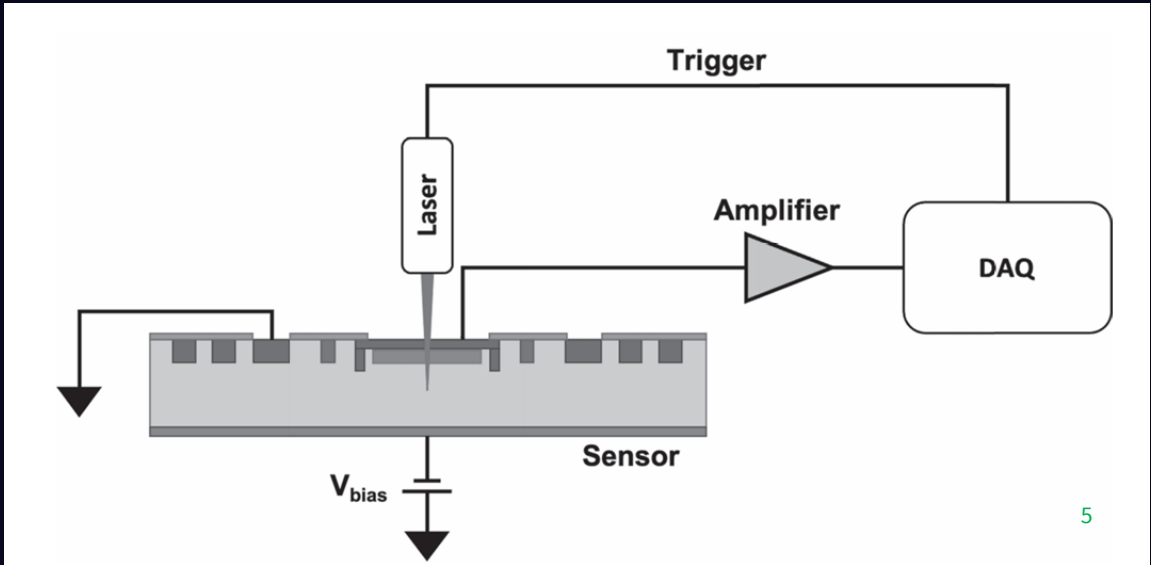
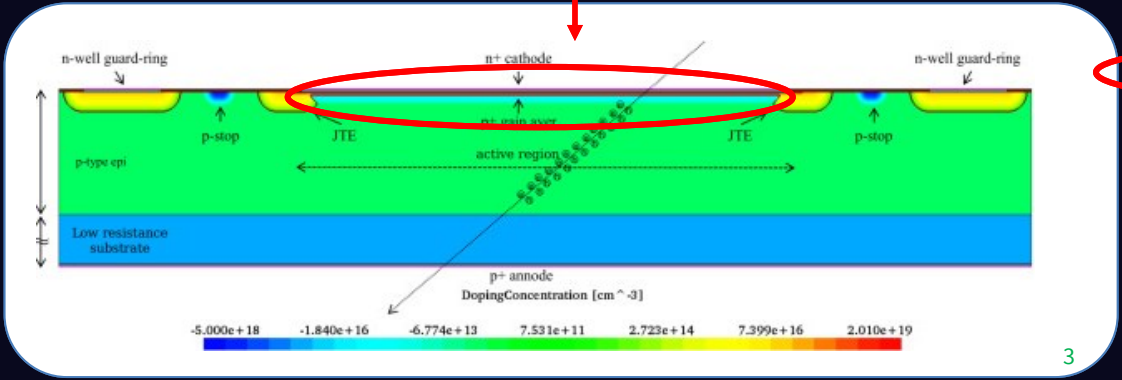
TRANSIENT CURRENT TECHNIQUE AND OTHER CHARACTERIZATION FOR SILICON SENSORS



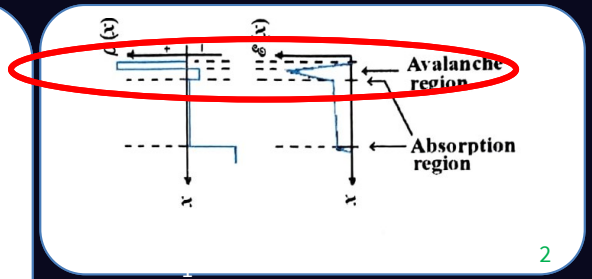
Ben Urbach

Low Gain Avalanche Detector (LGAD)

- LGADs have a highly doped thin layer to enhance the E-field and promote impact ionization, creating an avalanche



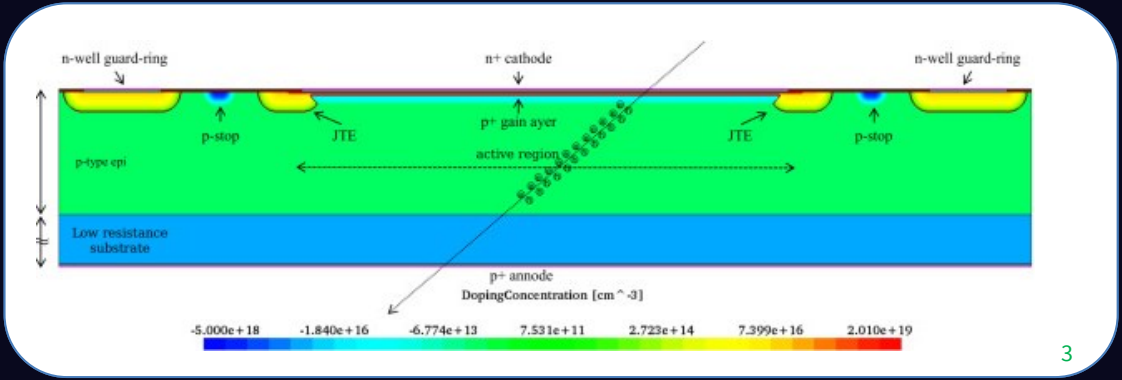
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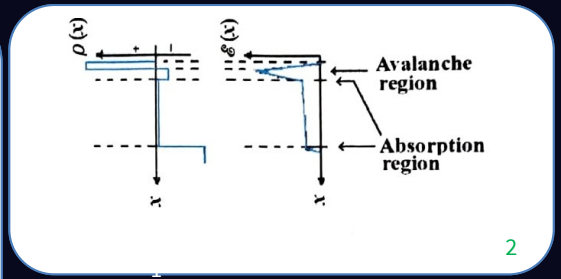
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Low Gain Avalanche Detector (LGAD)

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- Consist of 3 basic steps: Carrier generation, transportation/multiplication of carriers through gain region, interaction with external circuit.



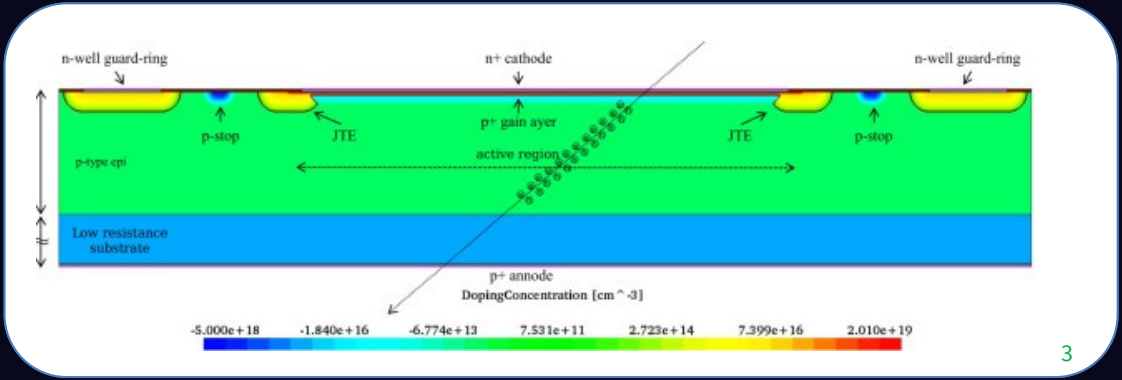
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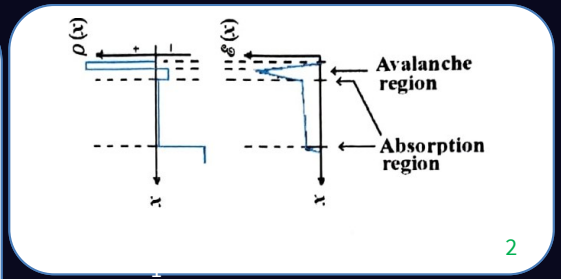
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- LGADs have a highly doped thin layer to enhance the E-field and promote impact ionization, creating an avalanche
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- Fast timing (20 ps), small pitch (50um), low noise



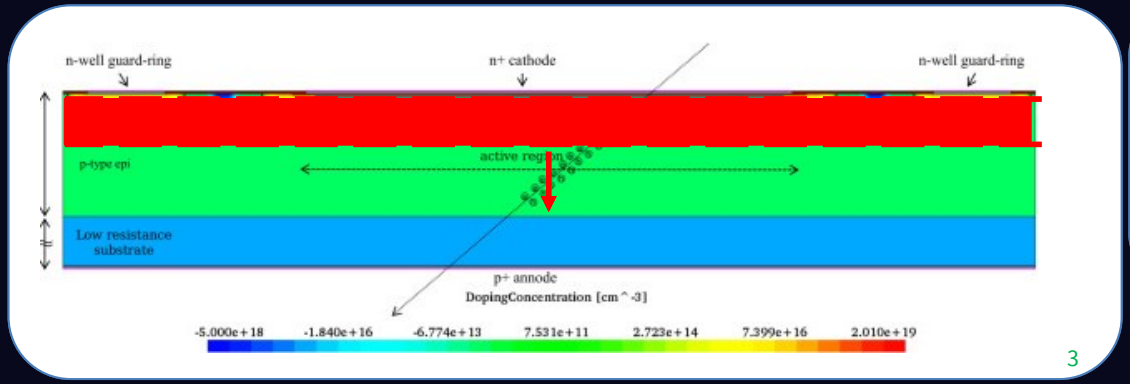
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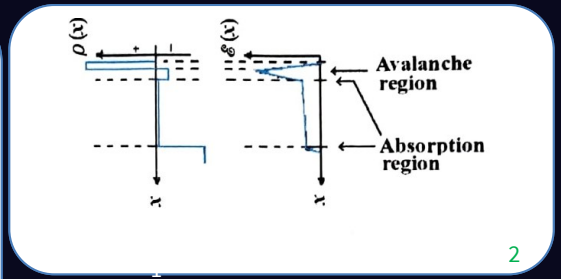
2

Low Gain Avalanche Detector (LGAD)

- LGADs have a highly doped thin layer to enhance the E-field and promote impact ionization, creating an avalanche (controlled)
- Consist of 3 basic steps: Carrier generation, transportation/multiplication of carriers through gain region, interaction with external circuit.
- Fast timing (20 ps), small pitch (50um), low noise
- Diode is put in **reverse bias** to **increase fields** in depletion region and **extend the depletion region into the gain layer and throughout the entire device**



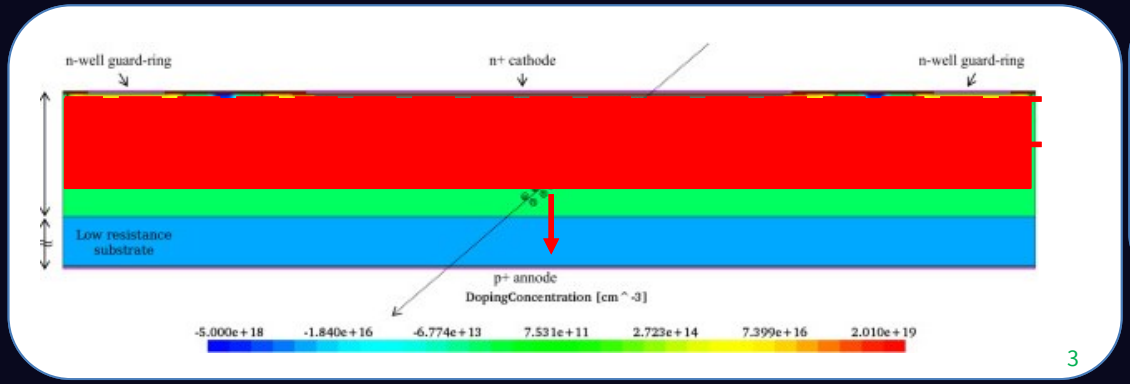
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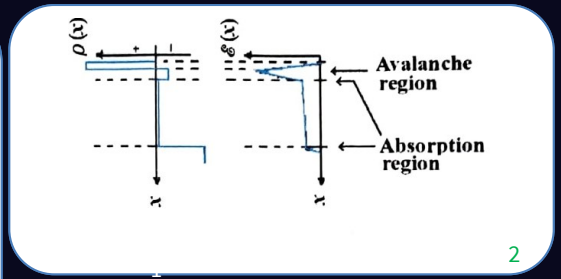
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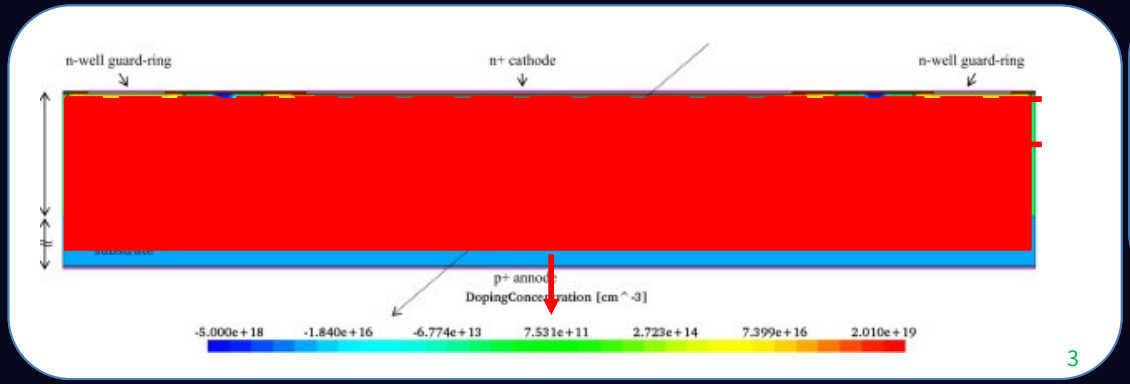
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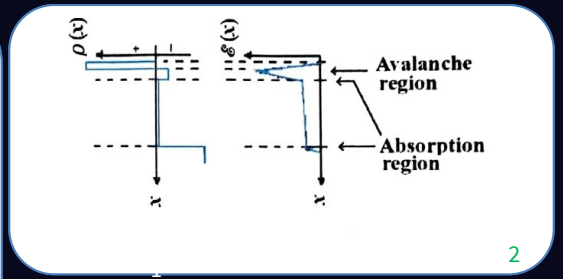
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3



2

Current-Voltage Measurements

IV

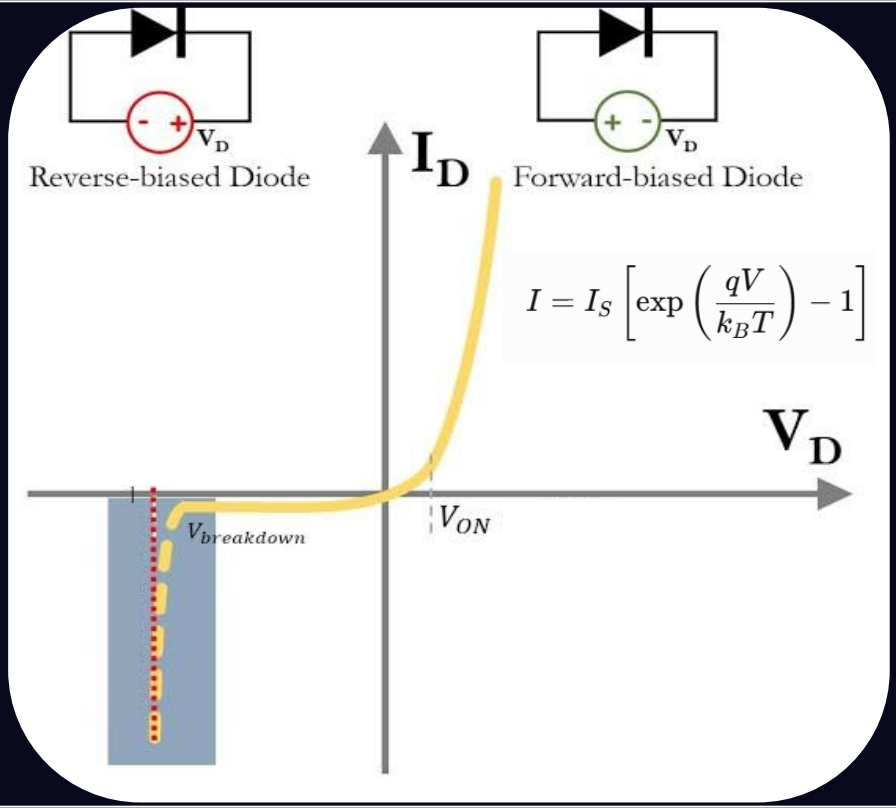
Current-Voltage (IV) Measurements
Forward Bias

- Varying Voltage to see the response of the device
- For diode, forward bias is determined essentially by Fermi-Dirac Distribution

$$f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)}$$

$$f(E) \approx \exp\left(-\frac{E - E_F}{k_B T}\right)$$

$$\Delta E = qV$$



Diagrams by All About Circuits [4]

Current-Voltage (IV) Measurements

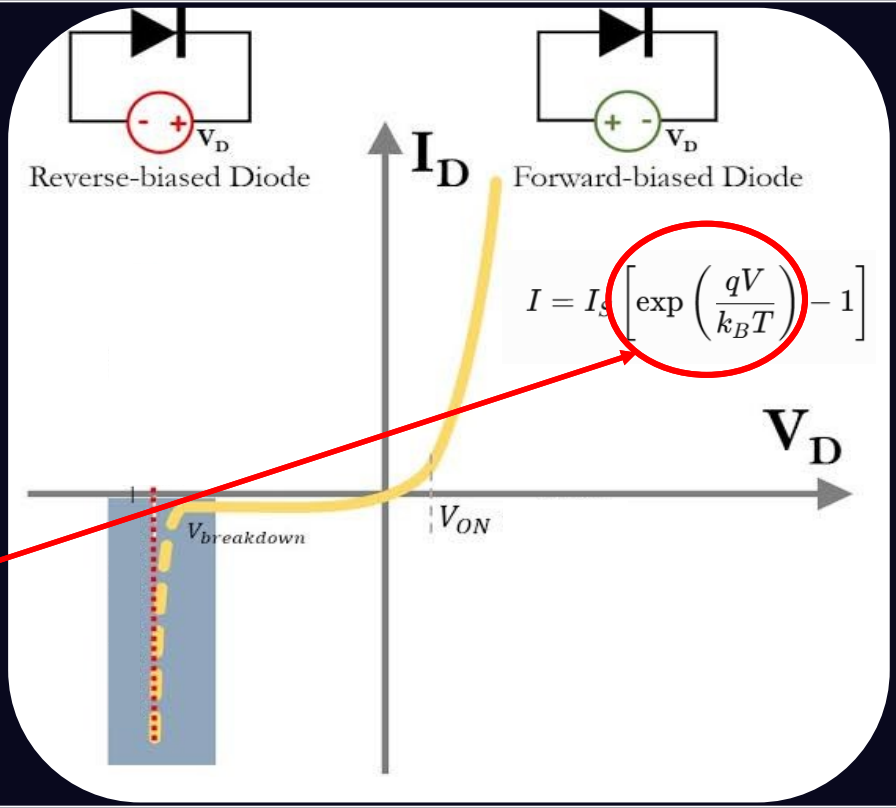
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Current-Voltage (IV) Measurements

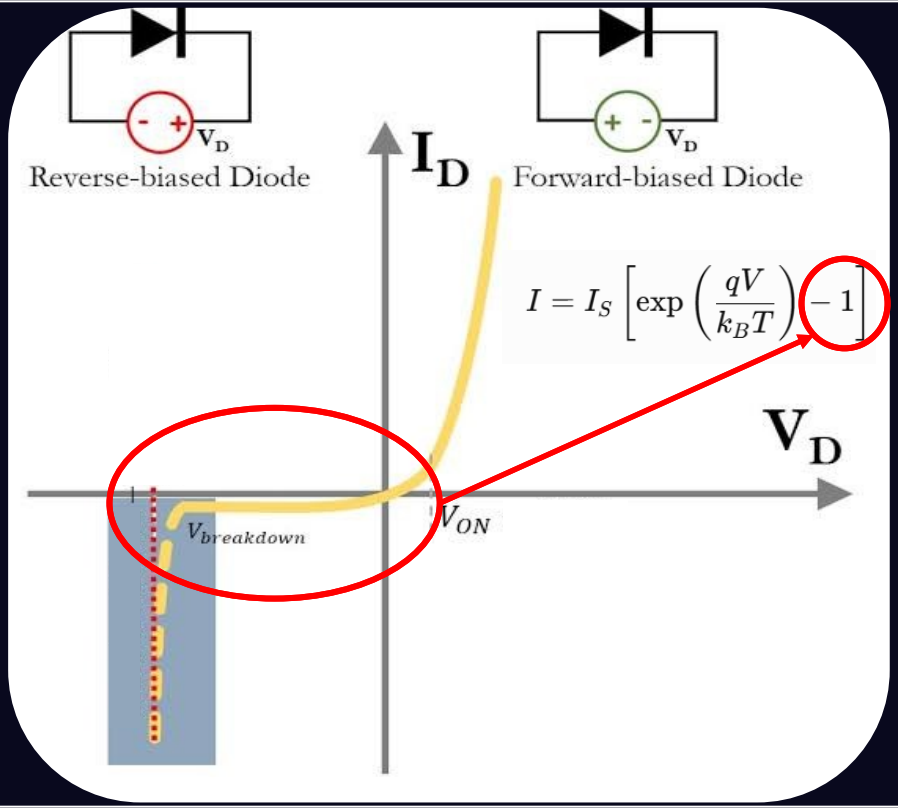
Forward Bias

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- For diode, reverse bias should be constant (I_S)

