Progress Towards Study of Charge Collection and Precision Timing of Small Pitch 3D Sensors

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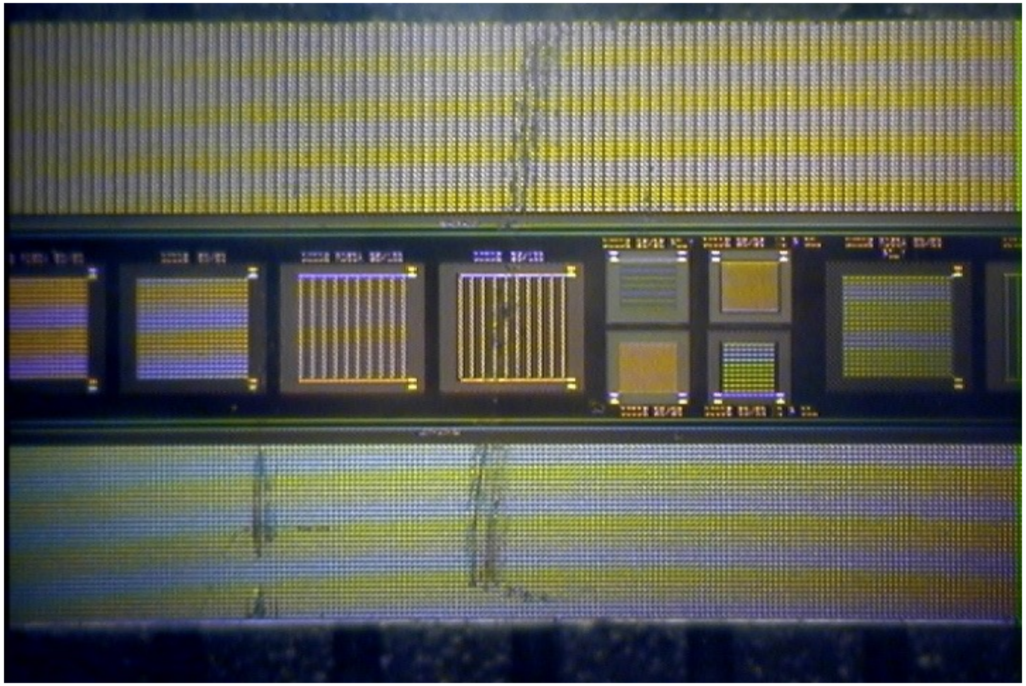
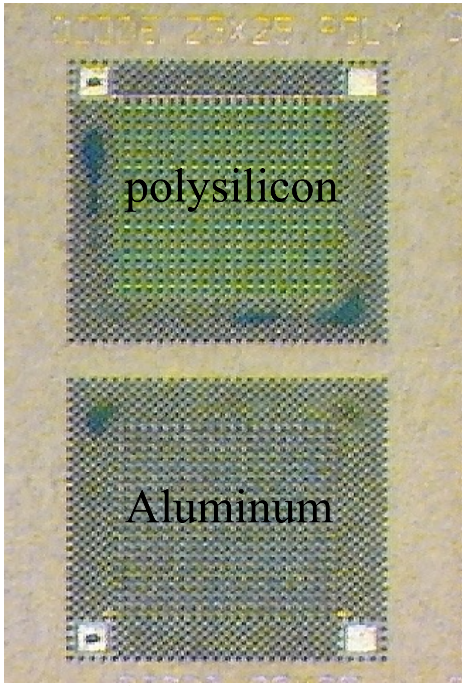
Small Pitch 3D Sensors

- 3D sensors with 50 x 250 μm^2 geometry are currently in use as radiation-hard tracking detectors in the Insertable B Layer at the ATLAS experiment
- In preparation for the High Luminosity LHC and corresponding detector upgrades, smaller pitch 3D sensors, especially 25x100 μm^2 and 50x50 μm^2 are being extensively studied
- Even smaller pitch geometries have promise for higher charge collection efficiencies at extreme fluences
- 25x25 μm^2 3D sensors have been developed at University of Trento & Fondazione Bruno Kessler (FBK)
  - These sensors may achieve impact ionization charge multiplication at low voltages, below breakdown, leading to restored efficiency after high integrated fluence

Sensor Design

- Test structures were fabricated at FBK, each having two 25x25 μm^2 sensors with 150 μm active thickness, 1 with polysilicon and 1 with aluminum connections
  - These sensors are the primary focus of the current study
- Polysilicon is partially transparent to light, allowing for laser studies from the front side

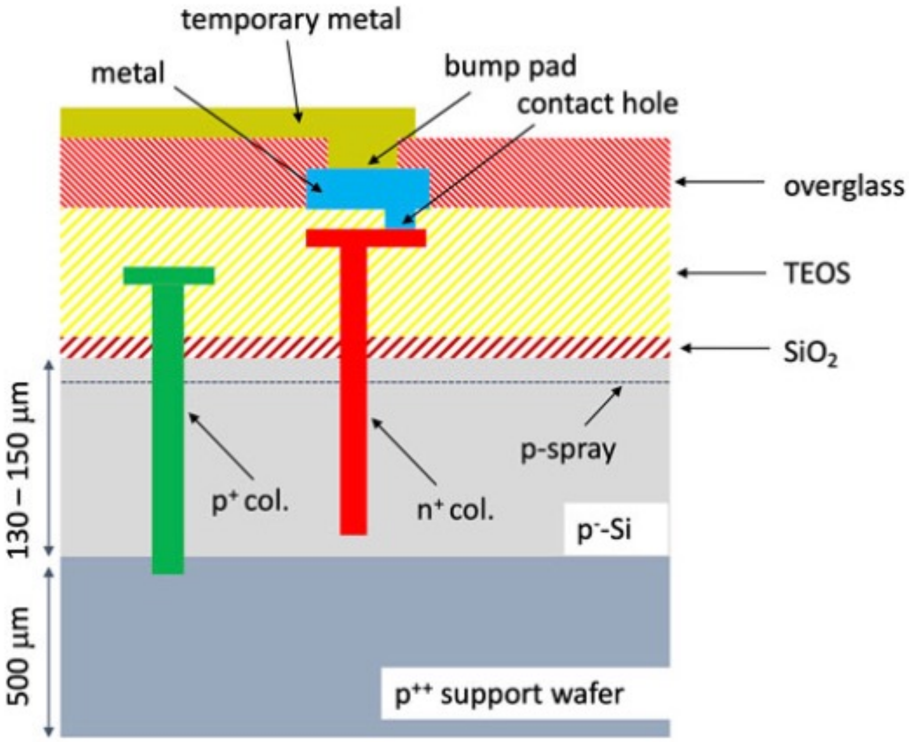




Sensor Fabrication

- For larger inter-electrode distances, mask aligner lithography technology worked well
- Yield was lower for smaller inter-electrode distances
- FBK has begun using step-and-repeat (stepper) lithography, which has shown improved yields
- There was also need to make thinner sensors, in order to reduce radiative energy loss
- Thin sensors must be bonded to a support wafer due to mechanical fragility
- This makes it necessary to be able to fabricate the sensor entirely from 1 side
  - Stepper lithography can accomplish this with high yields

