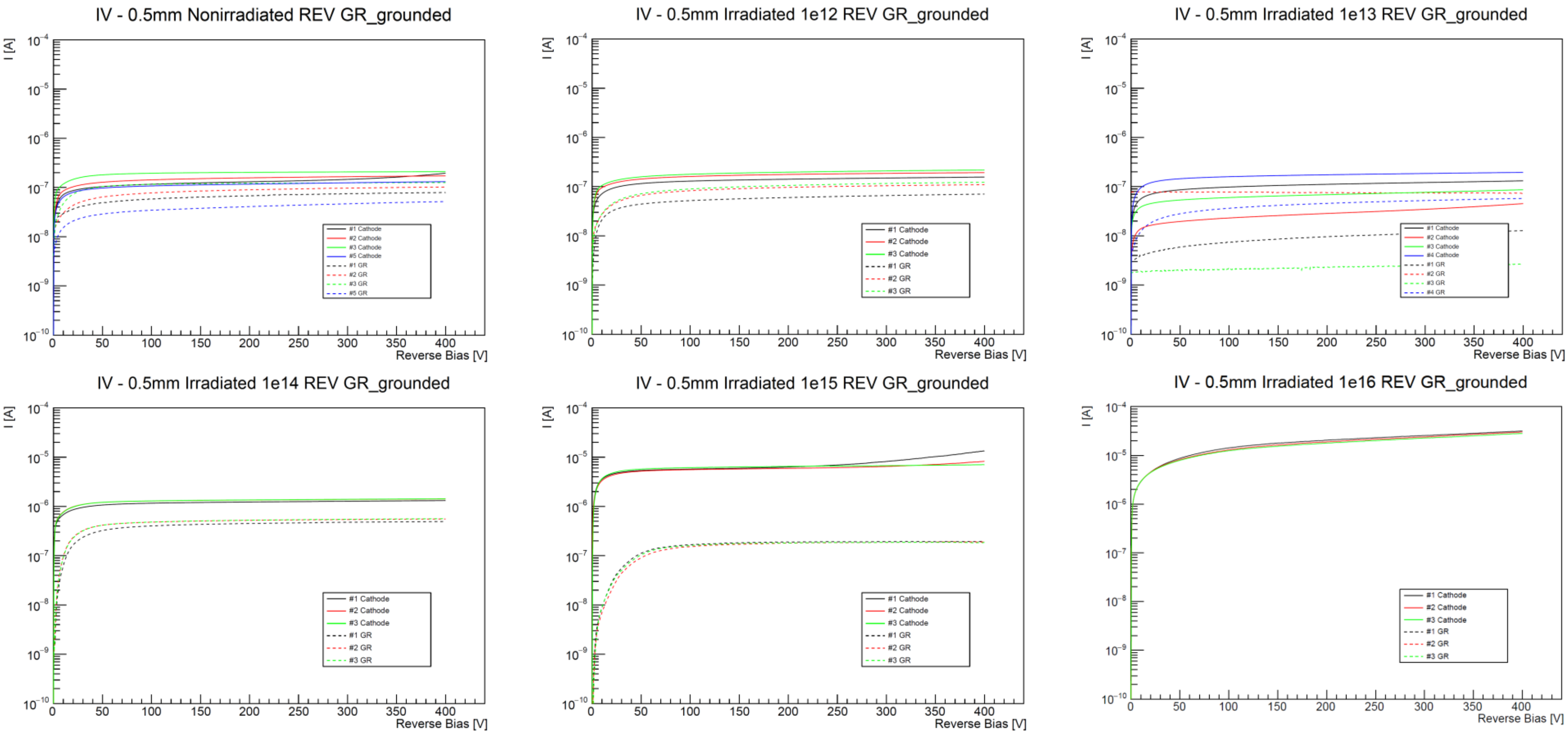
FWD IV – GR Floating



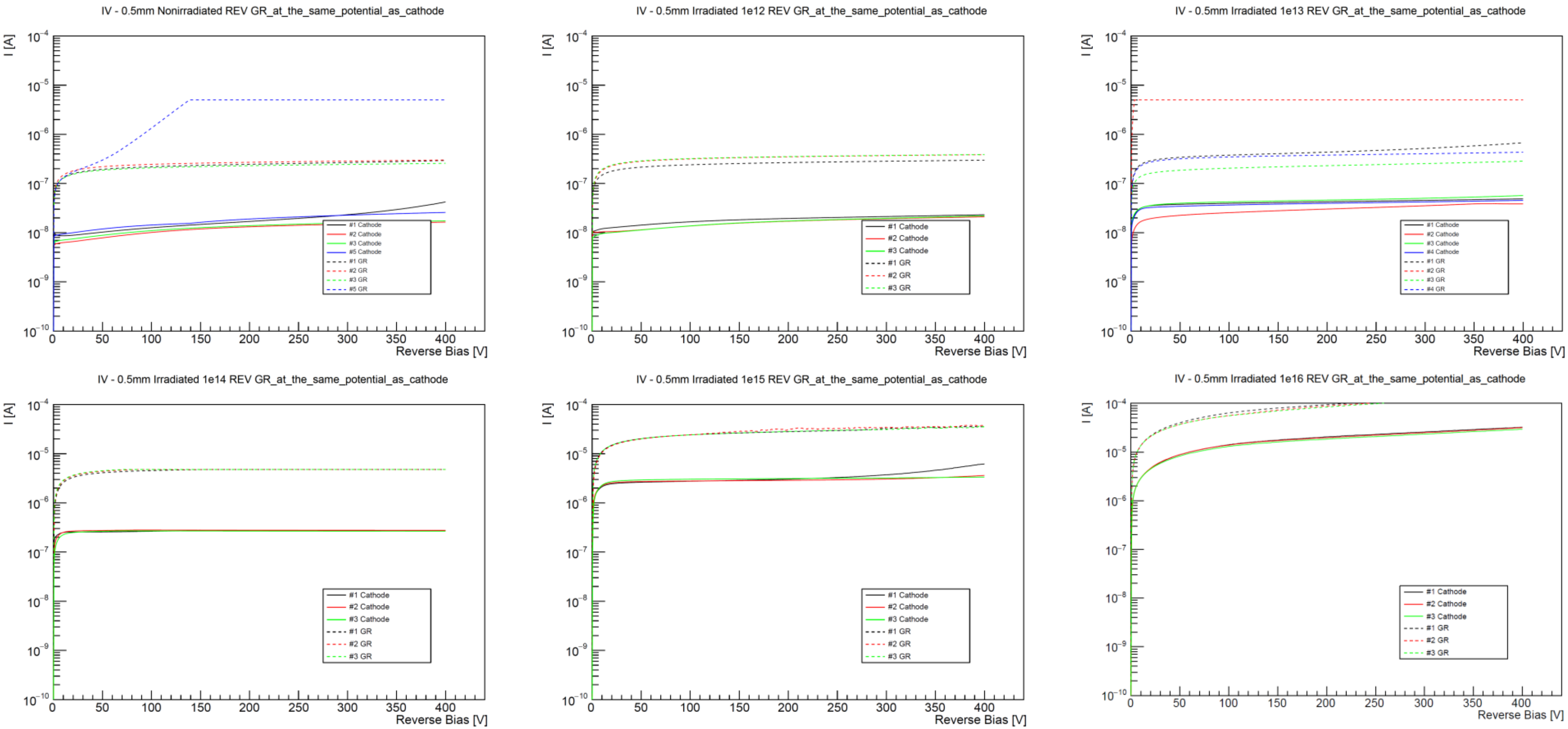
REV IV – GR Floating



REV IV – GR Grounded



REV IV – GR at the Same Potential as Cathode



CV – GR Floating

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