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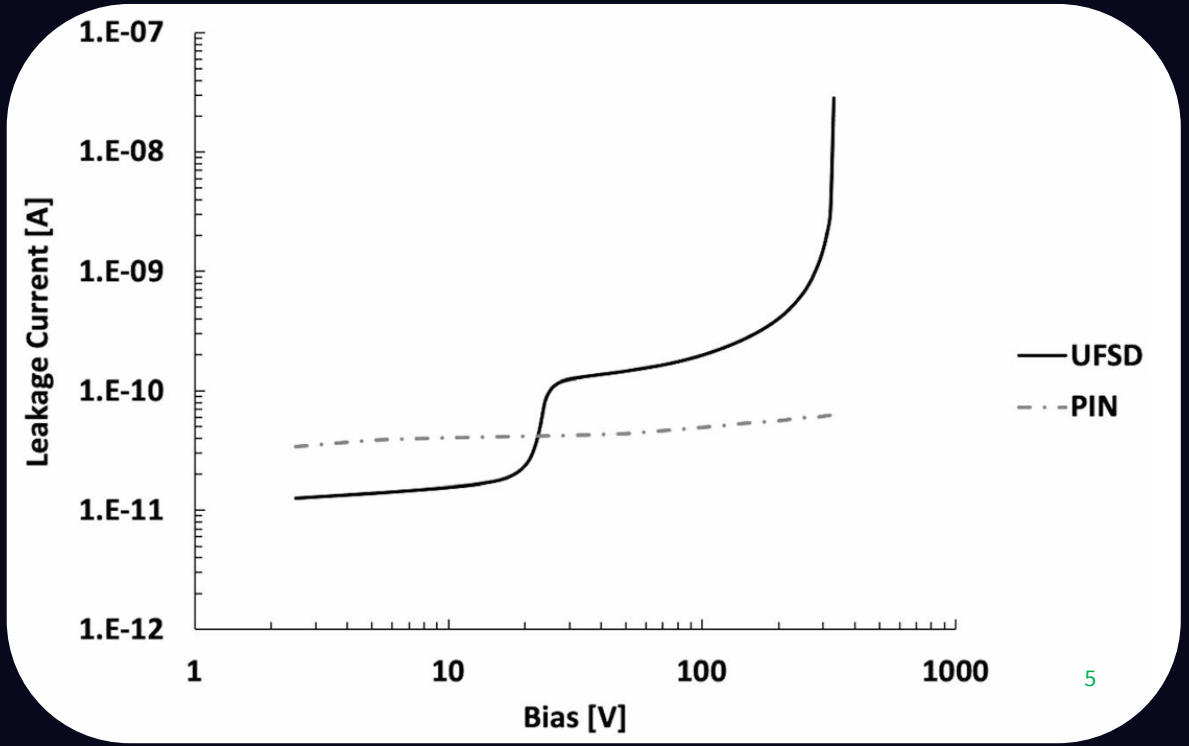
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Diagrams by All About Circuits [4]

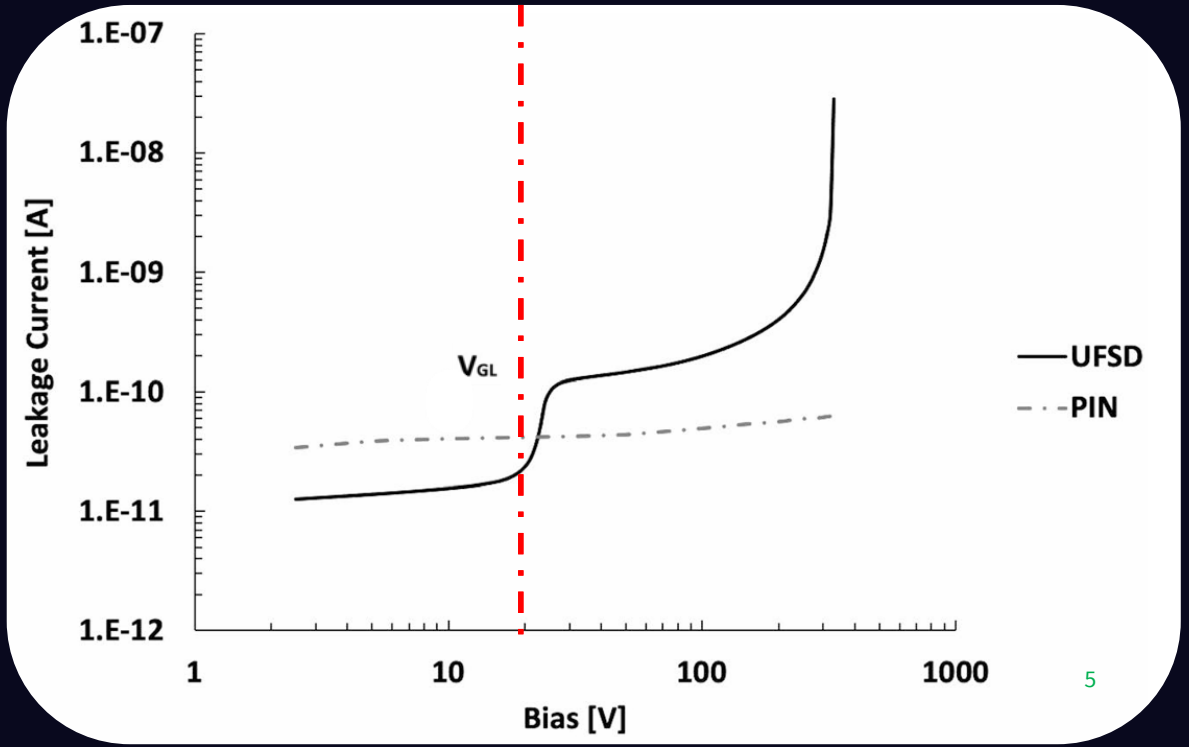
Current-Voltage (IV) Measurements
Reverse Bias

- In reverse bias, the ideal current is simply I_D
- For PIN: reality shows linear with V (shunt resistance)



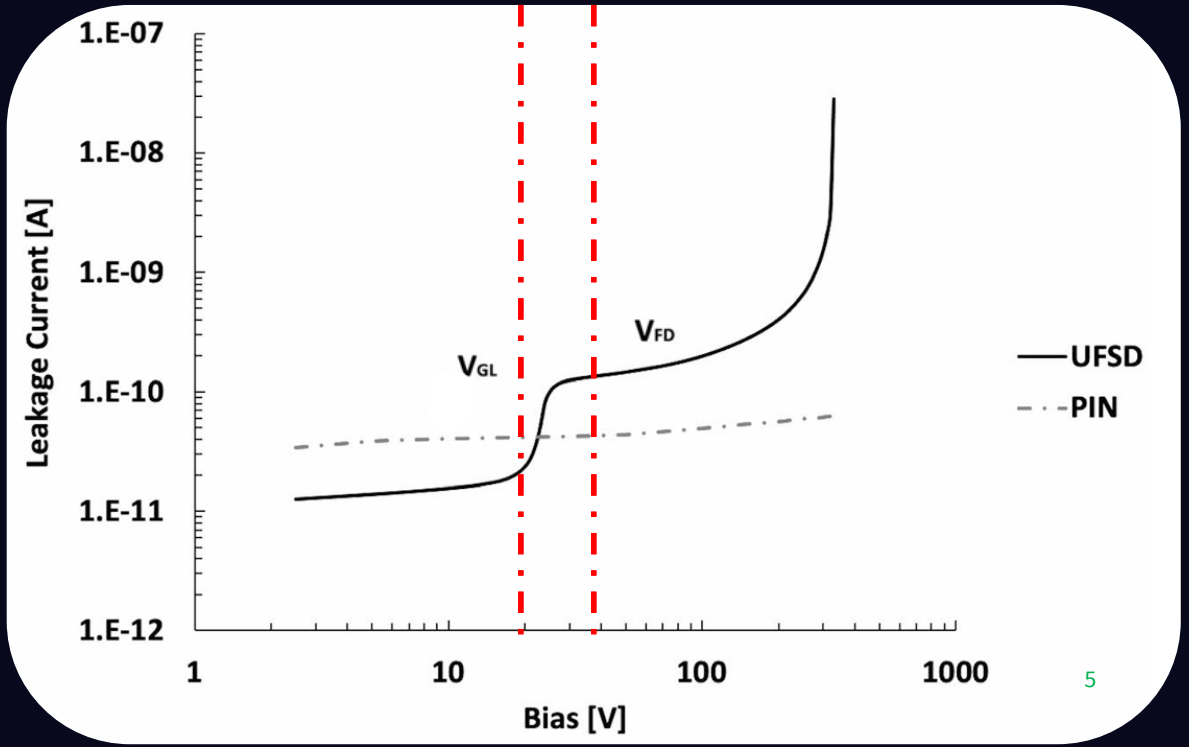
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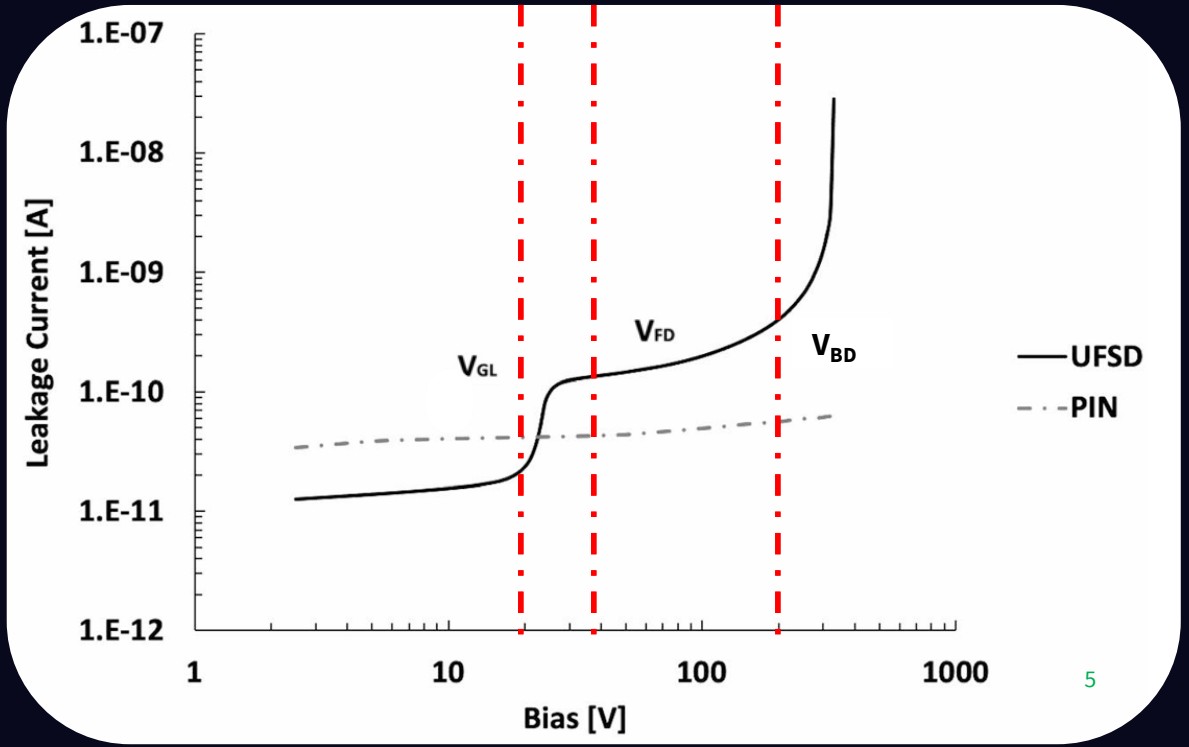
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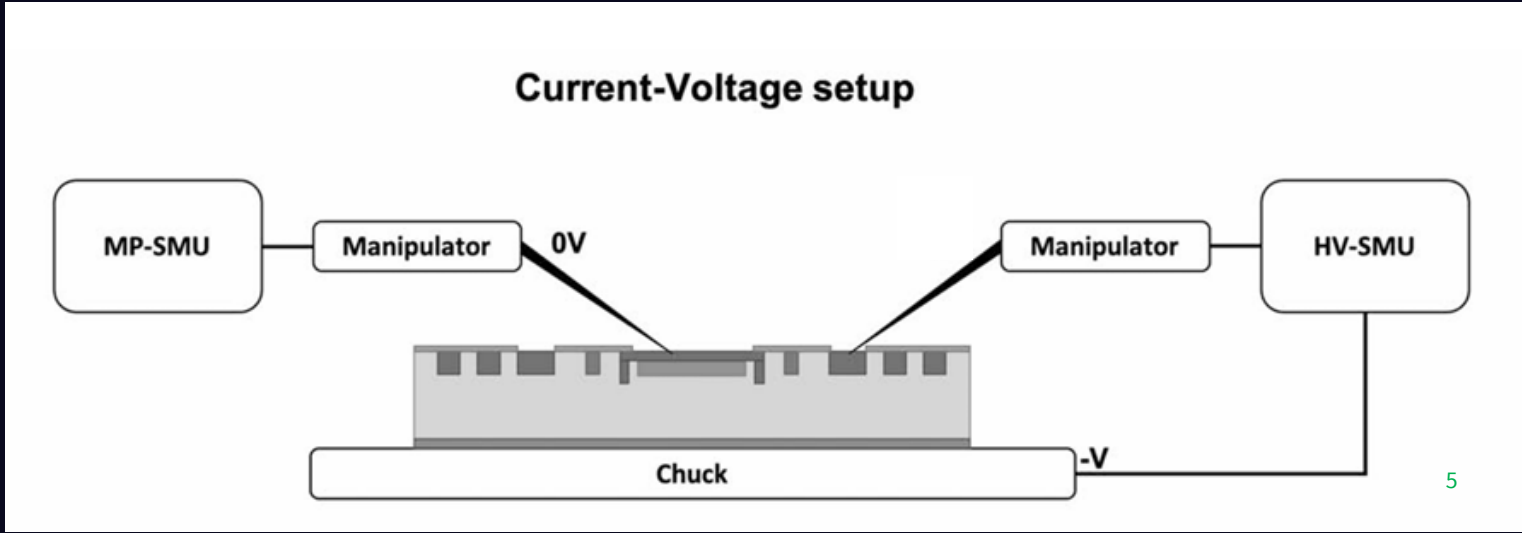


Current-Voltage (IV) Measurements
Reverse Bias

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- For PIN: reality shows linear with V (shunt resistance)
- For LGAD: knee shows gain layer depletion (V_{GL})
- Gain increases with voltage as E-field increases
- Level-off is full depletion V_{FD}
- Large increase is breakdown V_{BD}

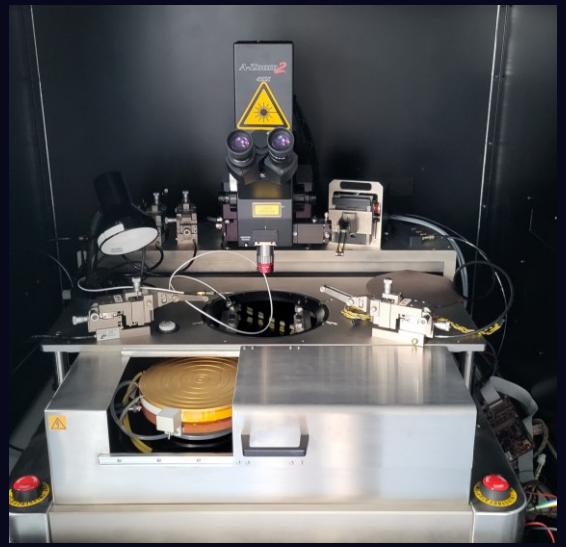


Our Lab- IV Setup



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Our Lab- Probe Station



Wentworth Probe Station



Agilent Semiconductor Analyzer B1500A (4 separate probe power supplying +/- 100V for IV and CV [2point 1kHz to 5MHz])



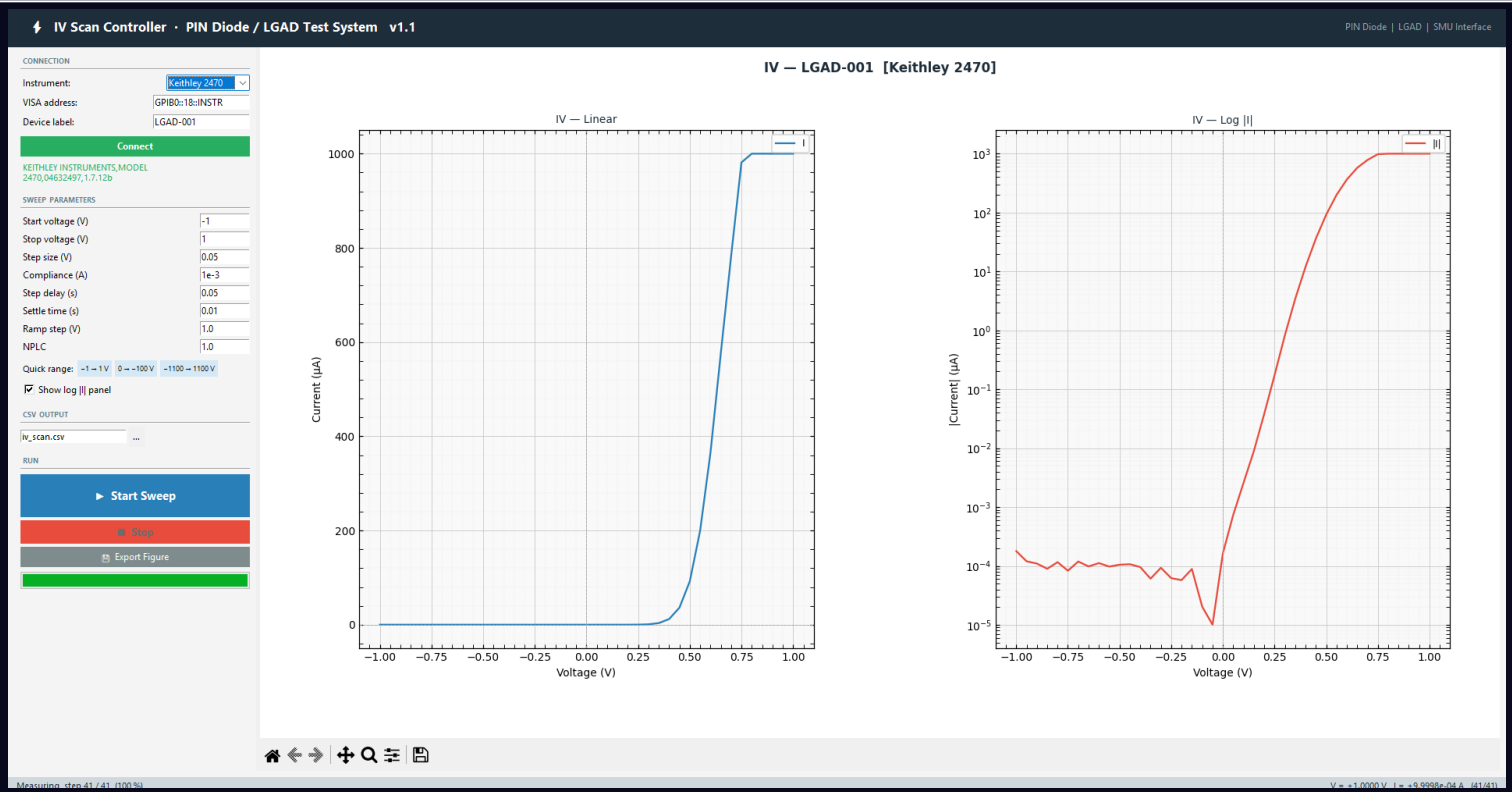
Temptronic Chiller (-65C to 200C)



Keithley 2470 (for high voltage IV (1100V) measurements)