- P-type substrate is bonded to a support wafer
- P-spray layer provides improved surface isolation between n-type electrodes
- P-type columns are etched first, using Deep Reactive Ion Etching, going into the support wafer, so the sensor can be biased from the backside
- N-type columns are etched next, with a gap between them and the support wafer, to avoid shorting
- tetra-ethyl-ortho-silicate (TEOS) is used to protect the columns
- Contact holes are etched in the TEOS layer in order to make contact with the n-type columns
- Sensors are designed with 150 µm active thickness, but diffusion from the support wafer may make this smaller



Boscardin M, Ferrari S, Ficorella F, Lai A, Mendicino R, Meschini M, Ronchin S, Samy MAA and Dalla Betta G-F (2021) Advances in 3D Sensor Technology by Using Stepper Lithography. Front. Phys. 8:625275. doi: 10.3389/fphy.2020.625275

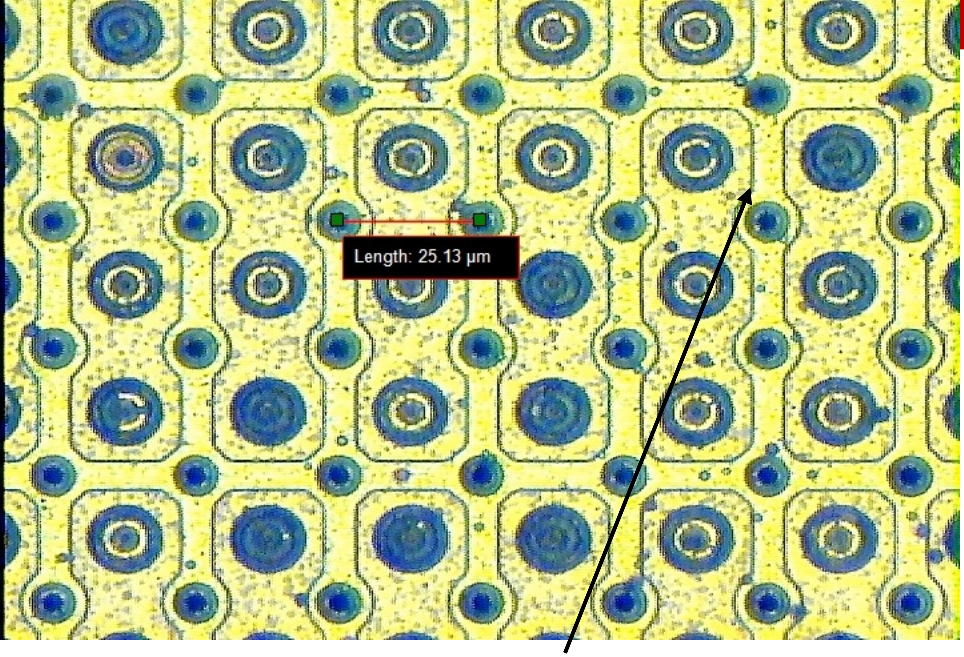
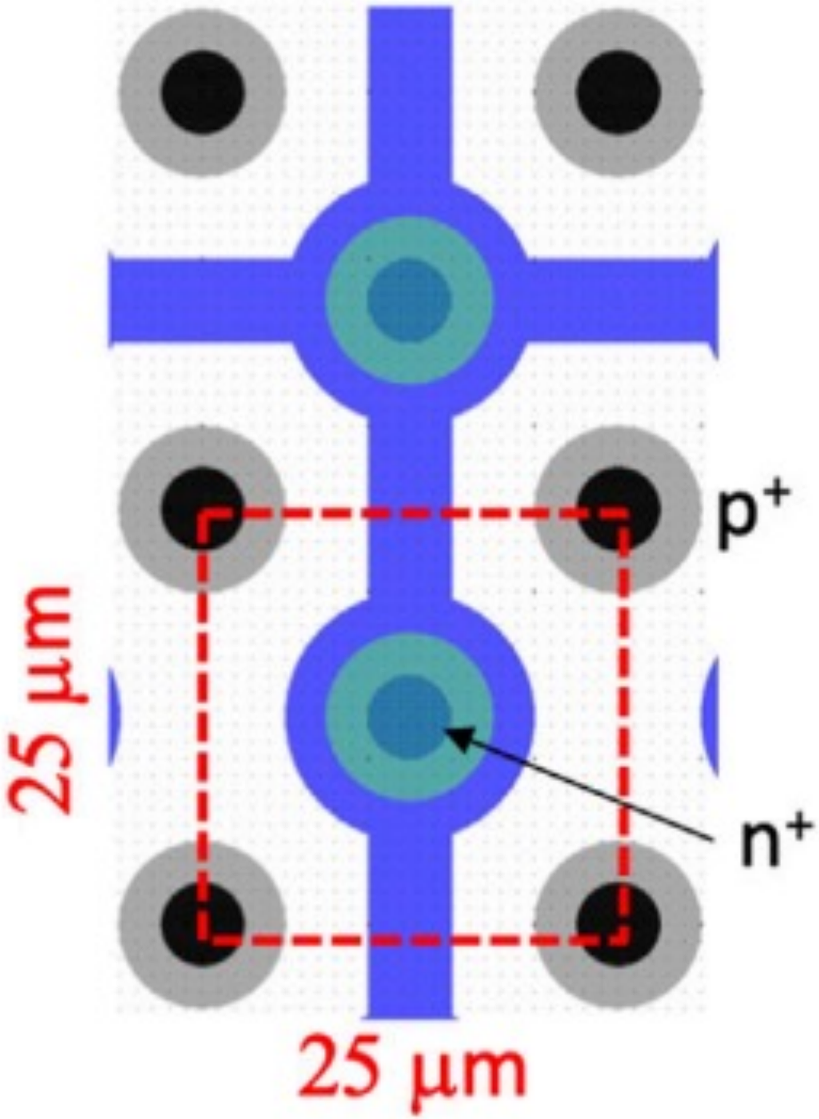