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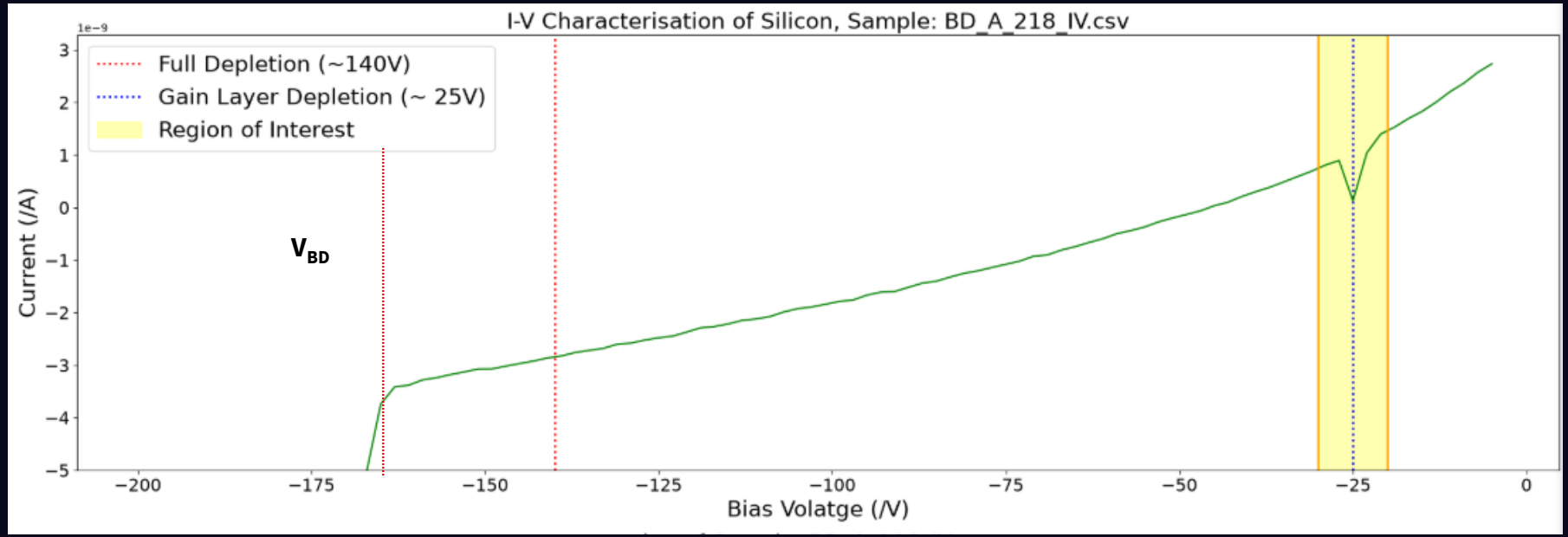
Our Lab- IV GUI



Graph by Oliver Waterman

THE UNIVERSITY of EDINBURGH

Our Lab- IV Results



Graph by Oliver Waterman

Capacitance-Voltage Measurements

CV

Capacitance-Voltage (CV) Measurements

- Capacitance is related to current by a change in voltage

$$C = \frac{dQ}{dV}$$

$$\frac{dQ}{dt} = \frac{dQ}{dV}\frac{dV}{dt}$$

$$I(t) = \frac{dQ}{dt} = \frac{dQ}{dV}\frac{dV}{dt} = C\frac{dV}{dt}$$

Capacitance-Voltage (CV) Measurements

- Capacitance is related to current by a change in voltage
- Applying a known alternating current function (charging and discharging)
- Solve for capacitance

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$$V(t) = V_{\mathrm{DC}} + V_{\mathrm{AC}}\sin(\omega t)$$

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- Capacitance related to depletion width (parallel plate)

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$$V(t) = V_{\mathrm{DC}} + V_{\mathrm{AC}}\sin(\omega t)$$

$$C = \frac{\varepsilon A}{d} \qquad d = \frac{\varepsilon_{\mathrm{Si}} A}{C}$$

$$W \approx \sqrt{\frac{2\varepsilon_s (V_{\mathrm{bi}} + V_R)}{qN_{\mathrm{eff}}}}$$

Capacitance-Voltage (CV) Measurements

- Capacitance related to depletion width (parallel plate)
- Depletion width is related to N_{eff}

$$I(t) = \frac{dQ}{dt} = \frac{dQ}{dV}\frac{dV}{dt} = C\frac{dV}{dt} \rightarrow C = A\sqrt{\frac{q\varepsilon_s N_A}{2(V_{bi} + V_R)}}$$

Capacitance-Voltage (CV) Measurements

- Capacitance related to depletion width (parallel plate)
- Depletion width is related to N_{eff} (from slope of 1/C^2)

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$$N_{\text{eff}} = \frac{2}{q\varepsilon_s A^2}\left|\frac{d(1/C^2)}{dV_R}\right|^{-1}$$

Capacitance-Voltage (CV) Measurements

- Capacitance related to depletion width (parallel plate)
- Depletion width is related to N_{eff} (from slope of 1/C^2)
- Varying the voltage, varies the width and scans N_{eff} through device (only for abrupt junction)
- Can easily solve for lower concentration

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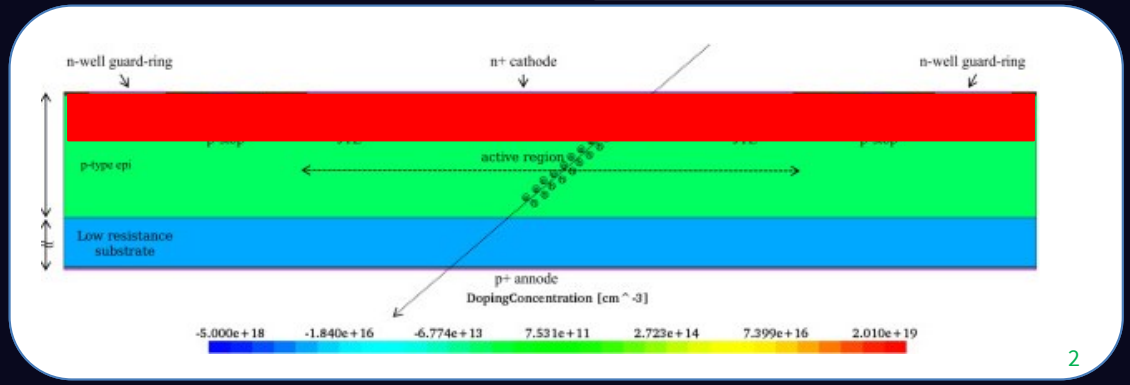
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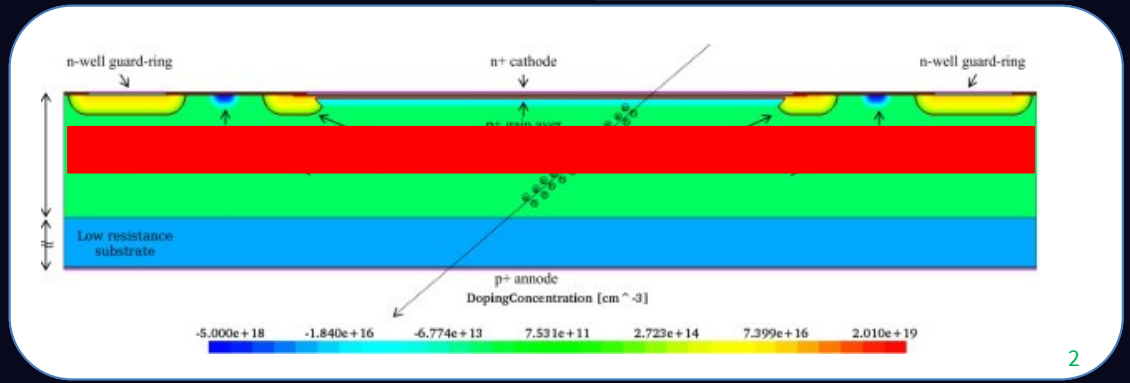
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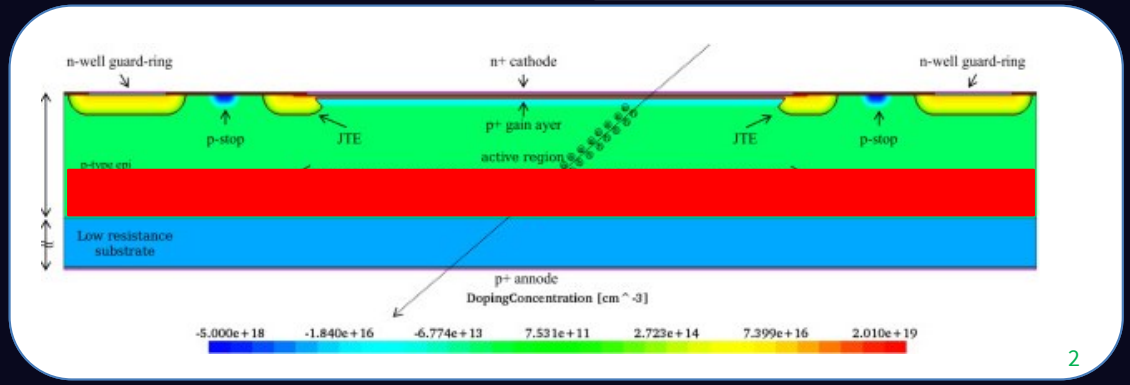
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Capacitance-Voltage (CV) Measurements

- Diode current response can be approximated as a resistor and capacitor in series

$$I(t) = \frac{dQ}{dt} = \frac{dQ}{dV}\frac{dV}{dt} = C\frac{dV}{dt}$$

$$I(t) = I_R(t) + I_C(t)$$

$$I_C(t) = \omega C V_0 \cos(\omega t)$$

$$I_R(t) = \frac{V_0}{R}\sin(\omega t)$$

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Capacitance-Voltage (CV) Measurements

- Diode current response can be approximated as a resistor and capacitor in series
- Differentiating V gives a 90 degree phase change for the capacitor portion

-0 degree-resistor
-90 degree-capacitor
-$0<\phi<90$- R (parasitic)+C

$$I(t) = \frac{dQ}{dt} = \frac{dQ}{dV}\frac{dV}{dt} = C\frac{dV}{dt}$$

$$I(t) = I_R(t) + I_C(t)$$

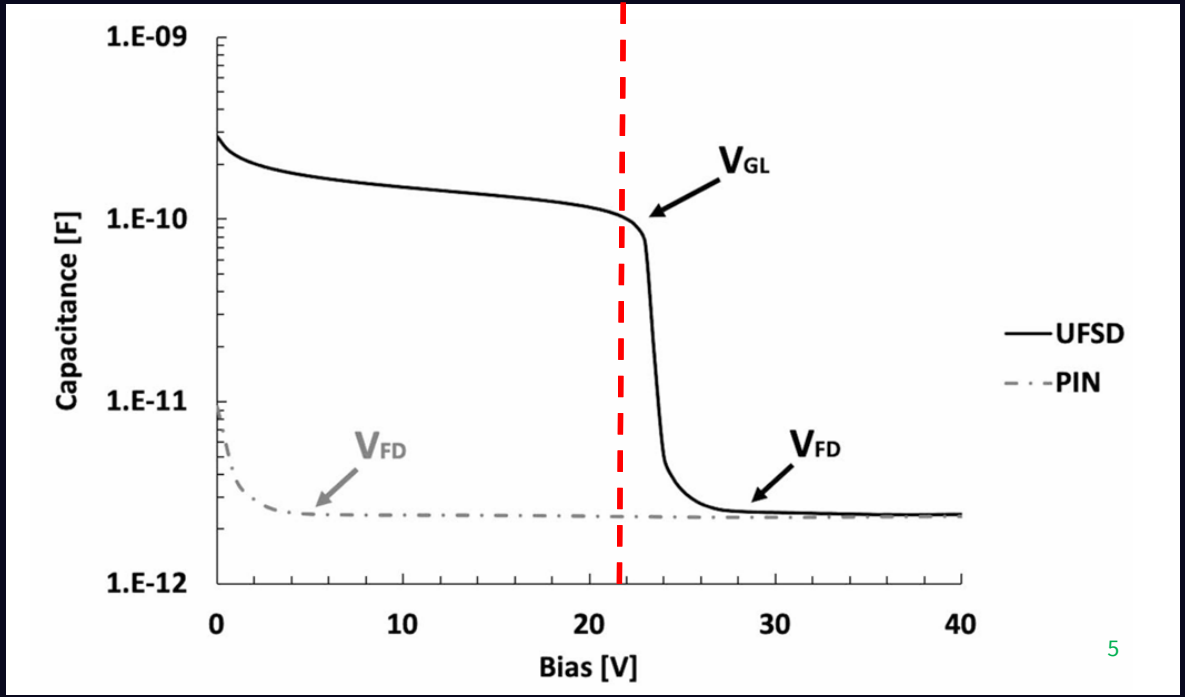
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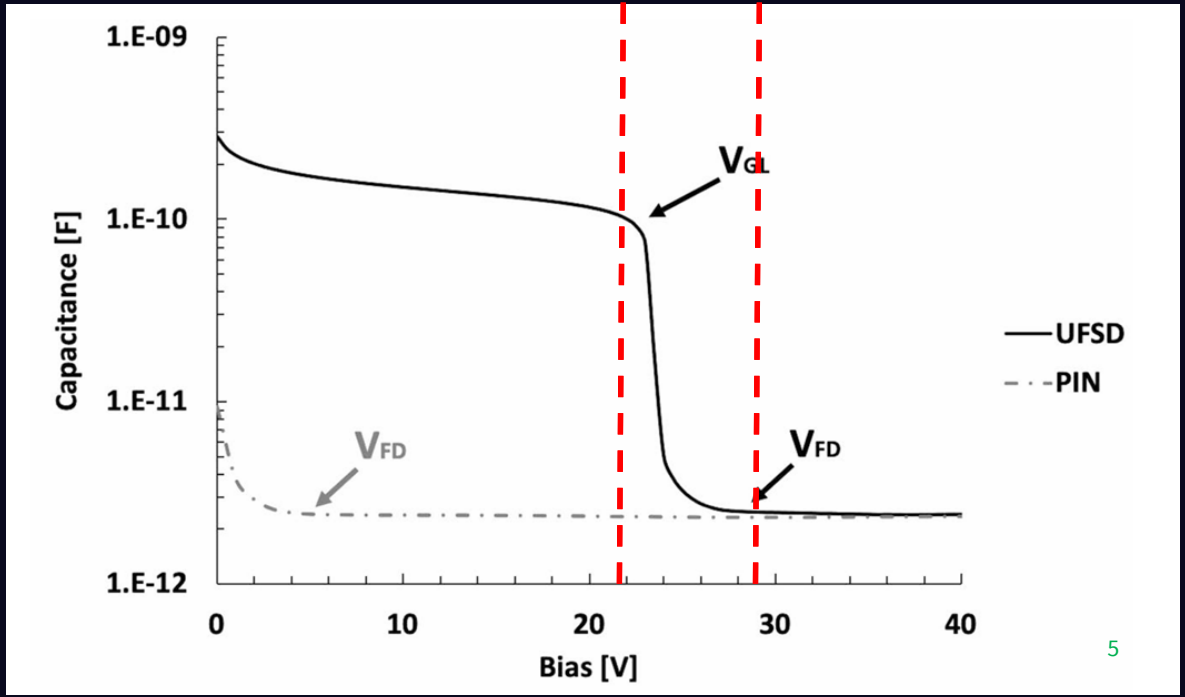
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- The knee indicates gain layer depletion voltage (V_{GL})

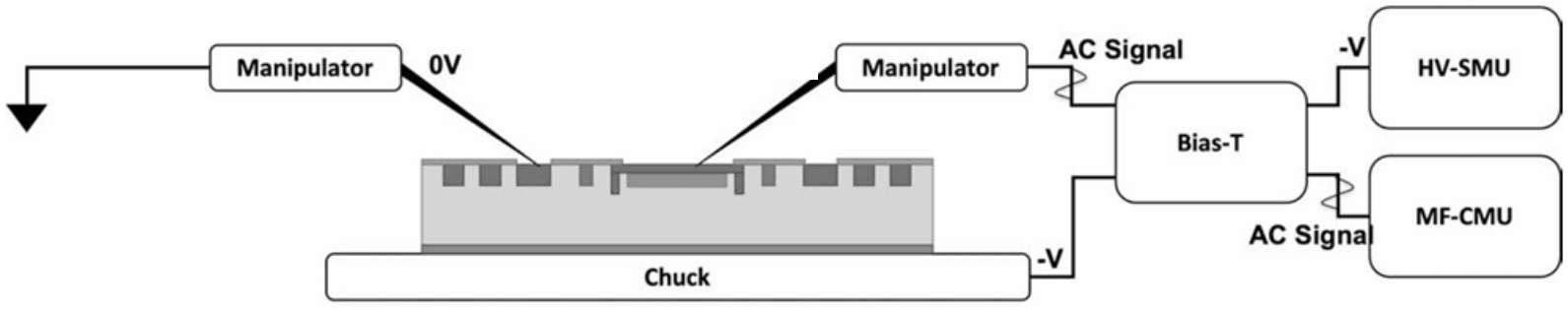


Capacitance-Voltage (CV) Measurements

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- The levelling off indicates full depletion (V_{FD})

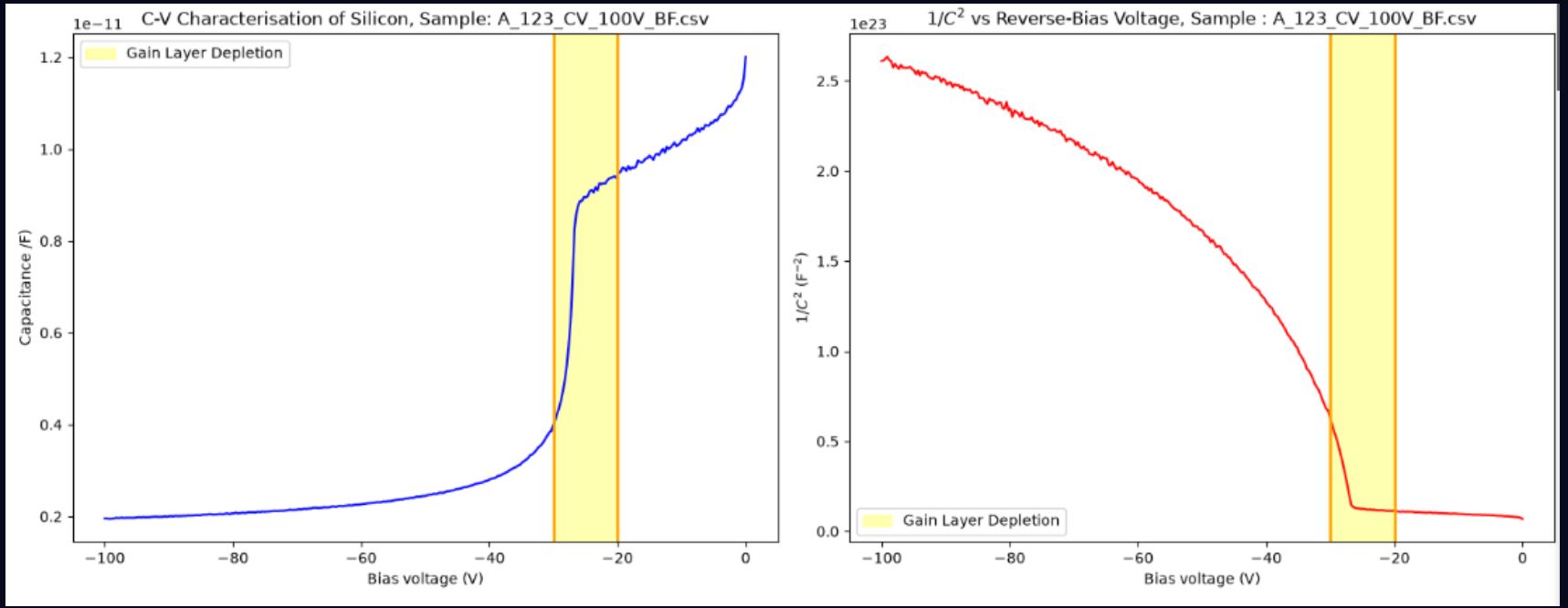


Our Lab- CV Setup



THE UNIVERSITY of EDINBURGH

Our Lab- CV Results



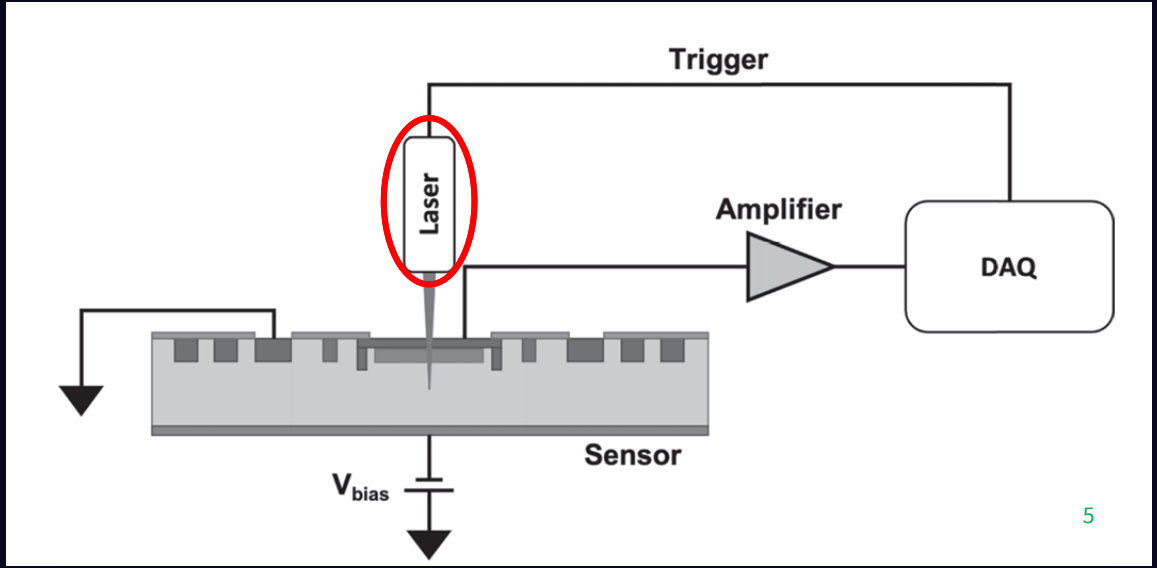
Graph by Oliver Waterman

Transient Current Technique

TCT

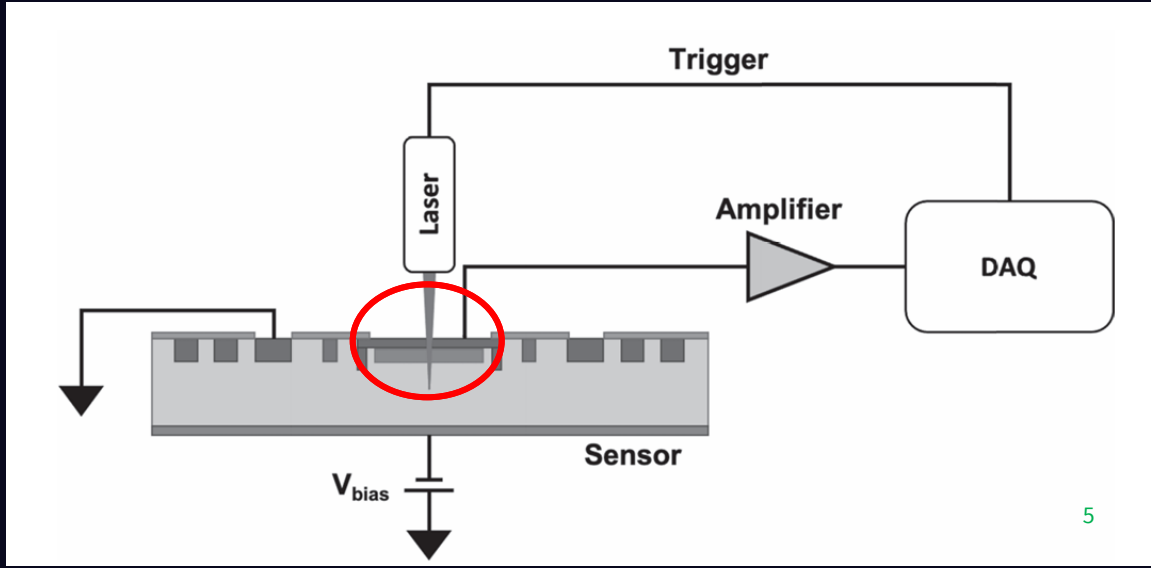
Transient Current Technique

- Pulsed laser injecting photons into silicon creates electron hole pairs



Transient Current Technique

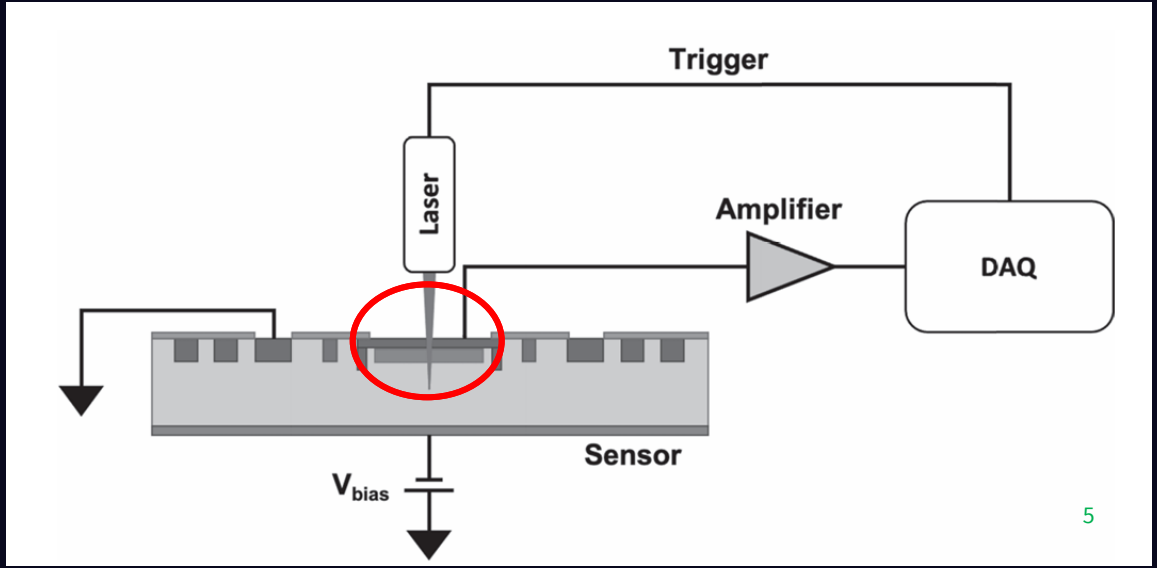
- Pulsed laser injecting photons into silicon creates electron hole pairs
- Moving charge induces current on the contact
- Dictated by Ramo-Shockley



$$I_{ind}(t) = -\frac{q}{V_w}\mathbf{E}_n\left(\mathbf{x}_q(t); V_w\right) . \frac{d}{dt}\mathbf{x}_q(t)$$

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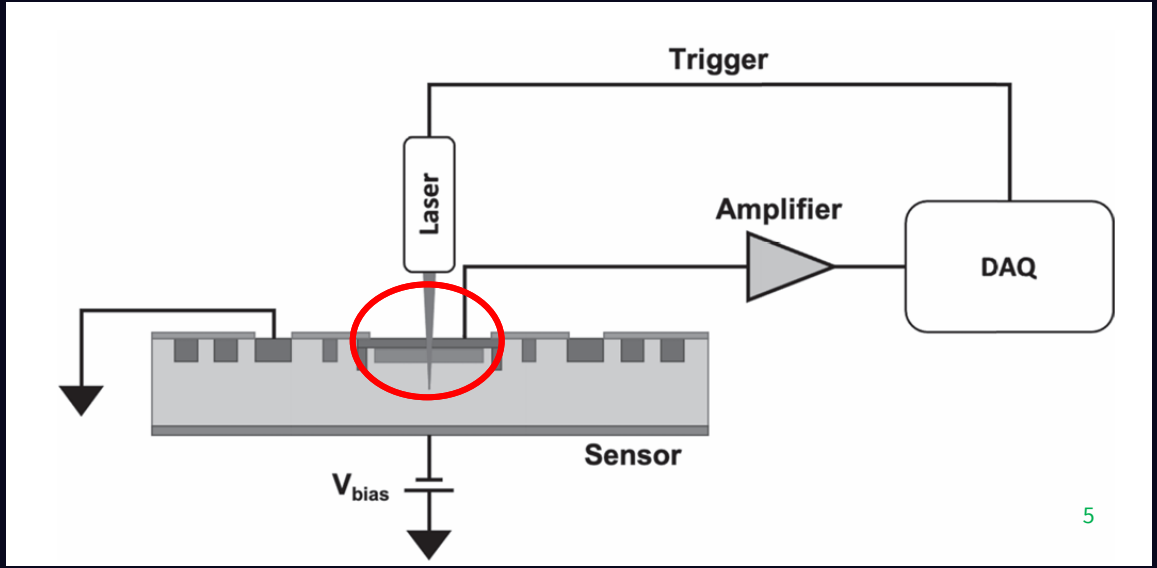
Weighting Field

coupling with the collector

$$I_{ind}(t) = -\frac{q}{V_w}\mathbf{E}_n\left(\mathbf{x}_q(t); V_w\right) \cdot \frac{d}{dt}\mathbf{x}_q(t)$$

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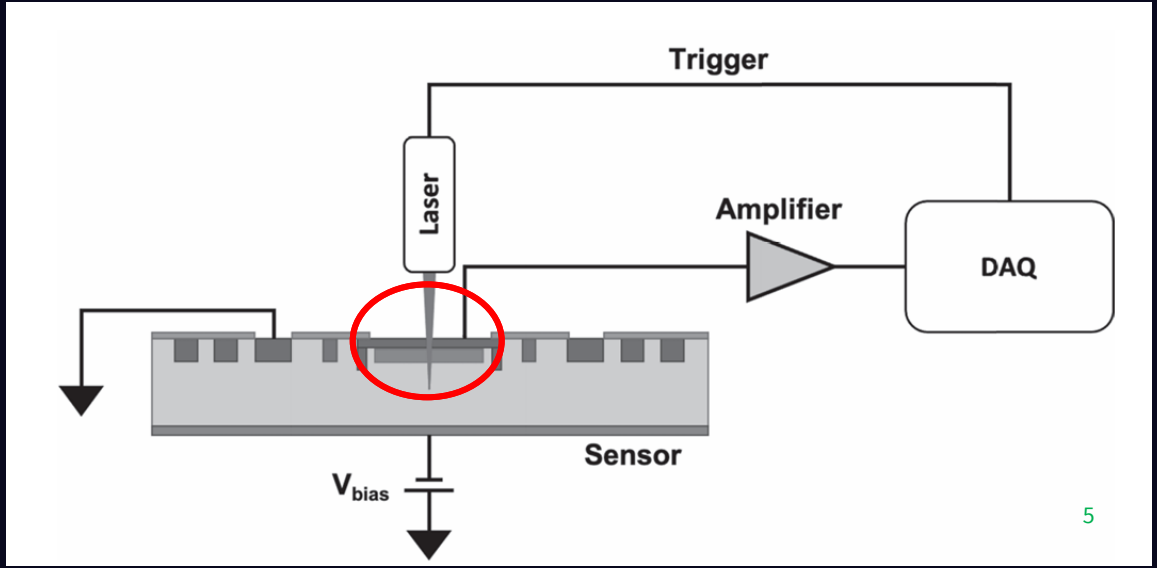
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→ Velocity of charge

Transient Current Technique

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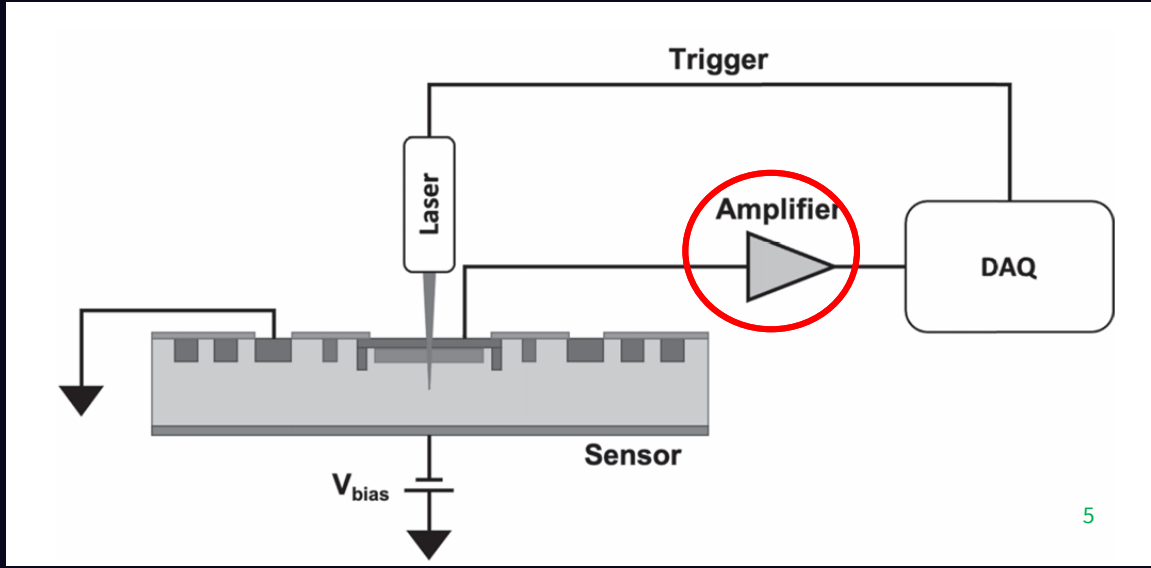
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Velocity of charge

Transient Current Technique

- Pulsed laser injecting photons into silicon creates electron hole pairs
- Current is amplified



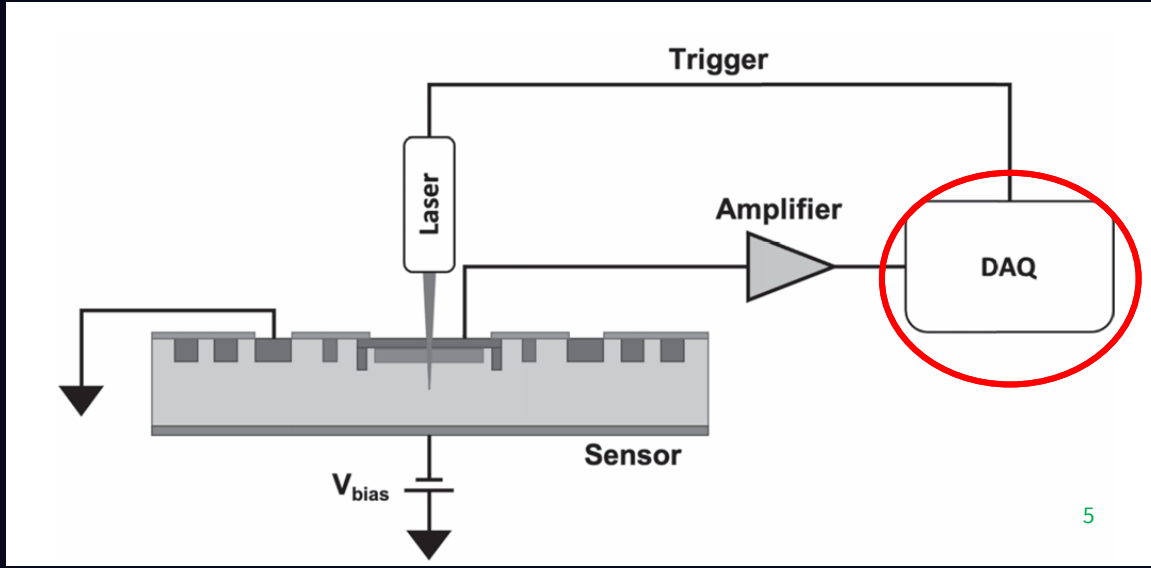
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Velocity of charge

Transient Current Technique

- Pulsed laser injecting photons into silicon creates electron hole pairs
- Current is amplified
- Current is collected by DAQ



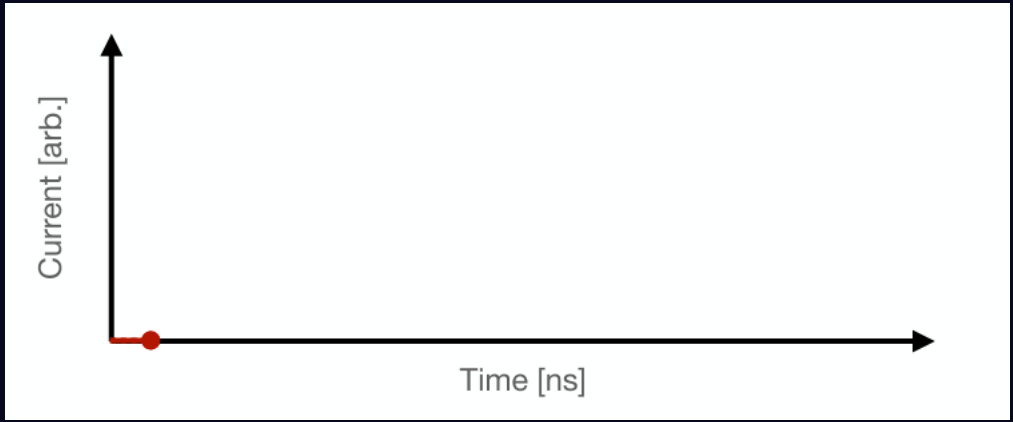
Weighting Field

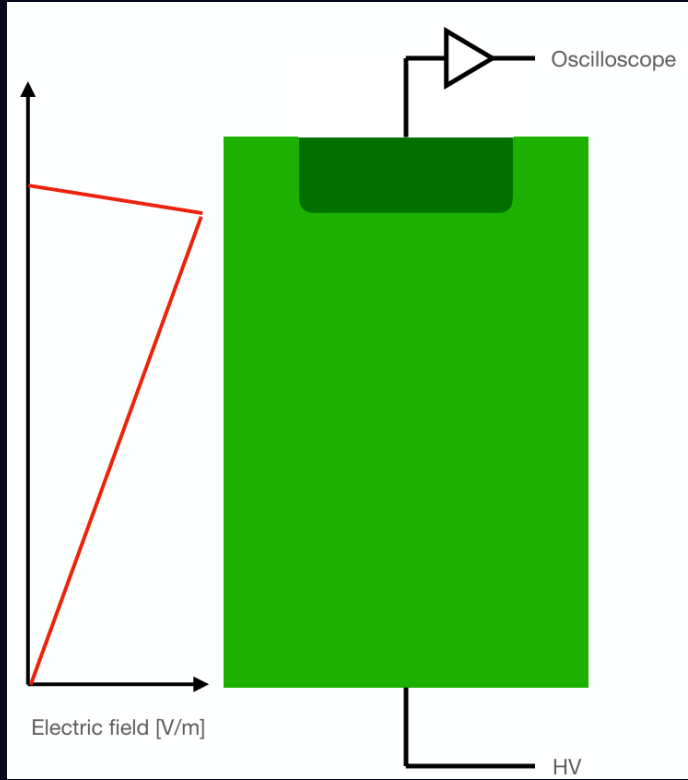
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Velocity of charge

Transient Current Technique

- Take a normal diode biased to depletion



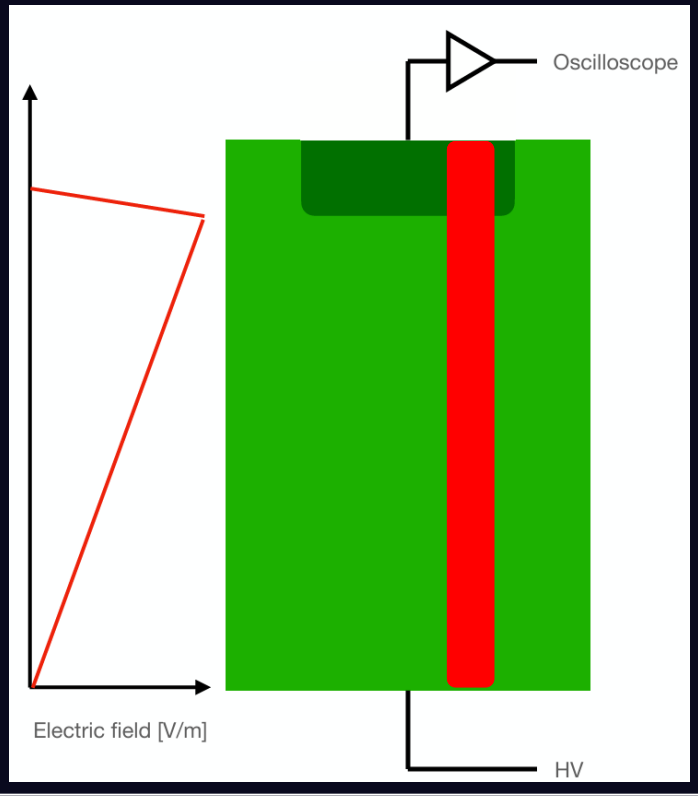


Diagrams by Daniel Hynds

Transient Current Technique

- Take a normal diode biased to depletion
- Charge is injected via a deeply penetrating laser wavelength (1064nm)