Image of a 25x25 µm^2 test structure with poly connections

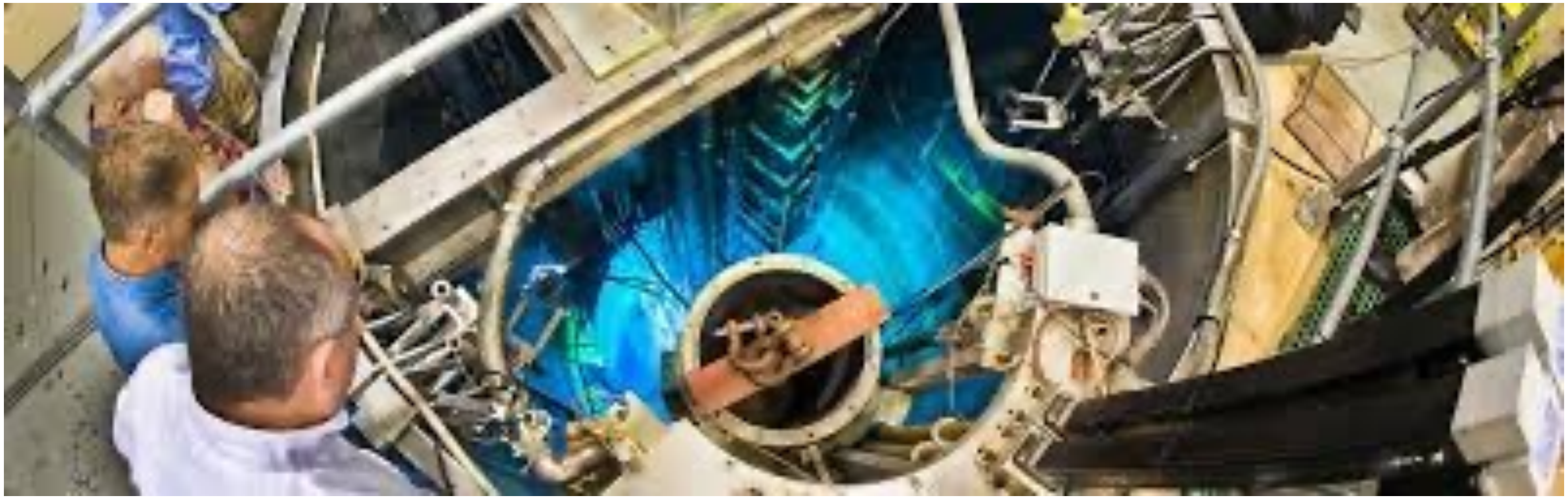
Diagram of electrode layout



Dalla Betta G-F and Povoli M (2022) Progress in 3D Silicon Radiation Detectors. Front. Phys. 10:927690. doi: 10.3389/fphy.2022.927690

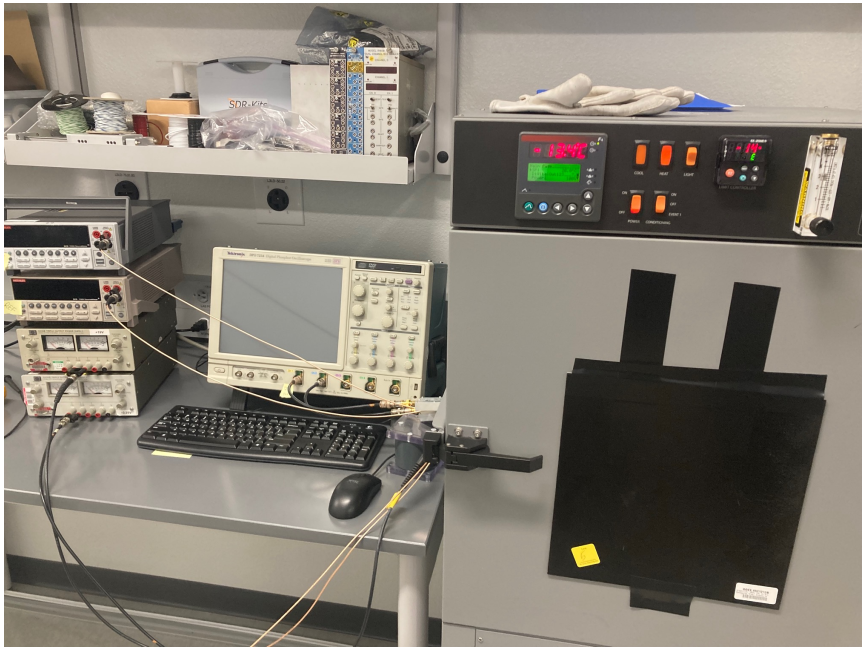
Irradiations

- 6 test structures were irradiated at the Annular Core Research Reactor (ACRR), a neutron source at Sandia National Lab, filtered to peak at 1 MeV
  - 3 irradiated to 1E16 neq/cm^2 , 3 to 2E16 neq/cm^2
  - Measured fluences: $(9.13\pm2.3)\times10^{15}$ neq/cm^2, (1.85 ± 0.5))$\times10^{16}$ neq/cm^2
  - Temperature kept below 100 ℃
- 12 were irradiated at the Irradiation Test Area (ITA), a 400 MeV proton beam at Fermilab
- 5 test structures were recently irradiated at the Los Alamos Neutron Science Center (LANSCE)
- All have been maintained at -25 ℃