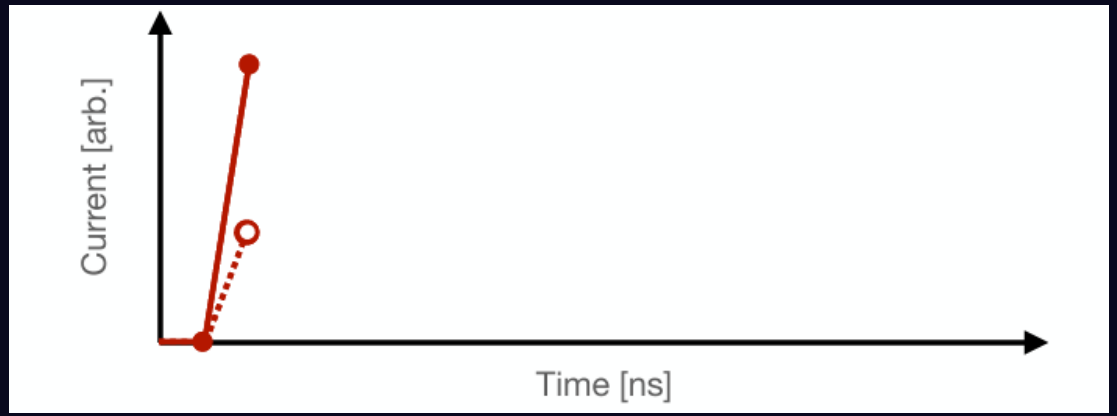


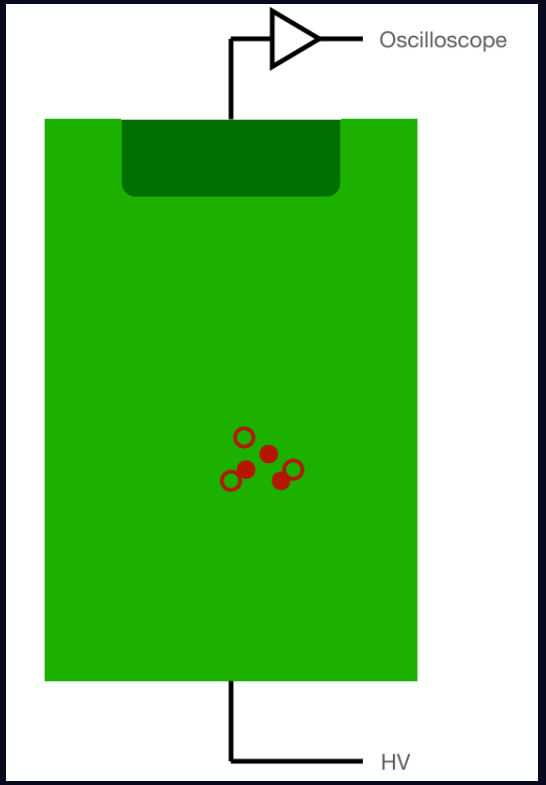


Diagrams by Daniel Hynds

Transient Current Technique

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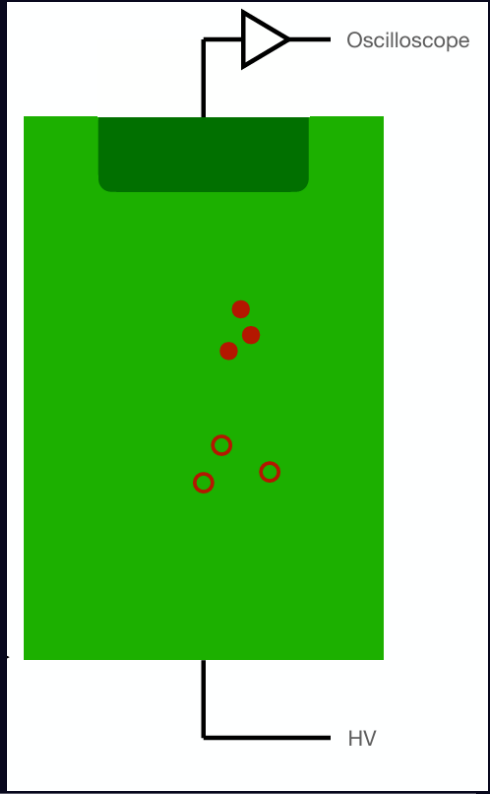


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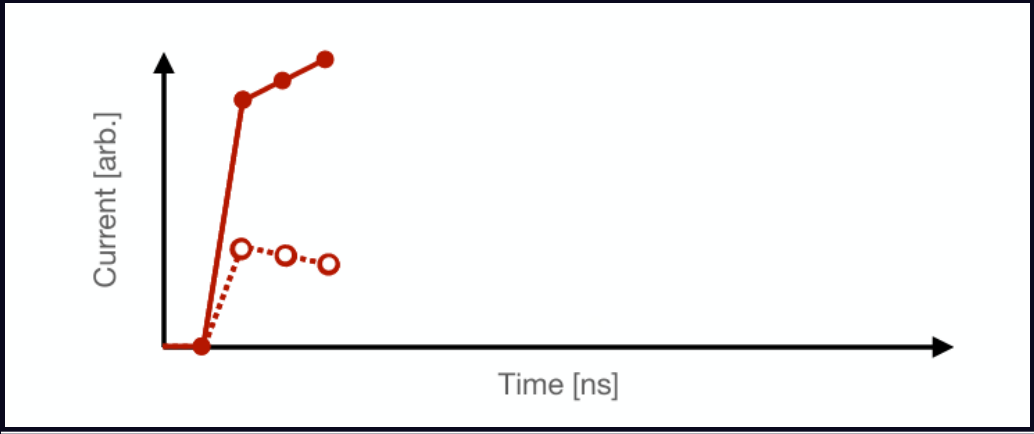


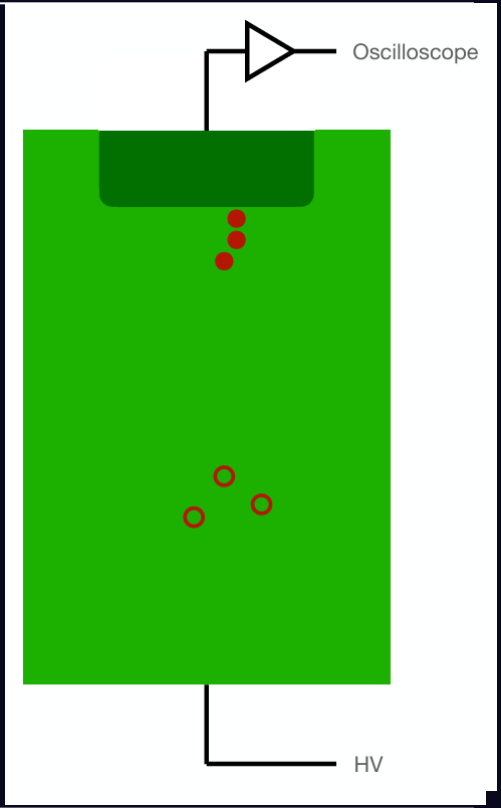


Diagrams by Daniel Hynds

Transient Current Technique

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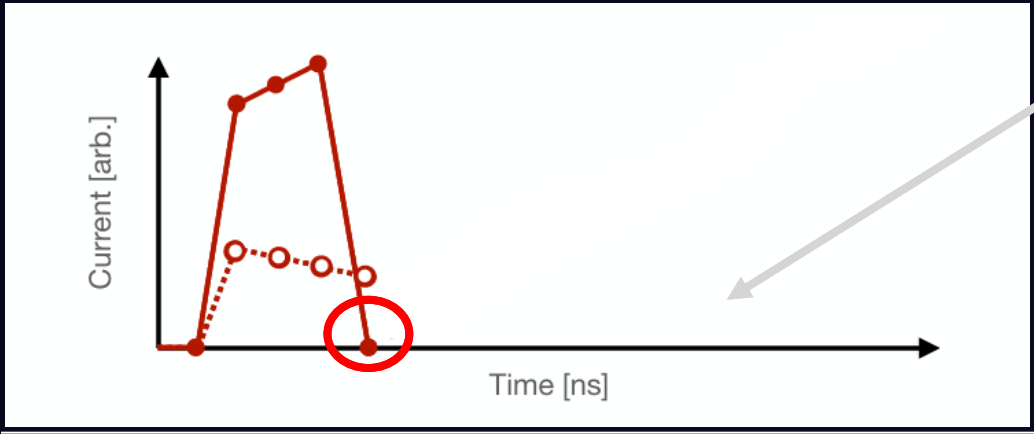


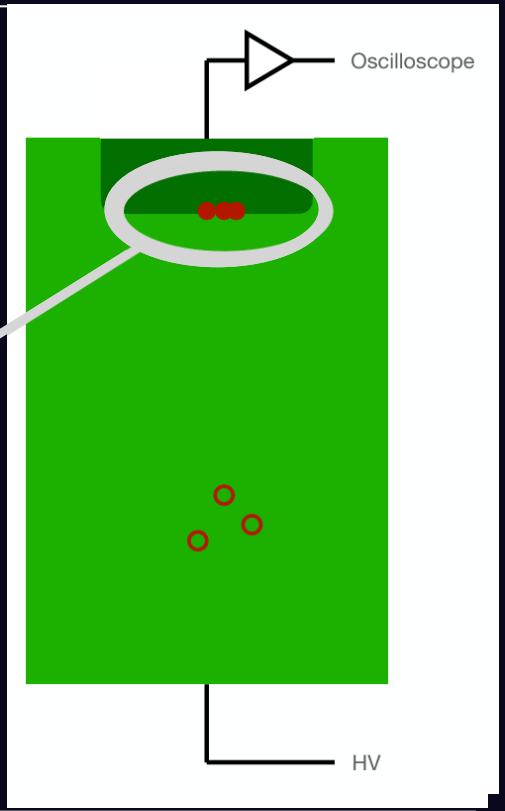


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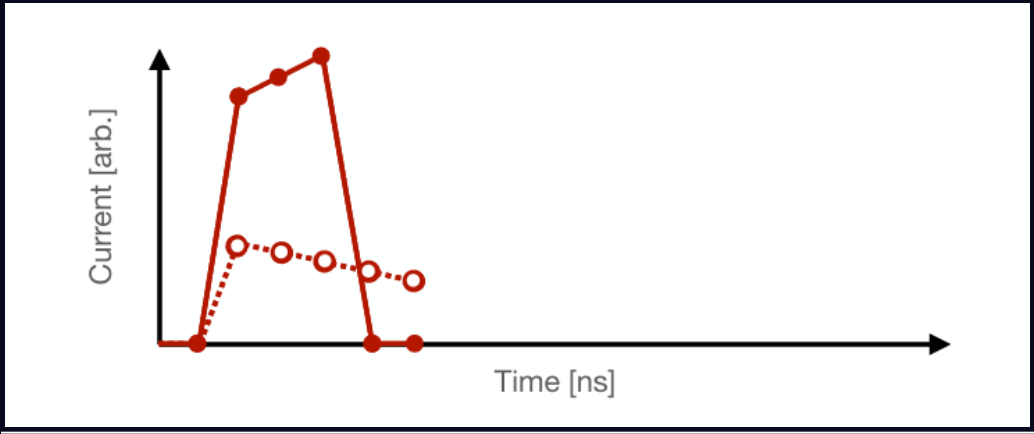


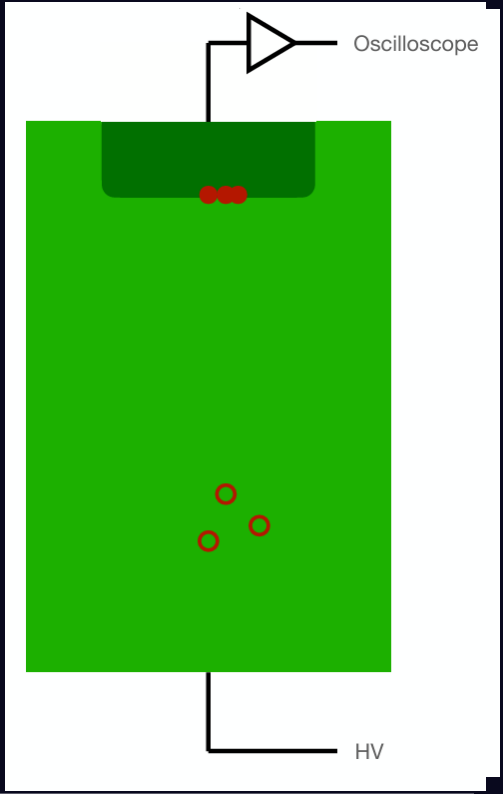
Diagrams by Daniel Hynds

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Transient Current Technique

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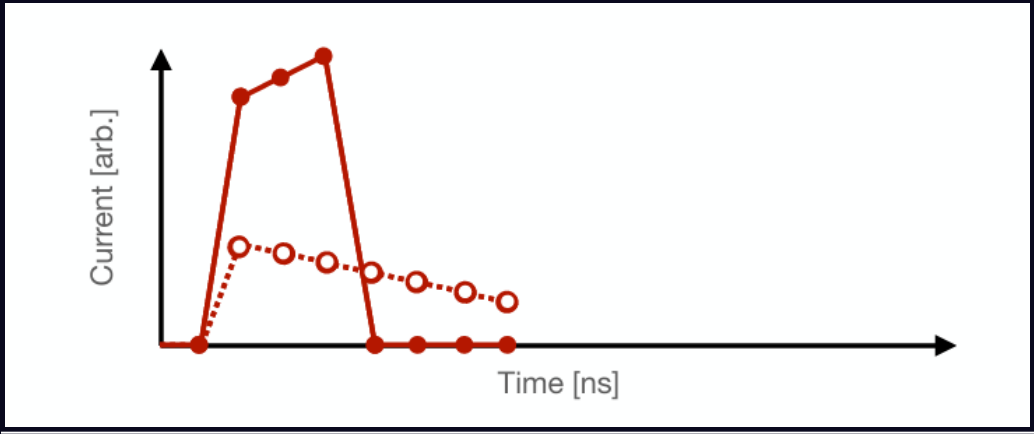


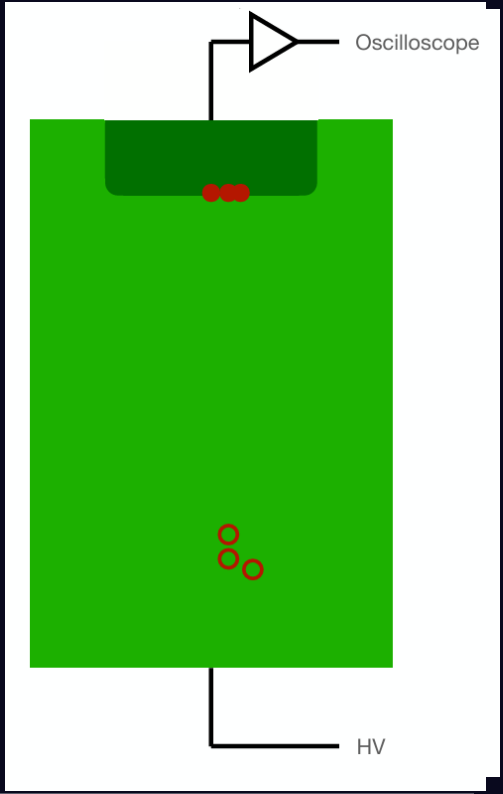


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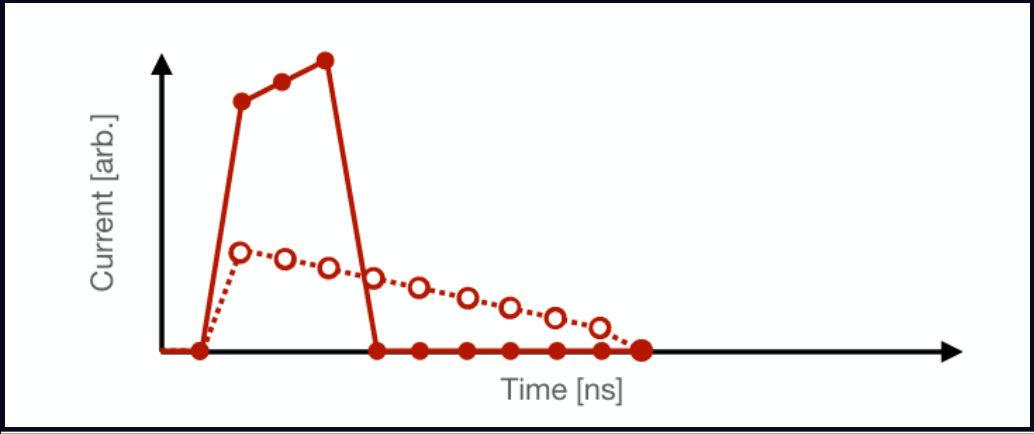


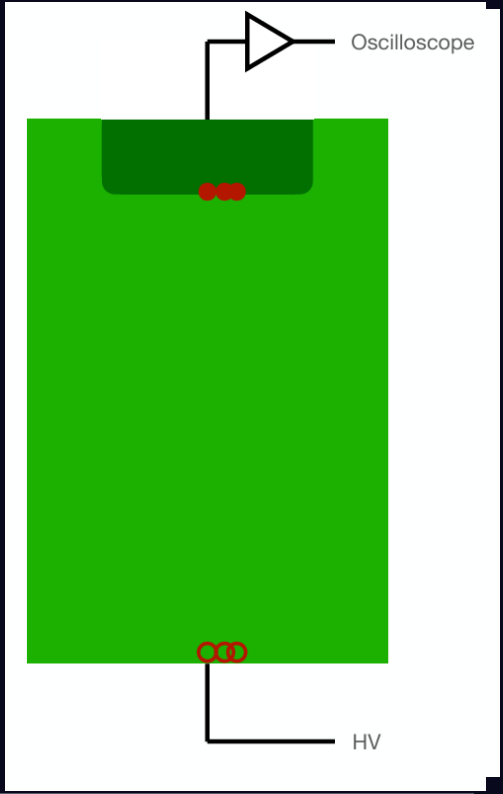


Diagrams by Daniel Hynds

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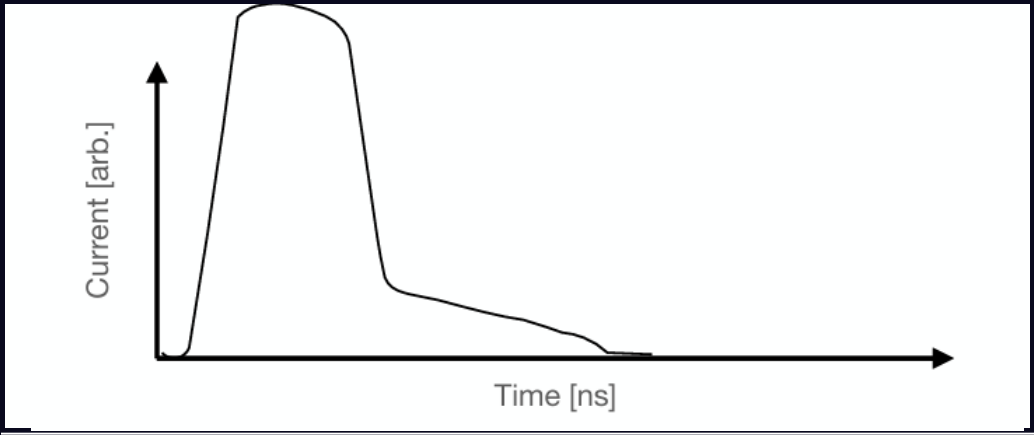


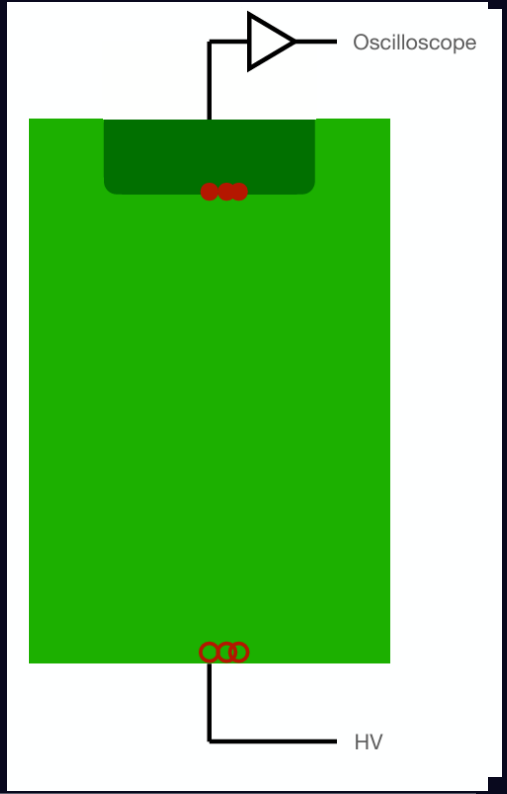
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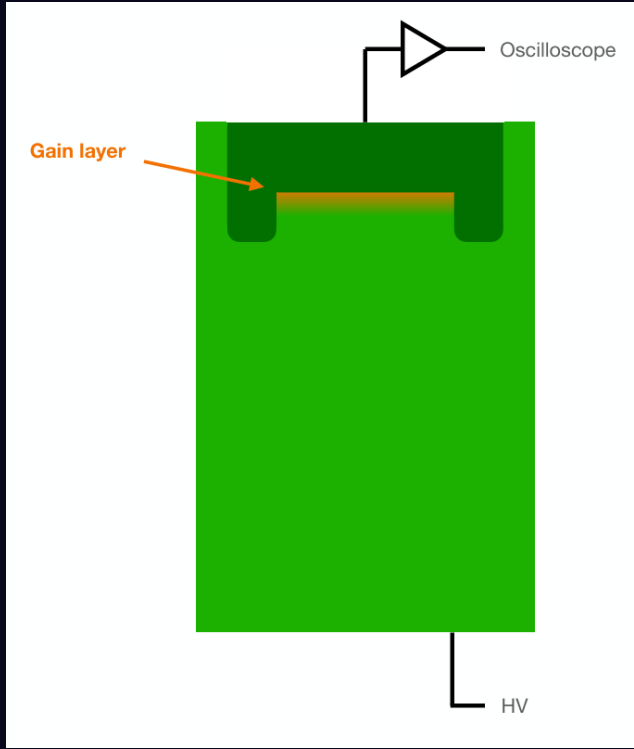