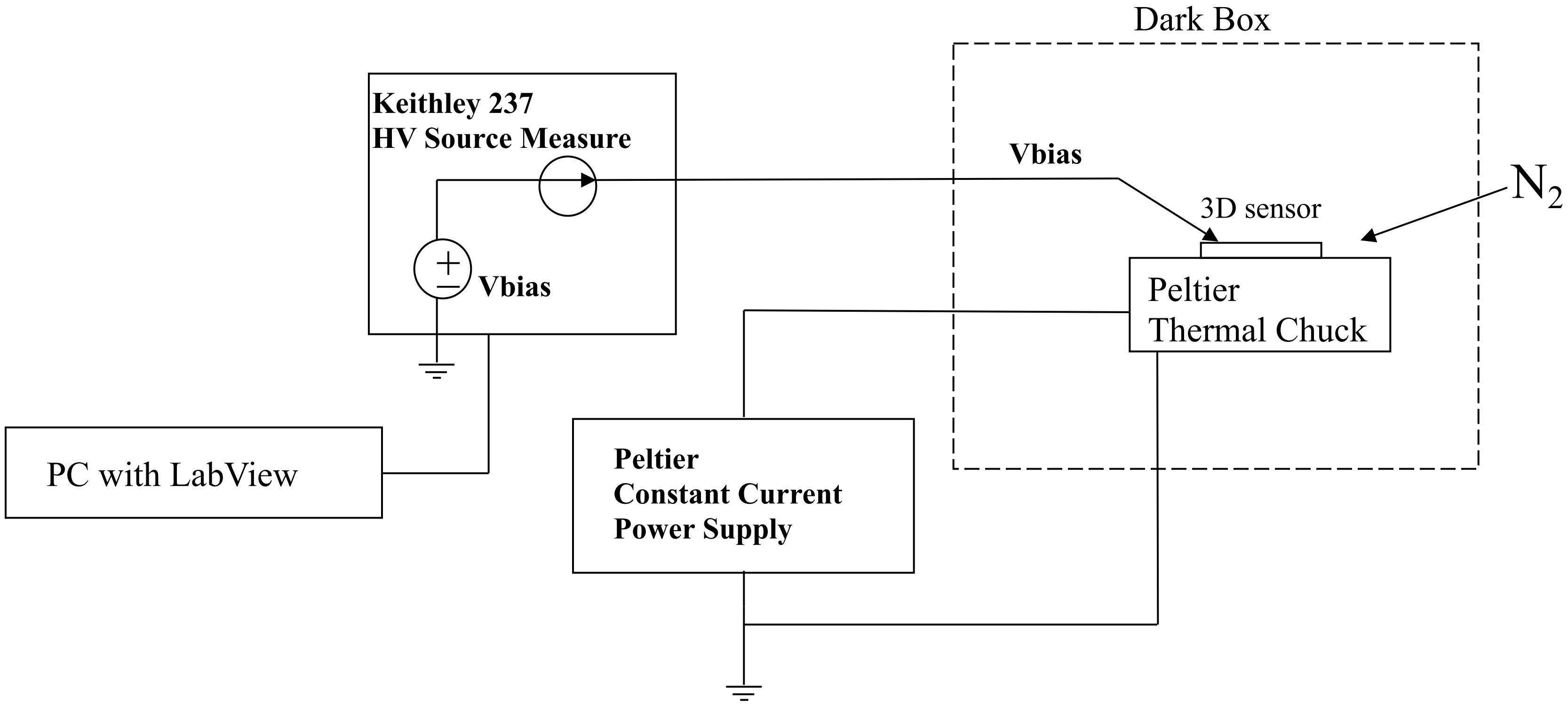


Characterization Measurements

- Leakage current vs. bias voltage & capacitance vs. bias voltage measurements were made for these sensors before and after irradiation
- A test stand for making charge collection measurements with a ^{90}Sr source is in development

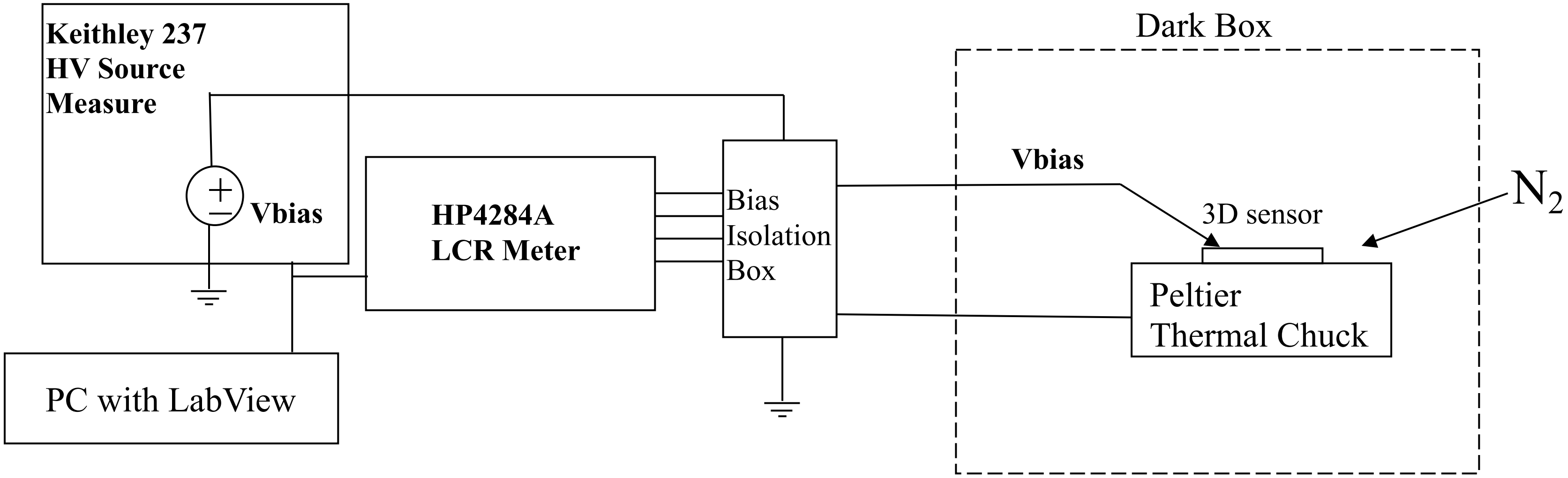


IV Measurement Block Diagram



- Set thermal chuck temperature to -25 °C w/ Peltier
- N_2 on sample to avoid condensation
- Apply reverse bias voltage with the K237 V-source
- Measure leakage current with the K237