Diagrams by Daniel Hynds

Transient Current Technique

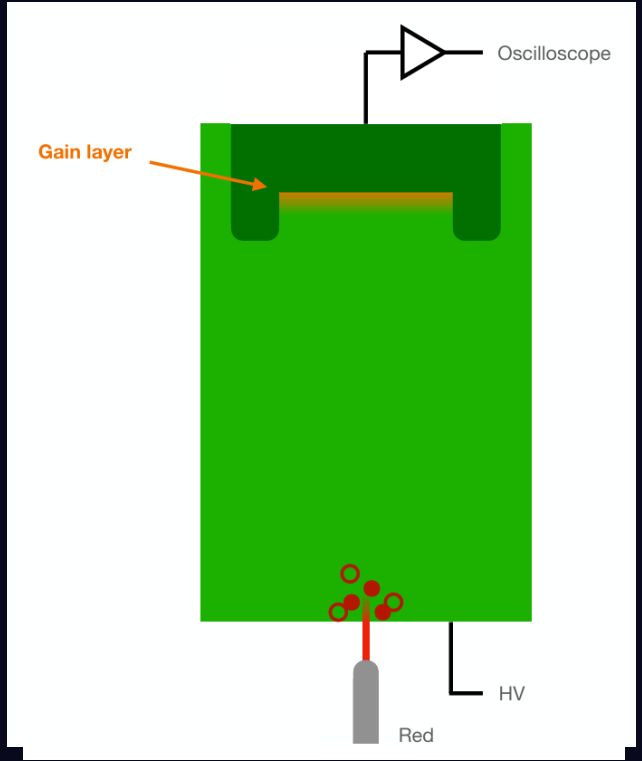
- Take an LGAD at full depletion



Diagrams by Daniel Hynds

Transient Current Technique

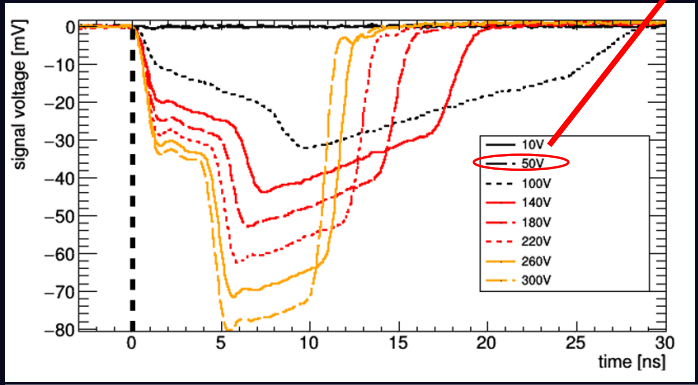
- Take an LGAD at full depletion
- Illuminated from the backside with shallow penetrating laser wavelength (red 660nm)

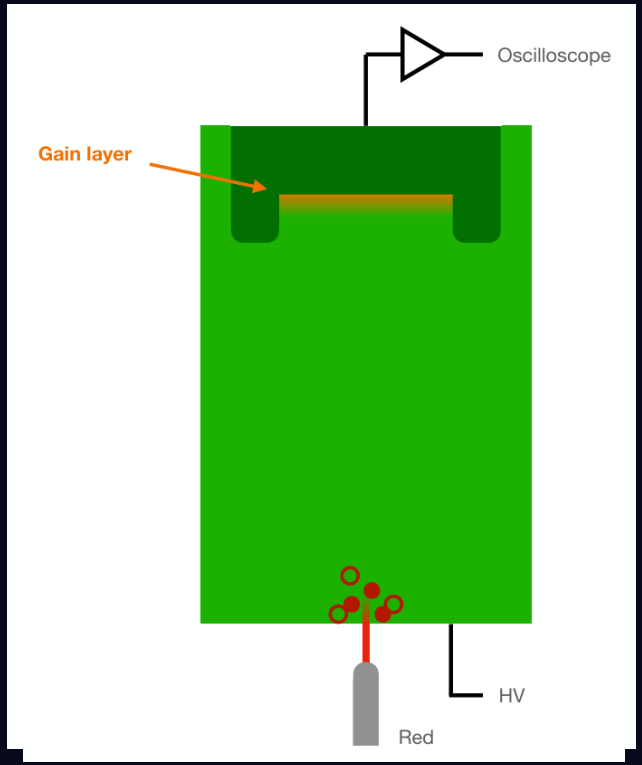


Diagrams by Daniel Hynds

Transient Current Technique

- Take an LGAD at full depletion
- Illuminated from the backside with shallow penetrating laser wavelength (red 660nm)
- Can identify V_{FD} ,



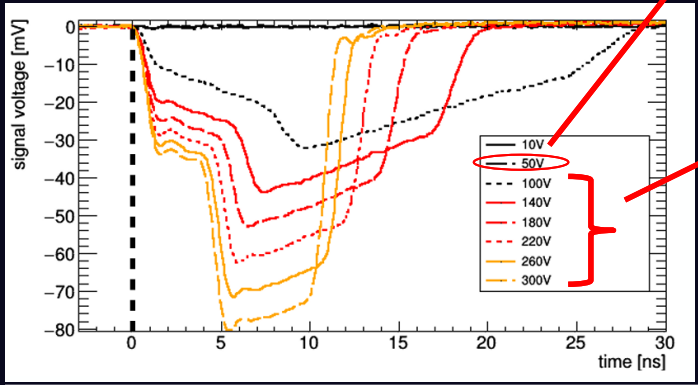


Diagrams by Daniel Hynds

Transient Current Technique

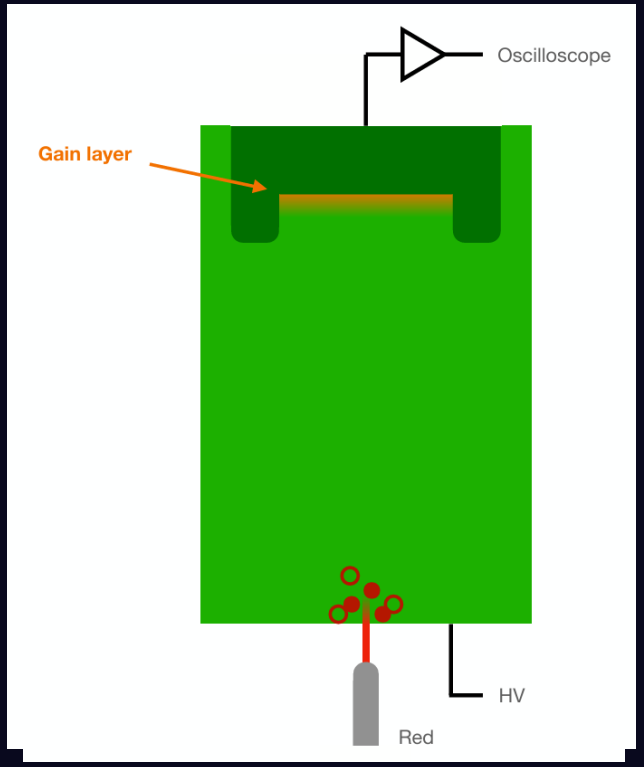
- Take an LGAD at full depletion
- Illuminated from the backside with shallow penetrating laser wavelength (red 660nm)

- Can identify V_{FD} , optimal running voltage, and drift velocities



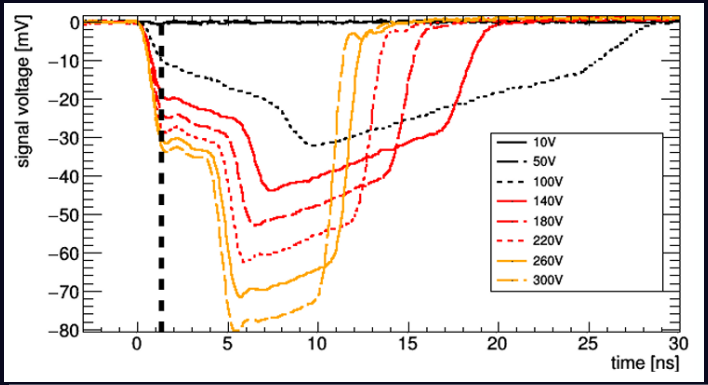
V_{FD}

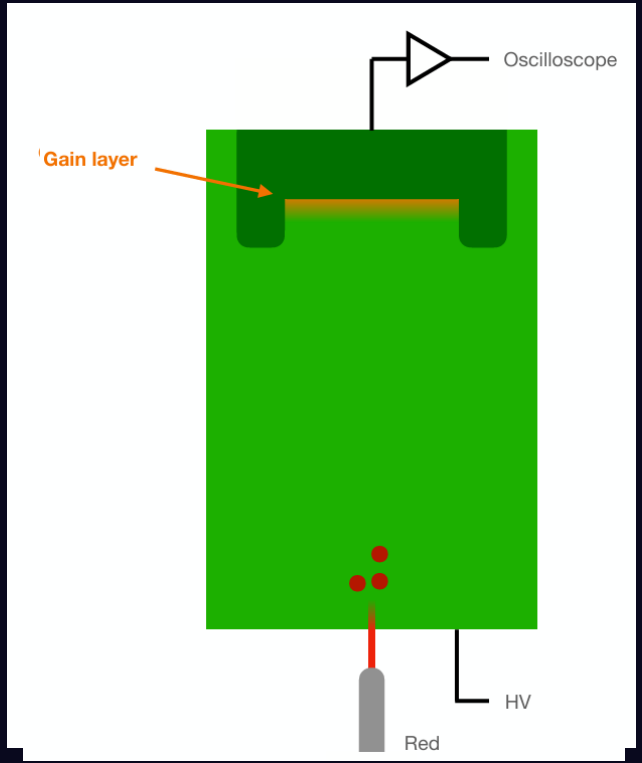
V_{Opt}?



Transient Current Technique

- Holes are collected immediately



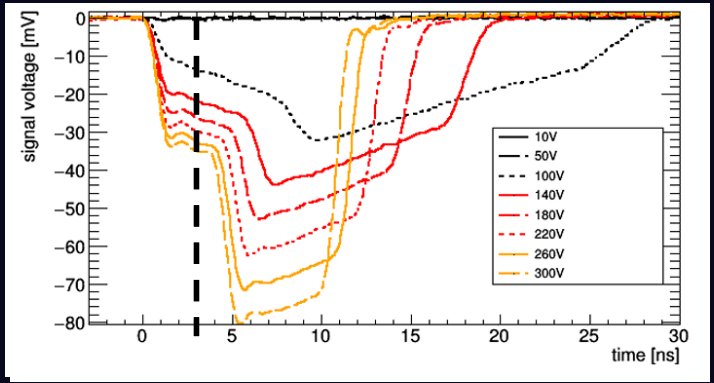


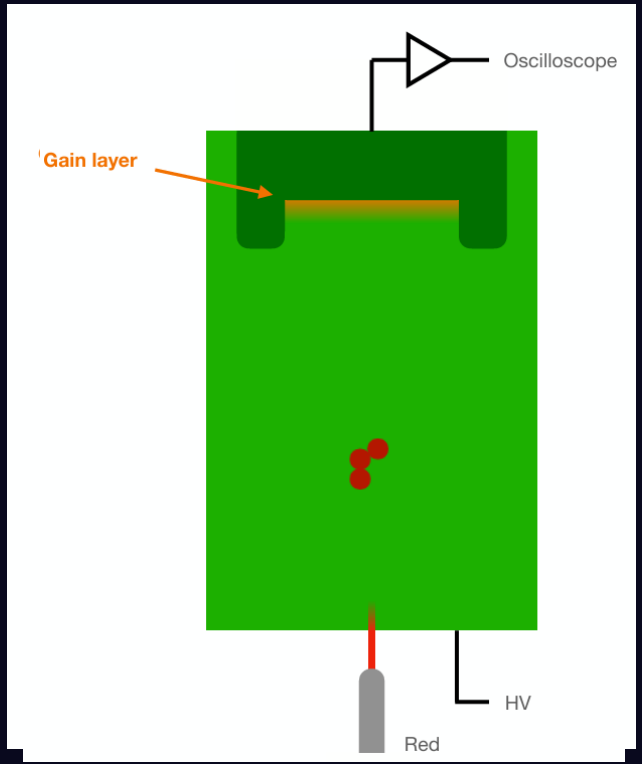
Diagrams by Daniel Hynds

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Transient Current Technique

- Holes are collected immediately
- Electrons drift towards gain layer

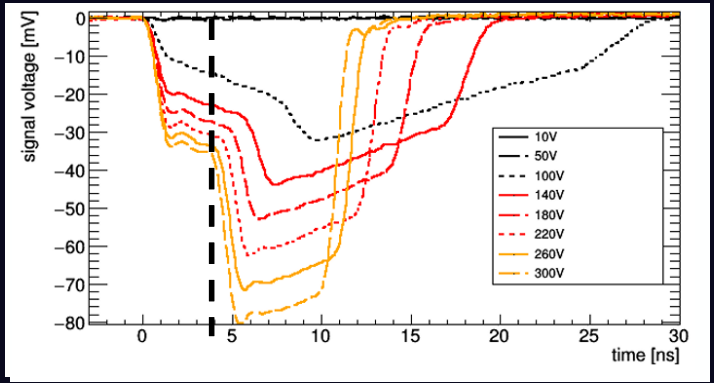


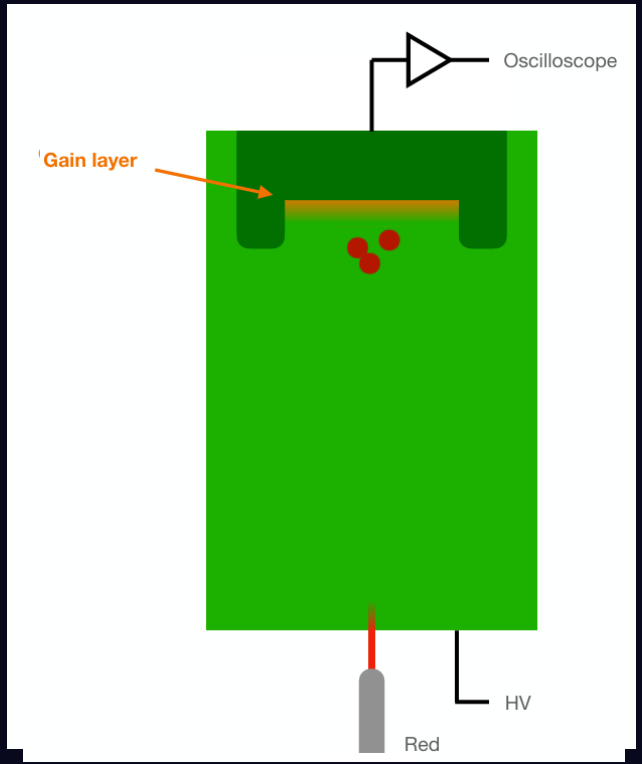


Diagrams by Daniel Hynds

Transient Current Technique

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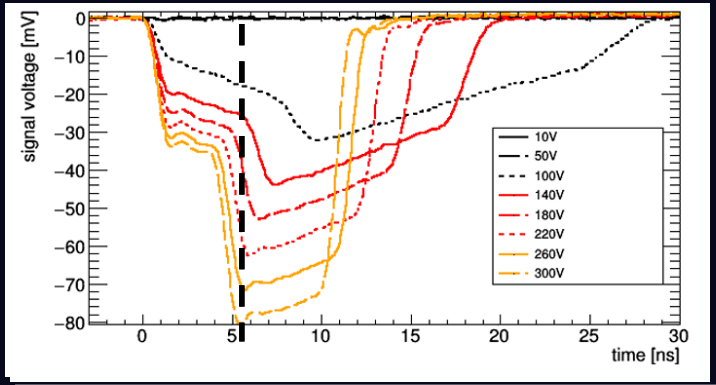


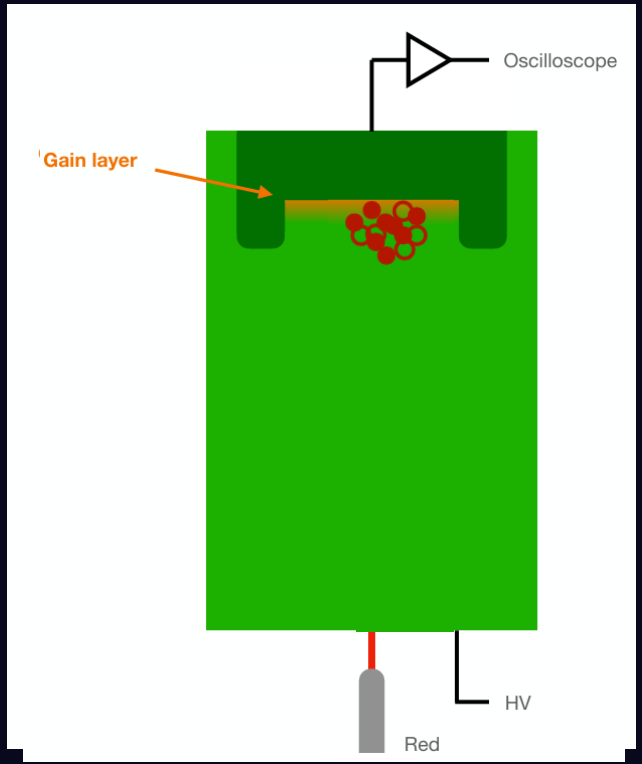
Diagrams by Daniel Hynds

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Transient Current Technique

- Holes are collected immediately
- Electrons drift towards gain layer
- Avalanche occurs at gain layer and electrons are collected



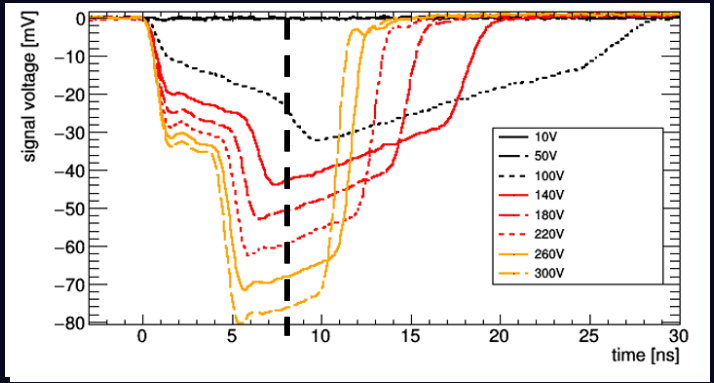


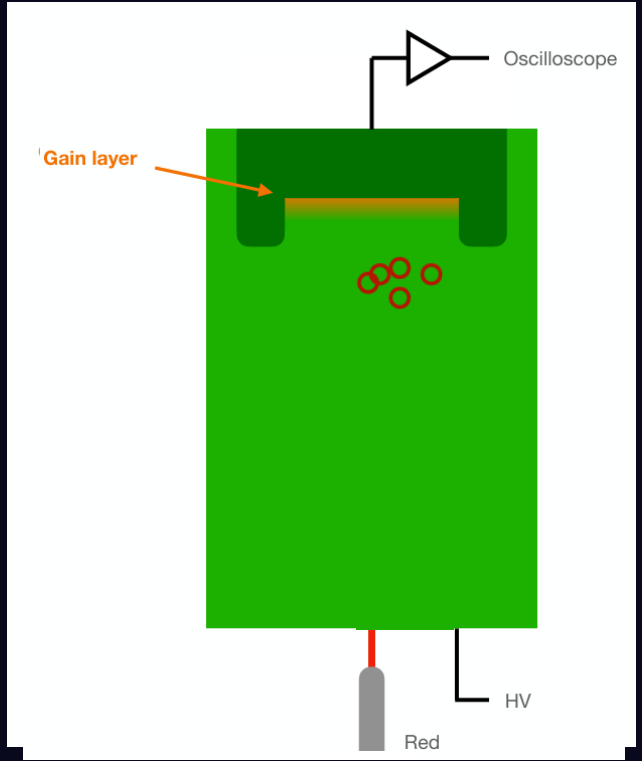
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- Holes drift to back contact