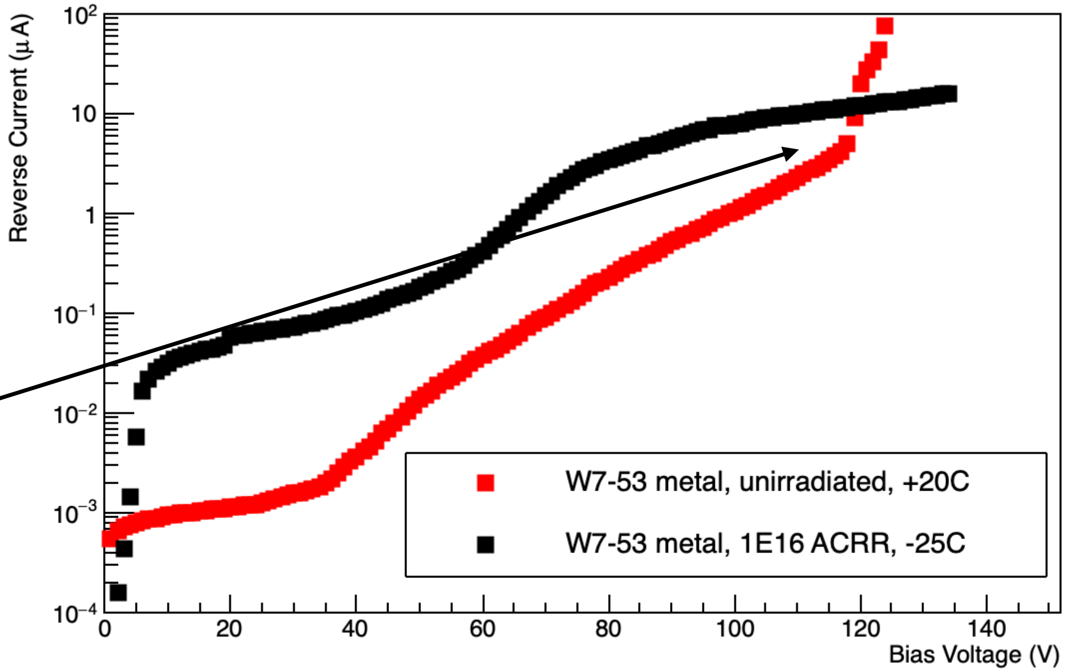
CV Measurement Block Diagram

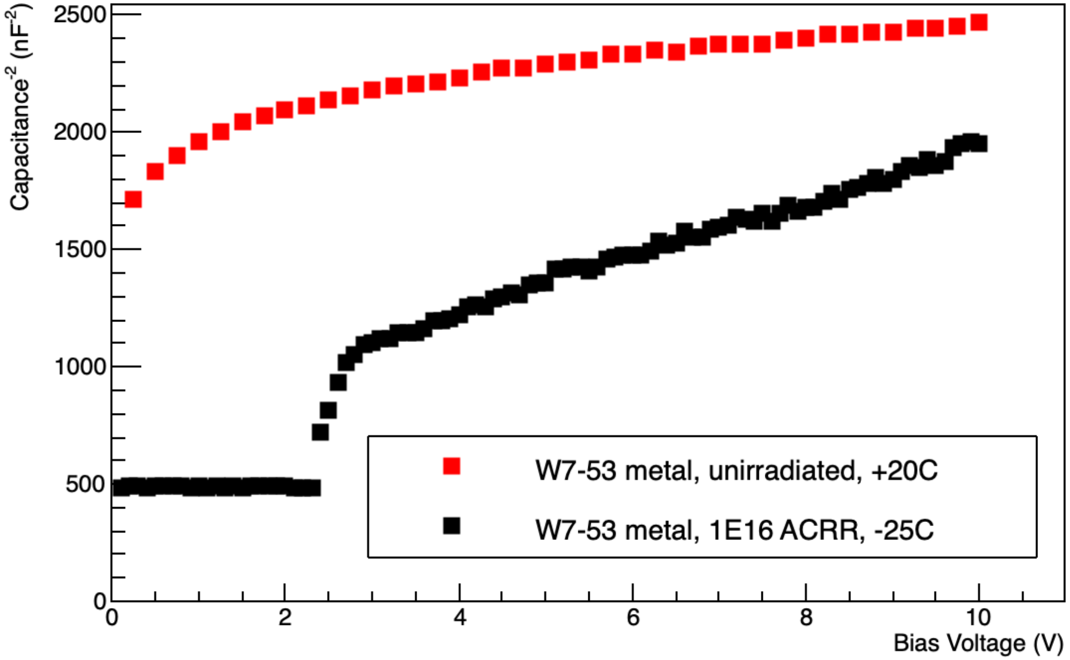


- Set thermal chuck temperature to -25 ℃
- N_2 on sample to avoid condensation
- Perform open correction to zero out cable capacitance
- Apply reverse bias voltage with the K237 V-source
- Measure sensor capacitance with the LCR meter at 1 kHz, 3 kHz, 10 kHz, 100 kHz, 1 MHz

IV/CV Plots

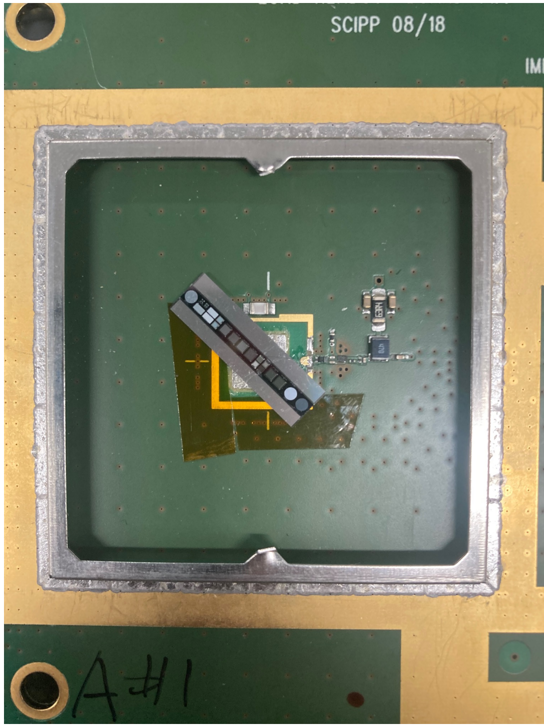
- Sample IV/CV plots for a sensor irradiated to 1E16 neq/cm^2 at ACRR
- Breakdown voltage increased from 118 V to 134 V
- Leakage current increases significantly between depletion and breakdown
- Breakdown is much faster for irradiated sensor – cannot collect any data above breakdown due to large currents
- Depletion voltage increases for irradiated sensor as well

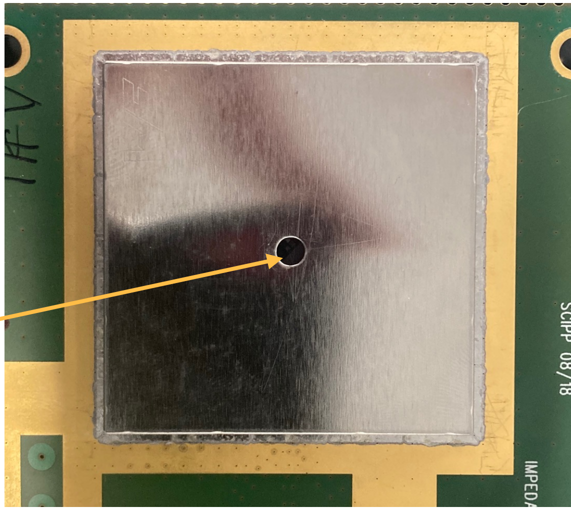




Charge Collection Setup

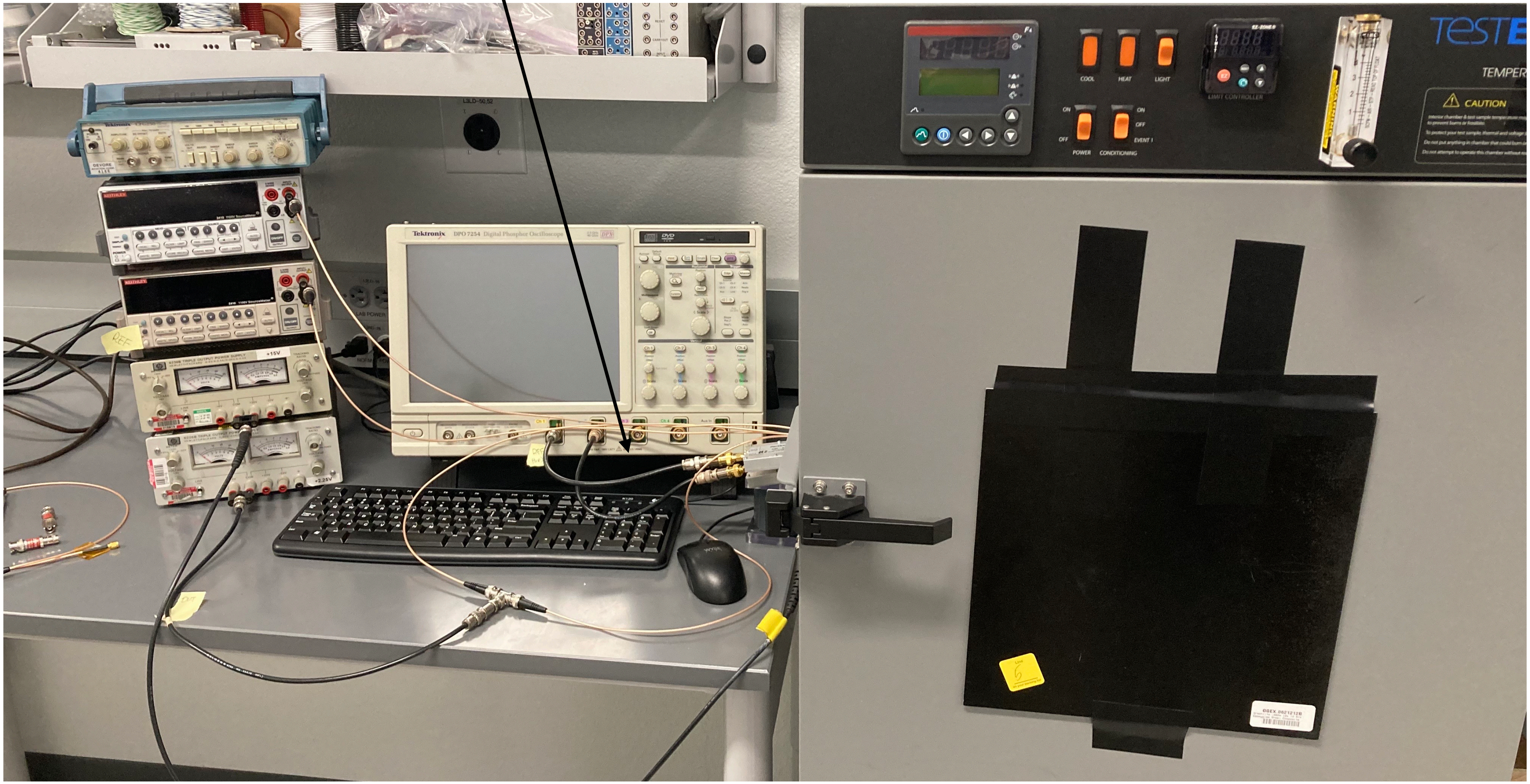
- Sensors are mounted onto readout boards developed by UCSC, wire bonded to a gold pad
- These boards have single channel readout 470 Ω transimpedance
- Covered with metal shield, for improved isolation
  - 5 mm diameter hole is necessary to admit MIP's, while providing maximal shielding





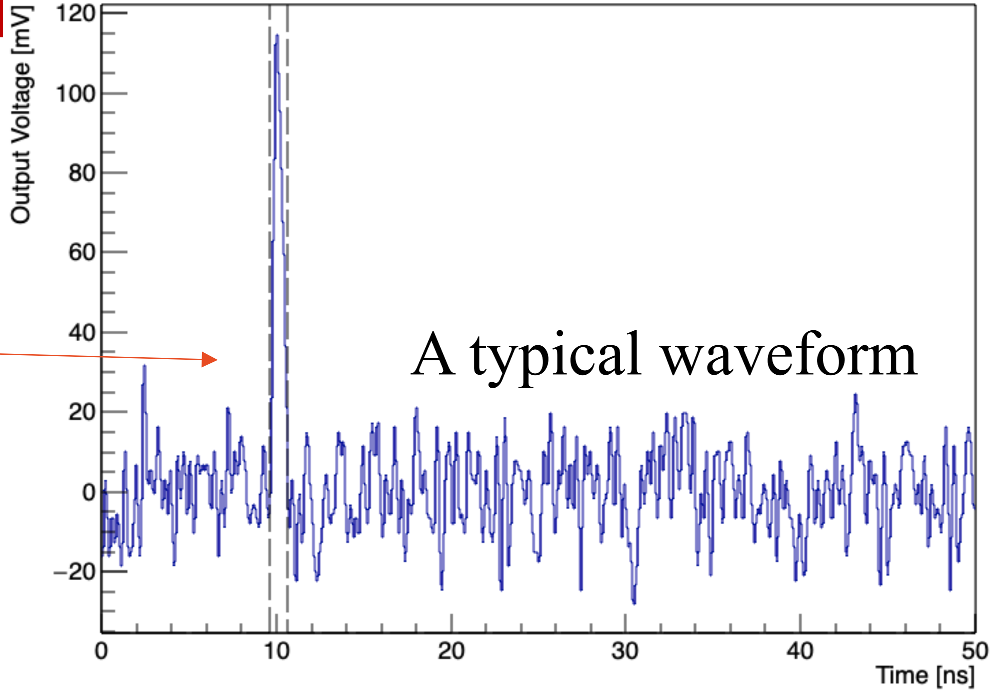
- A second UCSC board with an LGAD sensor is used for double coincidence
- A ^{90}Sr source provides MIP electrons
- Particulars AM-02B 2nd Stage Amp gives 35 dB gain
- Signal is read out by Tektronix 2.5 GHz, 40 GS/s oscilloscope
  - Signals are ~1-2 ns in width
- LabVIEW program collects signal each time the oscilloscope triggers

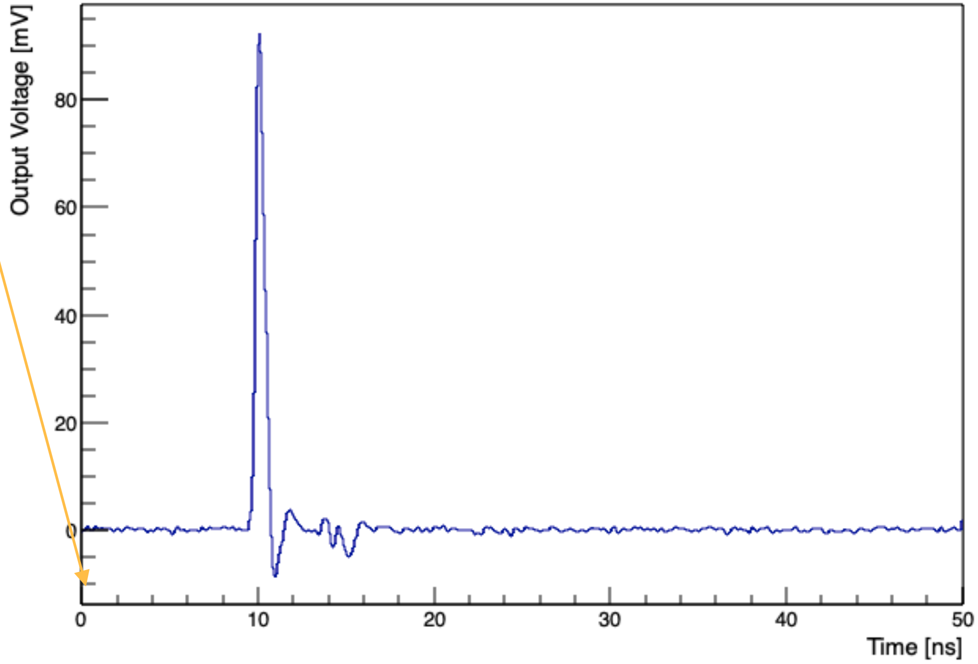
- Sensors & readout boards are operated inside thermal chamber, which is set to -30 °C
- Chamber is flooded with N_2 to avoid condensation
- Short cable length is important to preserve amplitude of high frequency signals