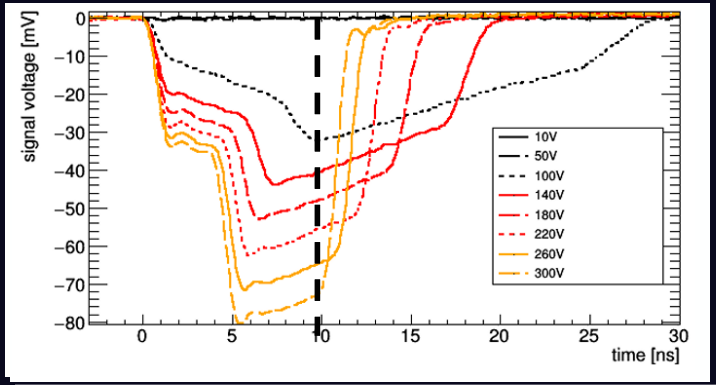
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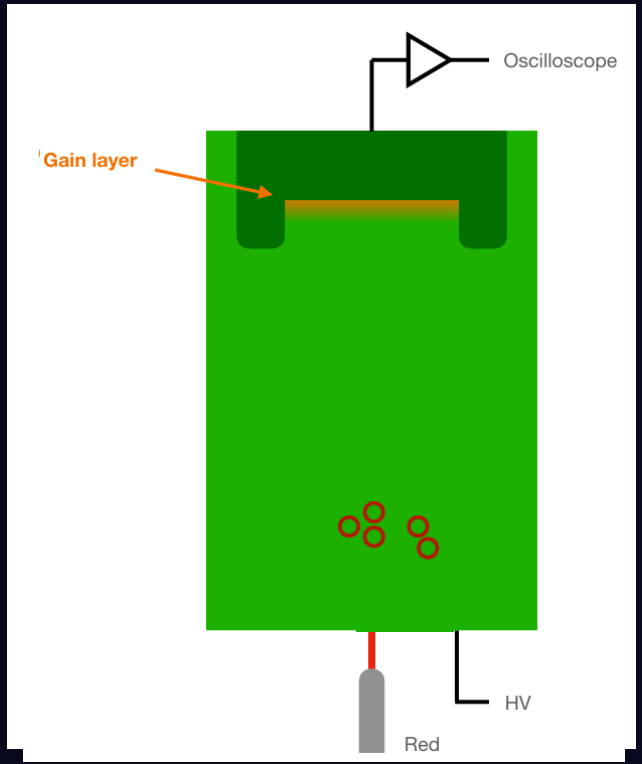
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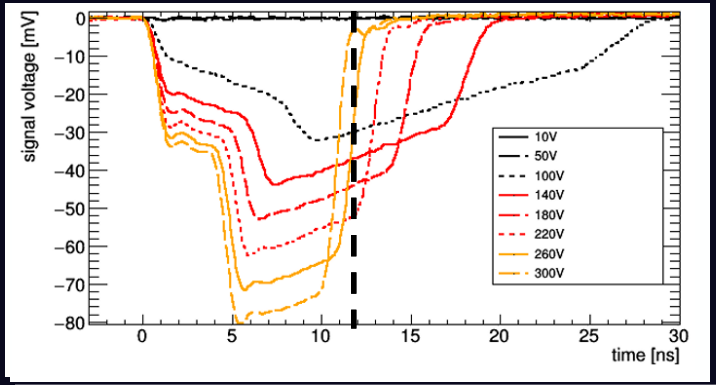
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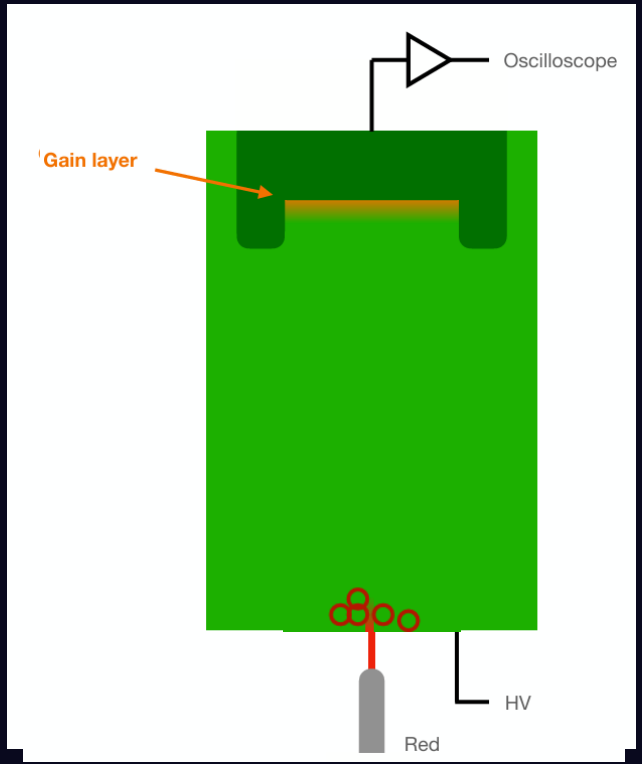
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- Holes are collected immediately
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- Avalanche occurs at gain layer and electrons are collected

- Holes drift to back contact
- Holes are collected on back contact





Diagrams by Daniel Hynds

Our Lab -TCT Setup (External)

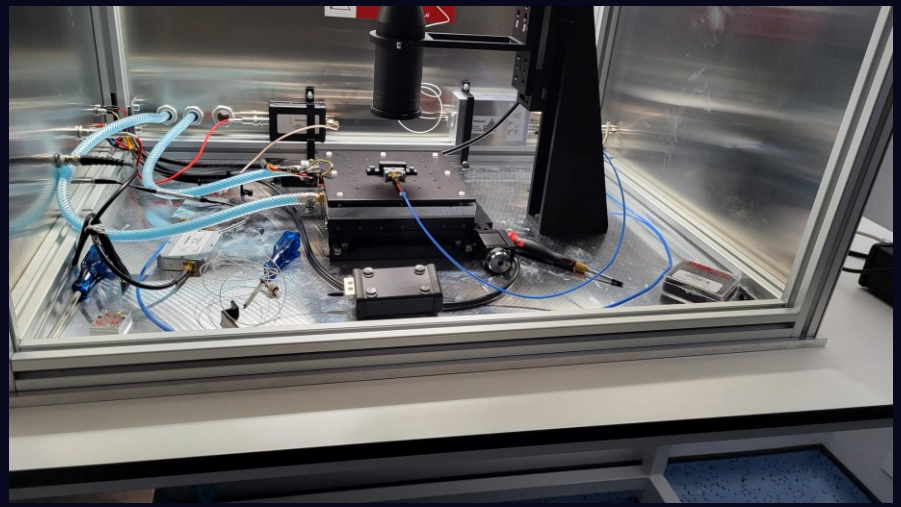




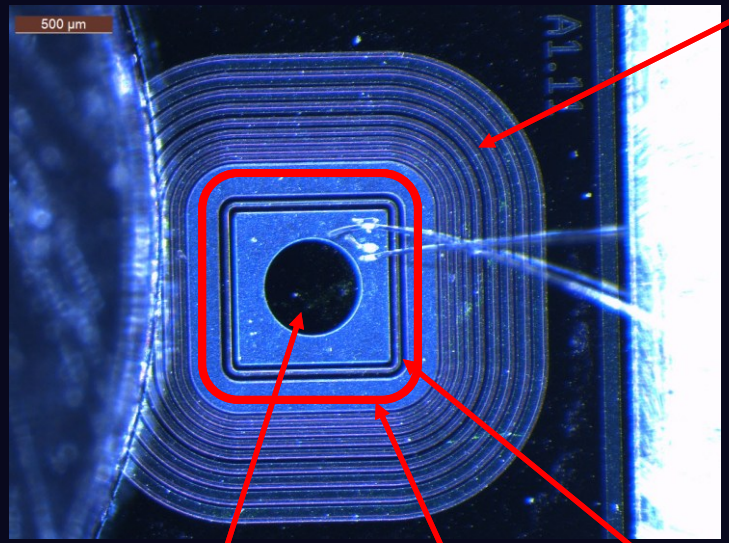
- Tektronix MDO4104C Oscilloscope (1GHz, 5GS/s
- Keithley 2470 (1100V max, 10fA resolution) DUT Bias GPIB controlled, but need Particulars to write driver
- TTi QL355TP 15V 5A max PS Amplifier pwr and Peltier pwr (only up to 75W/120W) Beckman Industrial Battery Powered Multimeter for PT100 resistance measurements (used with PT100 R v.s. T chart)
- Huber Mini Chiller 600 (40C to -20C)
- Particulars TCT Setup

Our Lab -TCT Setup (Internal)

- Translation stage
- IR (1064 nm) laser usb controlled-pulsed
- Red (660 nm) laser usb controlled (used also for alignment)
- Antifreeze/DI Water 50/50 mixture in tubes (maybe need to isolate with waterproof foam or something)
- Open slot for dry air input



LGAD A 1.11 from Micron Wafer



Guard Rings

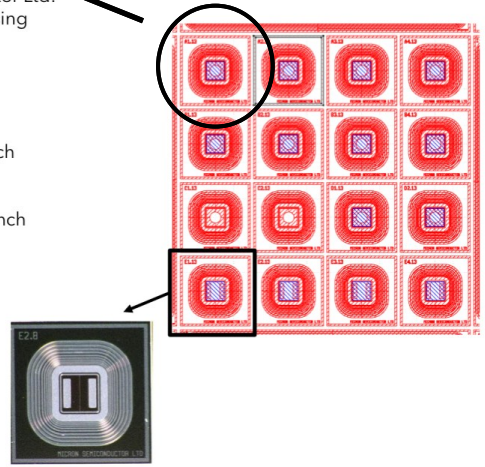
Opening in metal and oxide for illumination

Active area

Trench

Run-3455 produced by Micron Semiconductor Ltd:

- Wafer production based on increasing gain layer doping
- Active thickness = 250µm
- Pad area = 1x1 mm^2
- Devices:
  - A: 1x1 LGADs with JTE
  - B: 1x1 LGADs with JTE + Trench
  - C: 1x1 PIN (no gain)
  - D: 1x1 LGADs with Trench
  - E: 1x2 Pixels, isolated with Trench
- Medipix Arrays:
  - 55 µm pitch
  - 110 µm pitch



2D integrated charge scan of LGAD surface
Front-side illumination 1064 nm

Settings

HVPS: 135V (reverse bias)

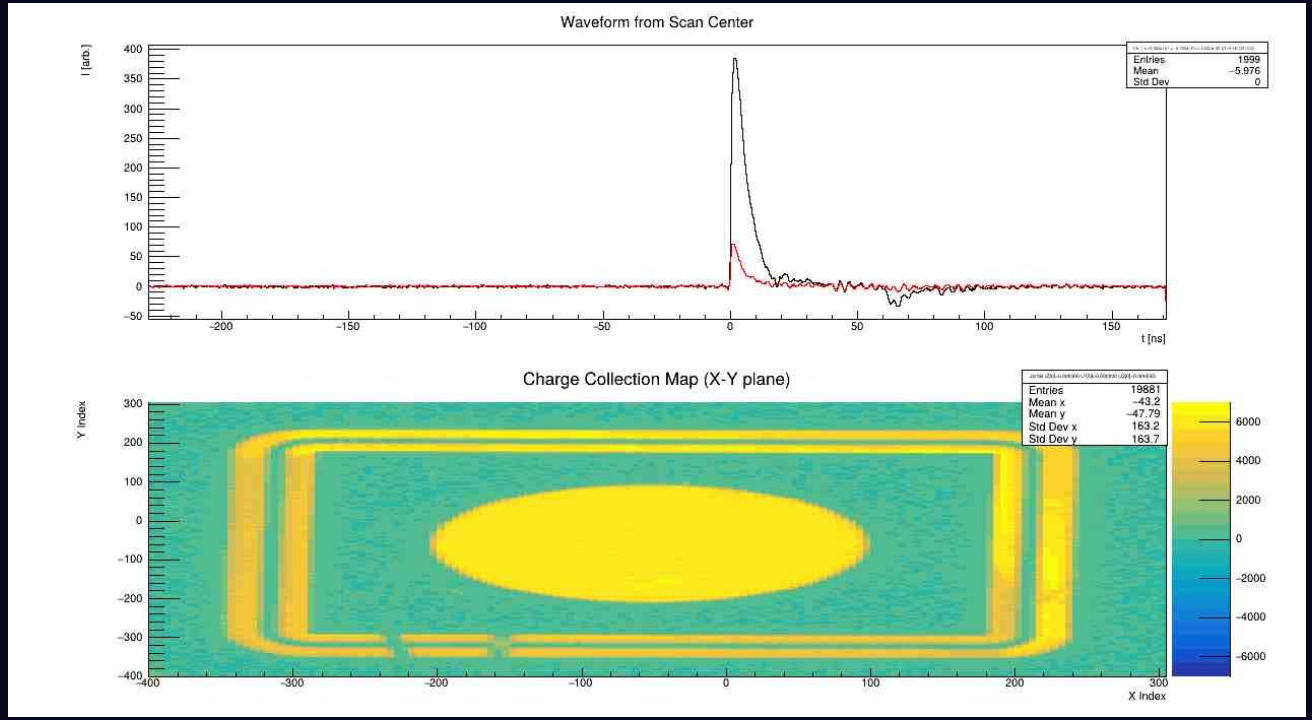
Oscilloscope:
Acquire mode:: average 64 waveforms
record length: 1000 points
Fast Aqu: OFF
CH1: Amplifier output
CH2: Trigger from laser output

Amplifier PS:
15 V/.189 A
Peltier PS
15V/5A
PT100 Multimeter: ON

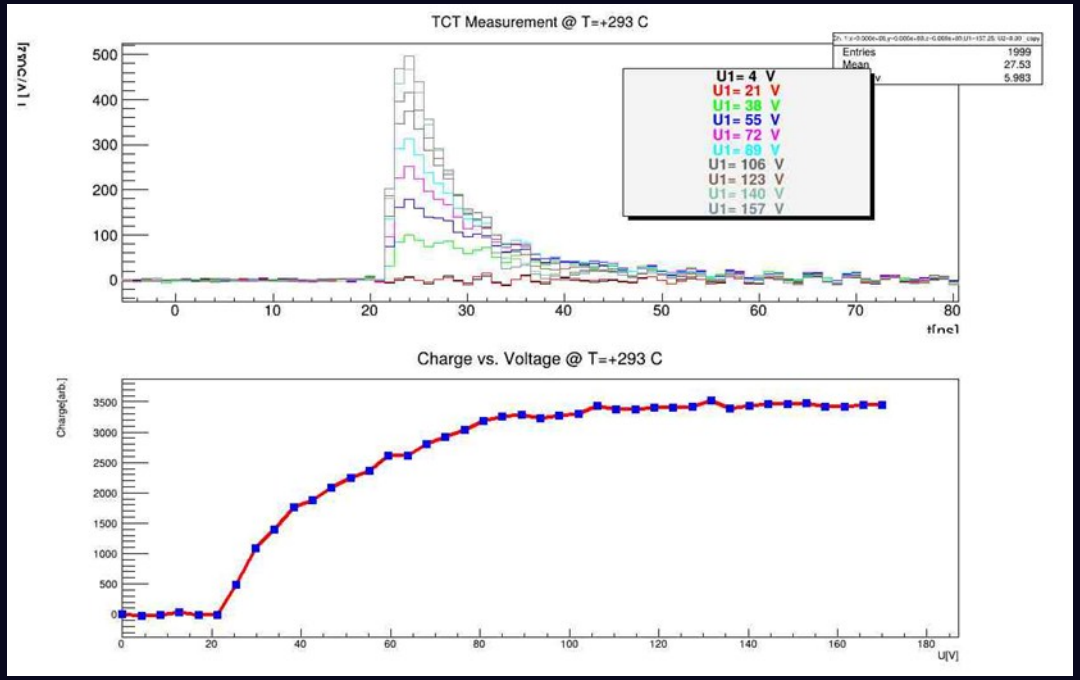
Laser:
ON
8mm aperture

(on computer)
Laser driver control
Pulse width=84%
Pulse frequency= 1KHz

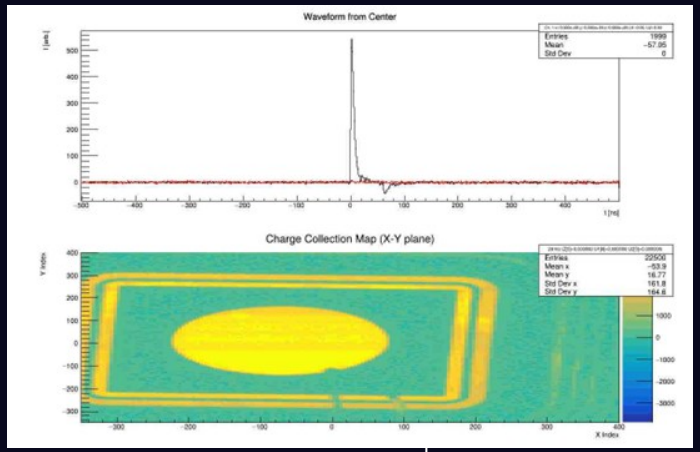
XIlab Native software:
Stages max speed 10mm/s



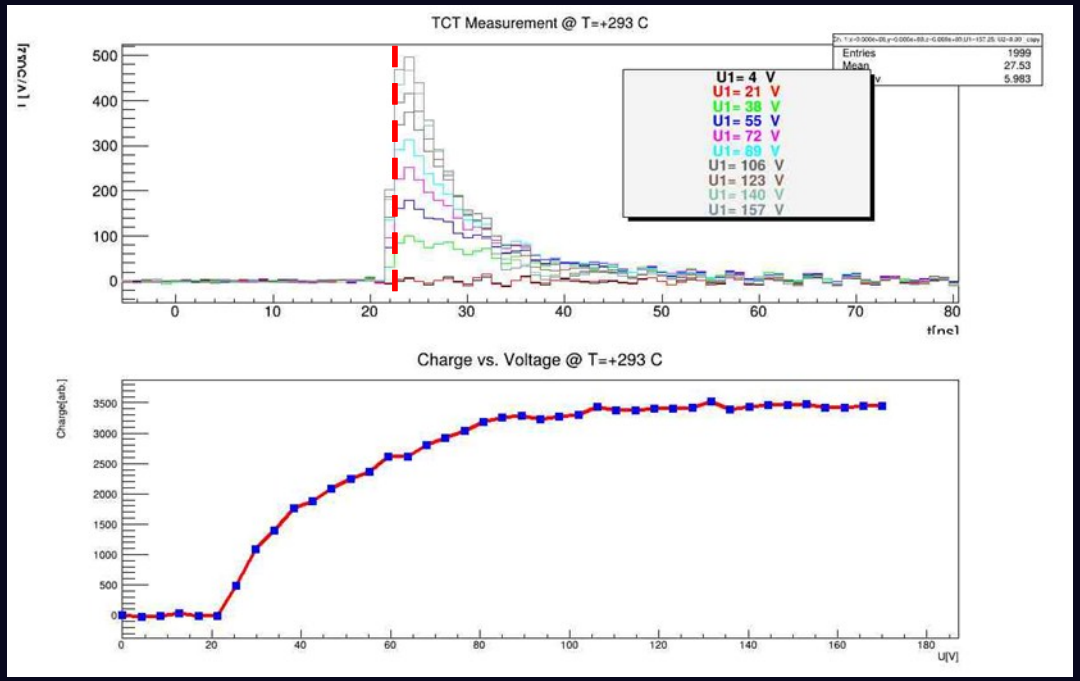
E 4.11R (Wafer 3455-6) Integrated Charge vs Bias scan
Front-side illumination 1064 nm



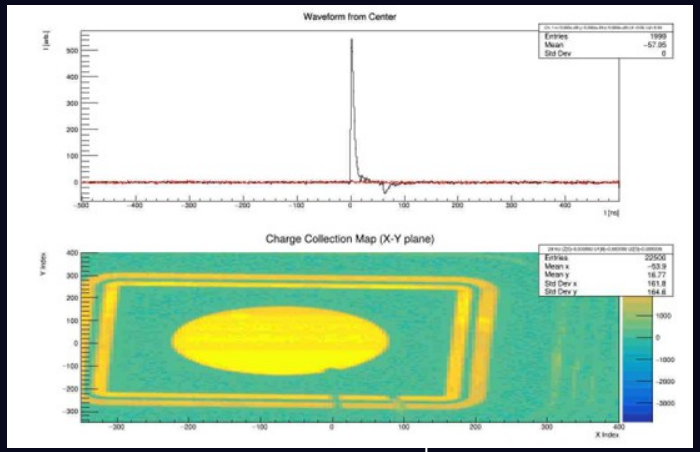
- 200 um, 1.3 E+13, no oxide cap on trench
- LGAD pixels isolated with trench



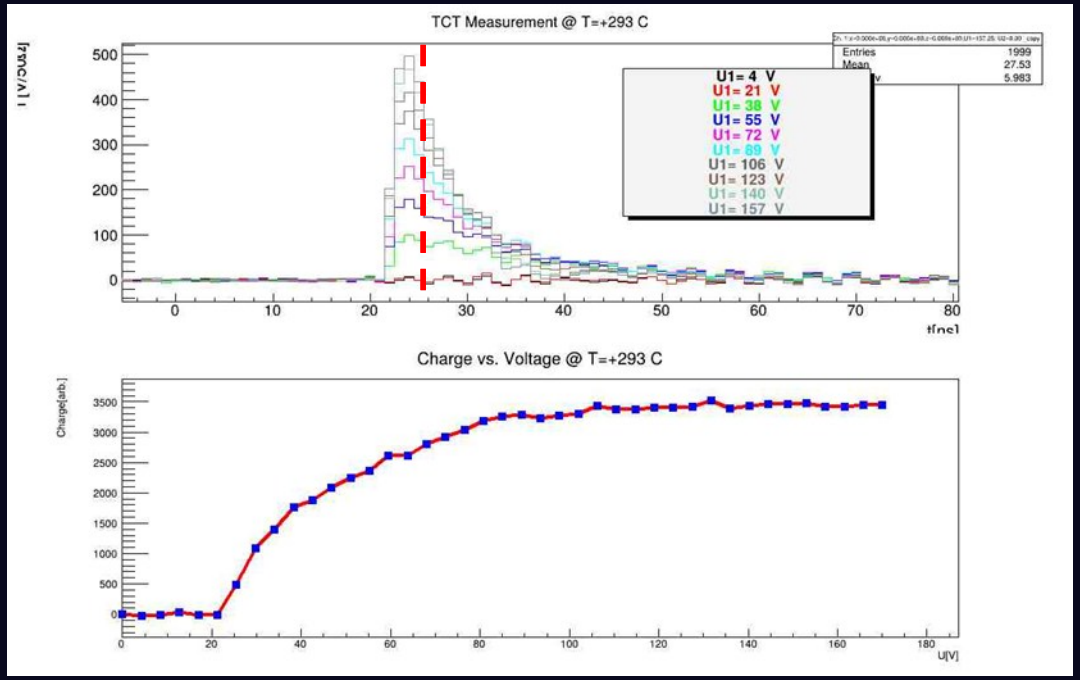
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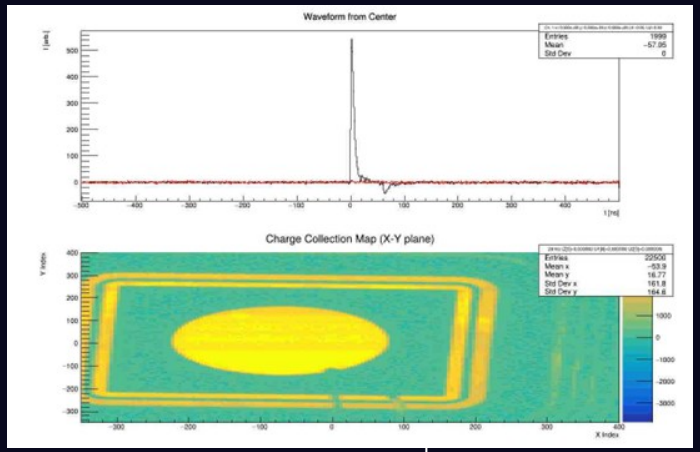
- Electrons collected