Data Analysis

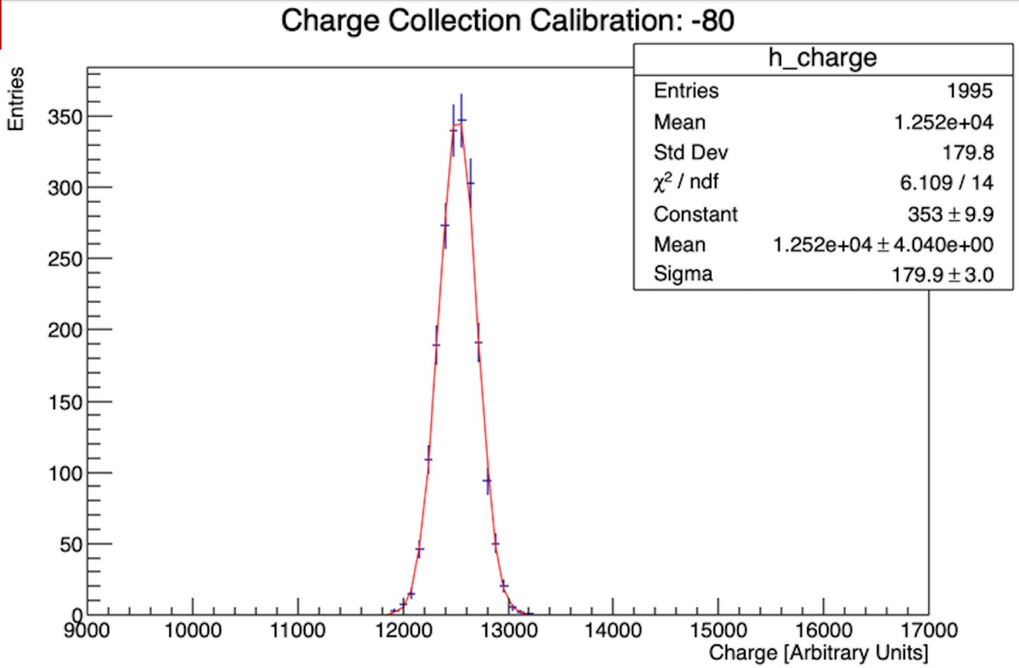
- We first average 2000 waveforms to find any DC offset
  - Typically offset is < 0.1 mV
- Subtract constant offset value from each point of each waveform
- Integrate each waveform between the points where it crosses 0 mV (in dashed lines)
  - ∑(width(.05 ns)×height)

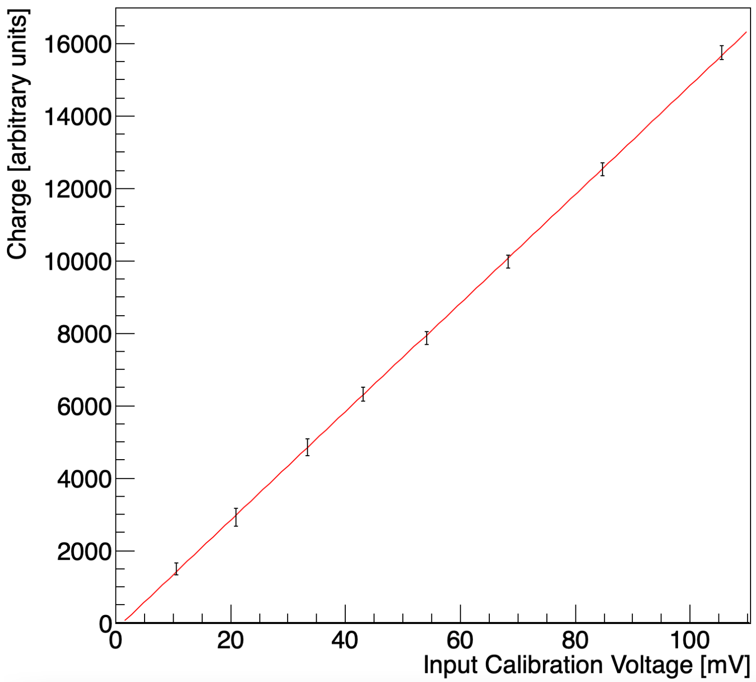

A typical waveform



Calibration Procedure

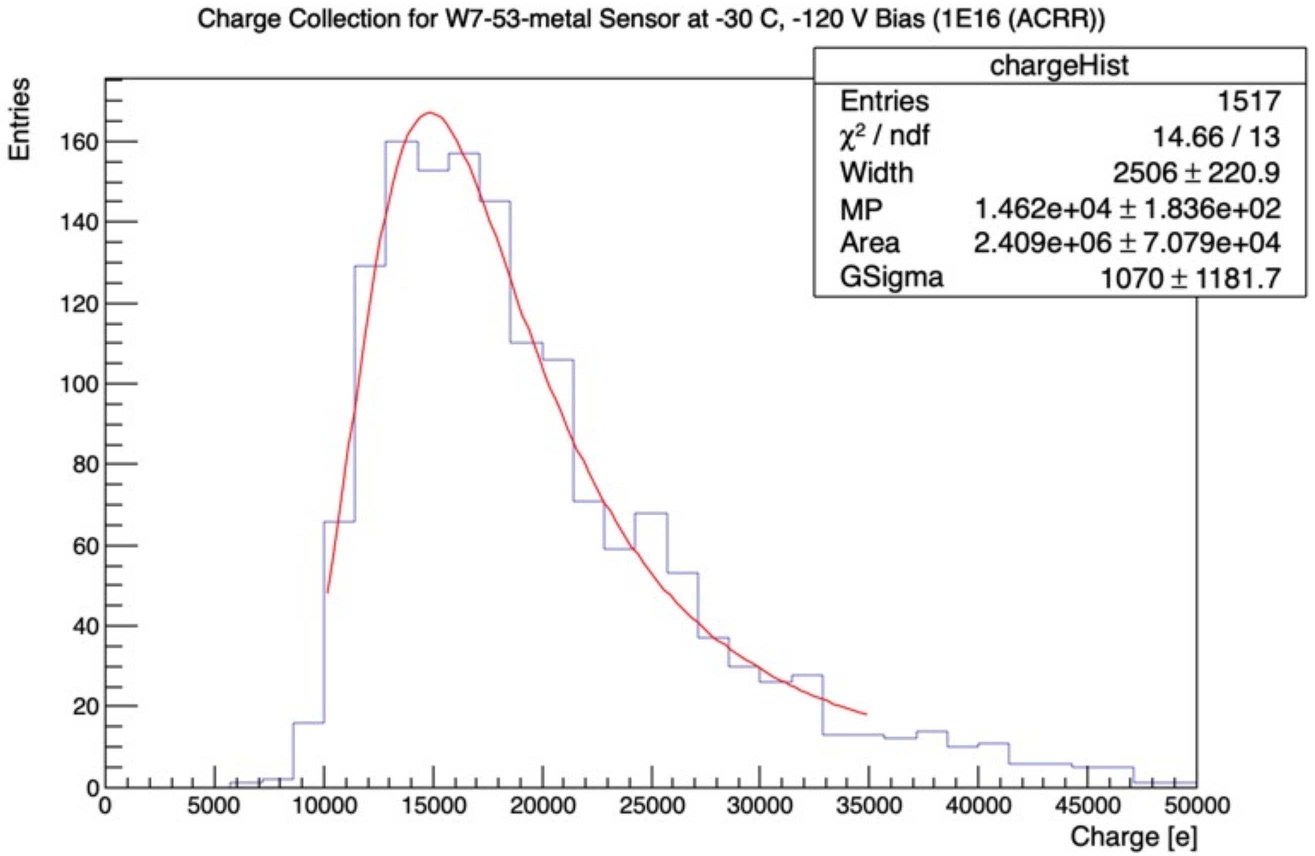
- This integrated value must be calibrated to standard units of charge
- The UCSC boards have a 0.30±0.05 pF calibration capacitor
- Pulse this capacitor with square voltage pulses of different sizes, and then read out and analyze the waveforms
- The resulting charge histogram is fit to a gaussian, the mean is plotted vs. the input pulse height
- We do this for input voltages from about 5 to 100 mV, then fit with a line
- The slope of the line provides conversion to units of electron charge



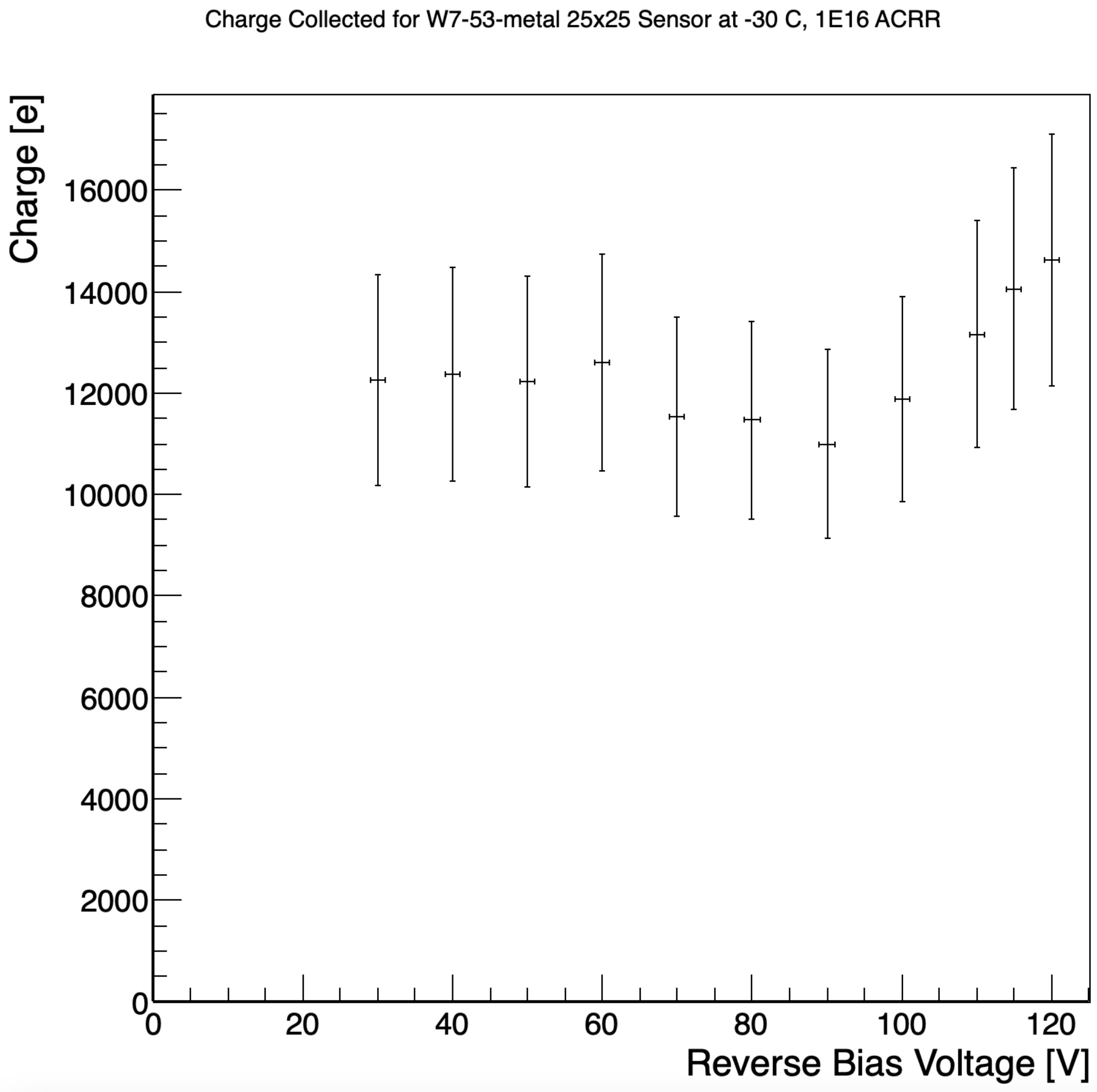


Data Collection and Analysis

- Then, vary bias voltage, collecting data at each voltage
- Fit the data with a Landau + gaussian convolution
- Measurements for unirradiated sensors are in preparation, and the graph below is for a sensor exposed to 1E16 neq/cm^2 at ACRR



- Plot MPV (Landau peak) vs. bias voltage
- Continuing to improve S/N in order to be able to fit at lower bias voltages
- Error bars reflect uncertainty in calibration capacitance



Timing Measurements

- This data is also being used to measure timing resolution
- The timing resolution σ_{ref} of the reference LGAD has been previously measured
- Plotting the start time of the reference signal minus the start time of the test sensor signal should give a gaussian
- Fitting this distribution gives $\sigma_{\text{tot}}^2 = \sigma_{\text{ref}}^2 + \sigma_{\text{test}}^2$ and we can solve for σ_{test}

Conclusions

- A set of small pitch 3D silicon sensors developed and fabricated by the University of Trento and FBK have been irradiated and are under study at New Mexico
- Current vs. bias voltage and capacitance vs bias voltage measurements have been made for sensors pre- and post-irradiation, breakdown voltages increase from between 90 and 120 V to between 120 and 140 V
- A test stand for charge collection is being developed, with promising results from a sensor irradiated to 1E16 neq/cm^2 at ACRR
- More sensors will be characterized in this way in the coming months, with intent to explore increased efficiency at extreme fluences, due to charge multiplication, as well as precision timing