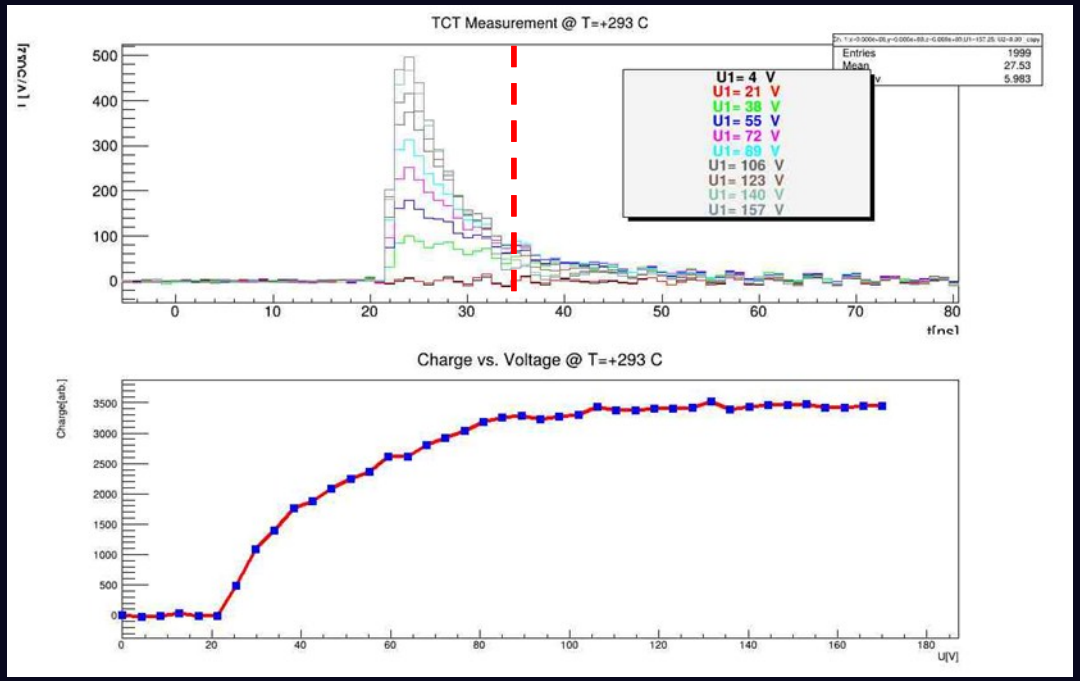
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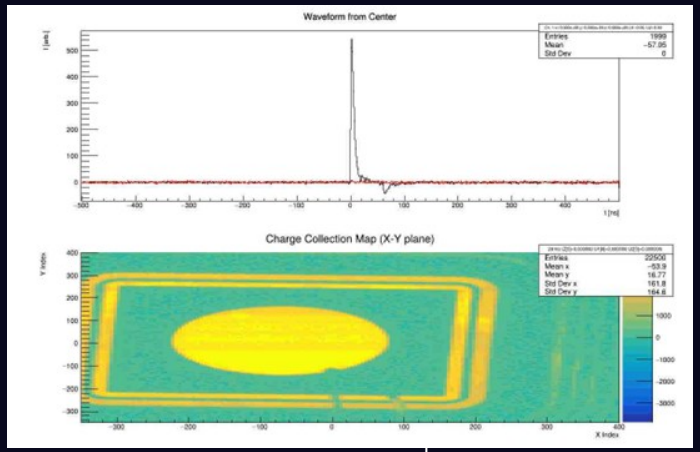
- Electrons collected
- Holes drift



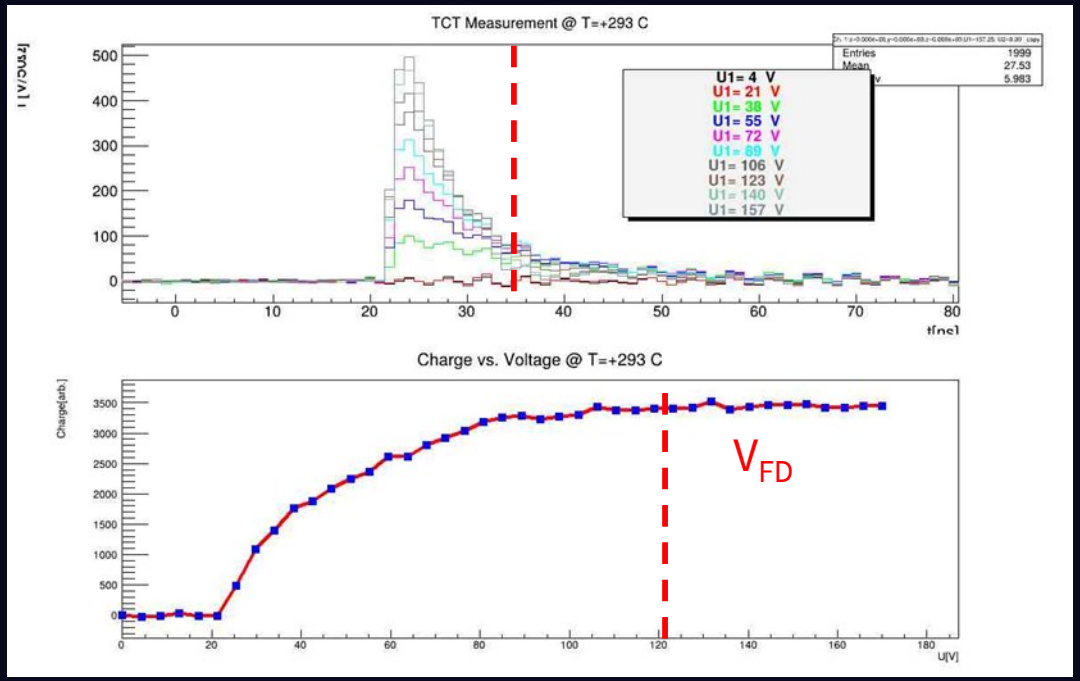
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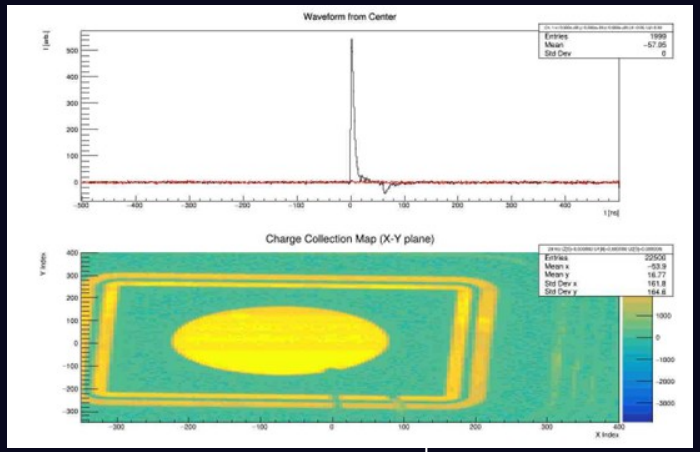
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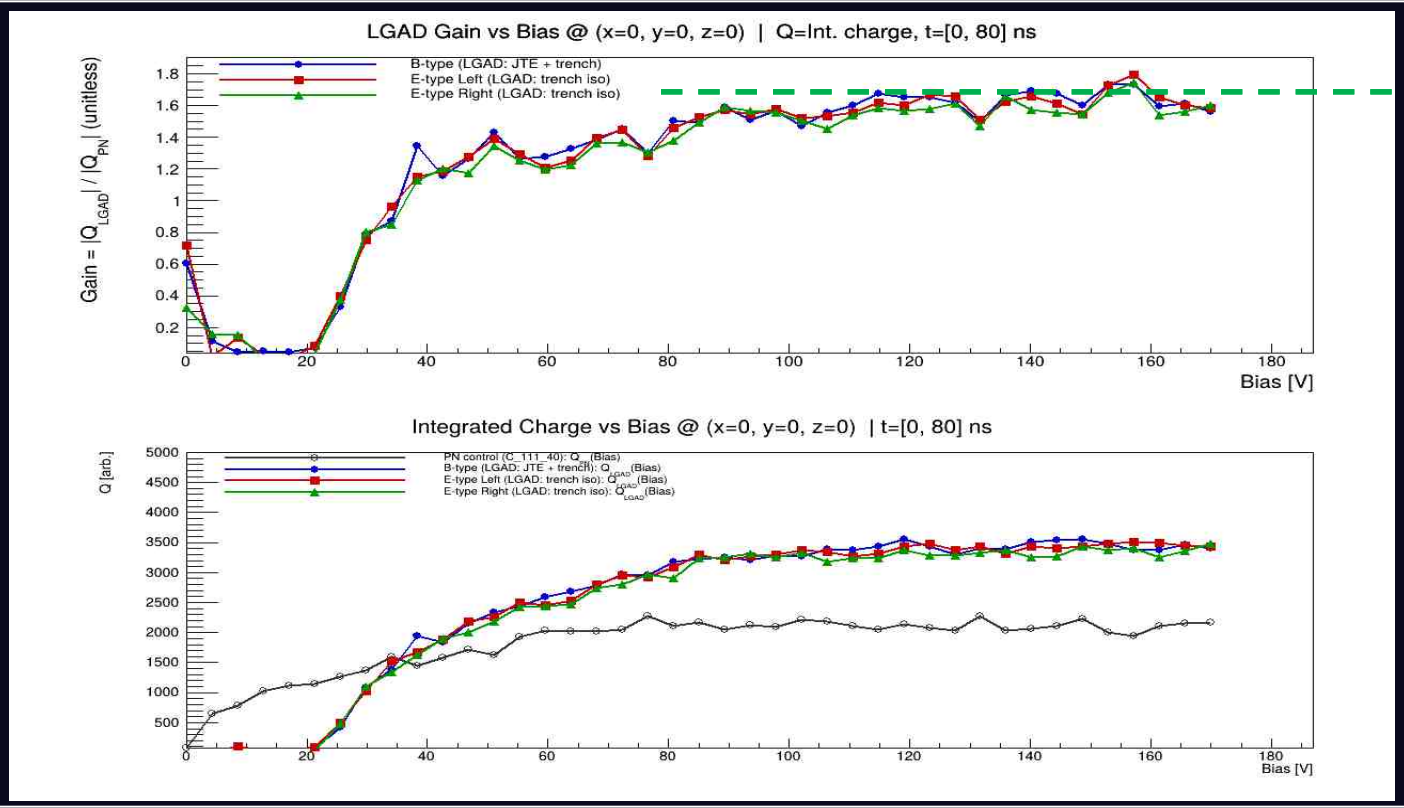
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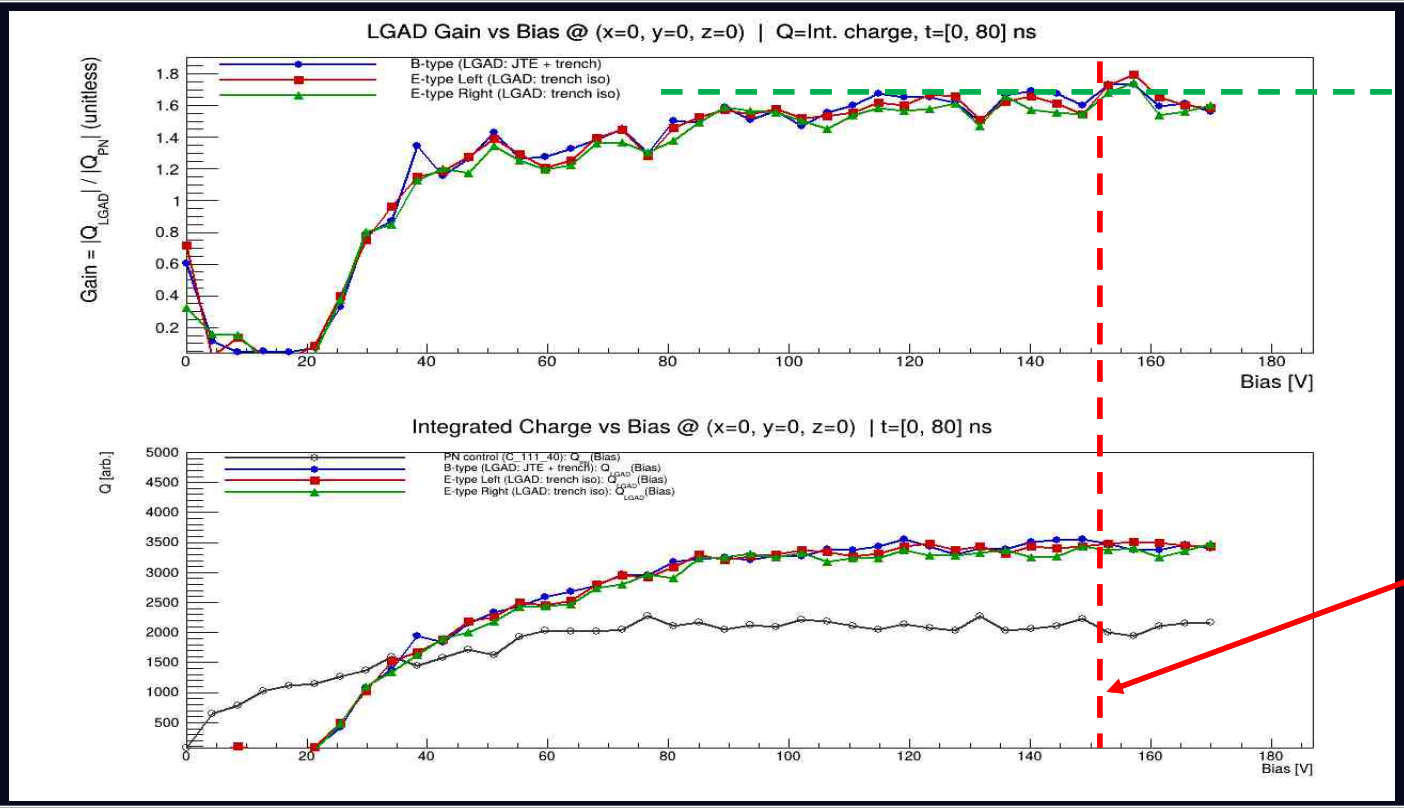


Gain of B 4.11 and E 4.11 (Wafer 3455-6 -- 200 um, 1.3 E+13, No oxide cap on trench) vs Bias



1.7x Gain

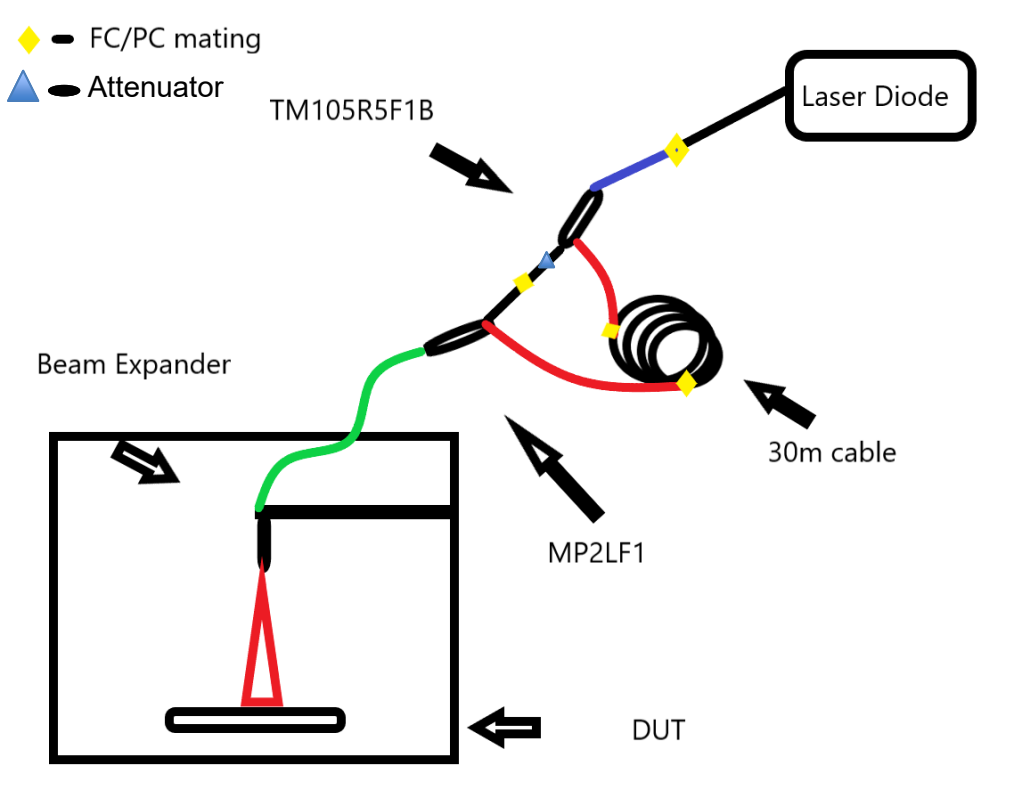
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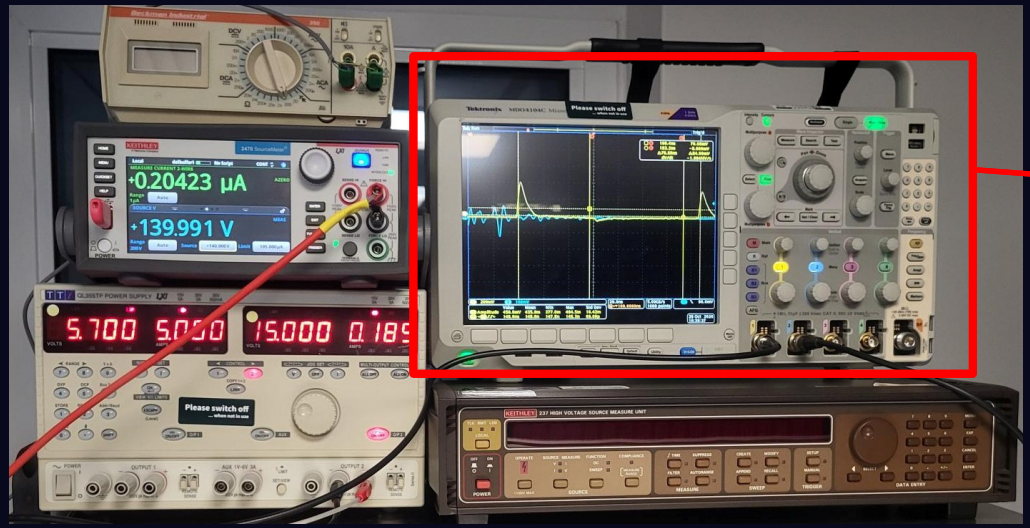
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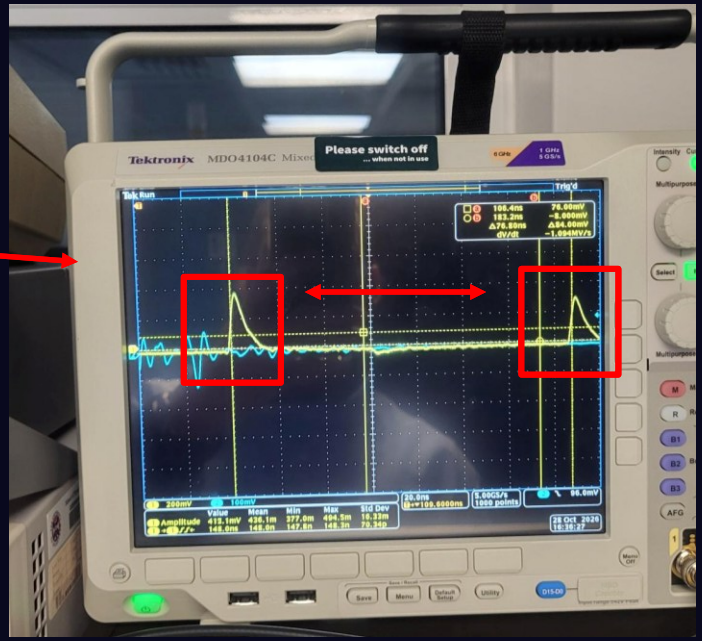
V_{Opt}

Time Resolution Measurements Setup



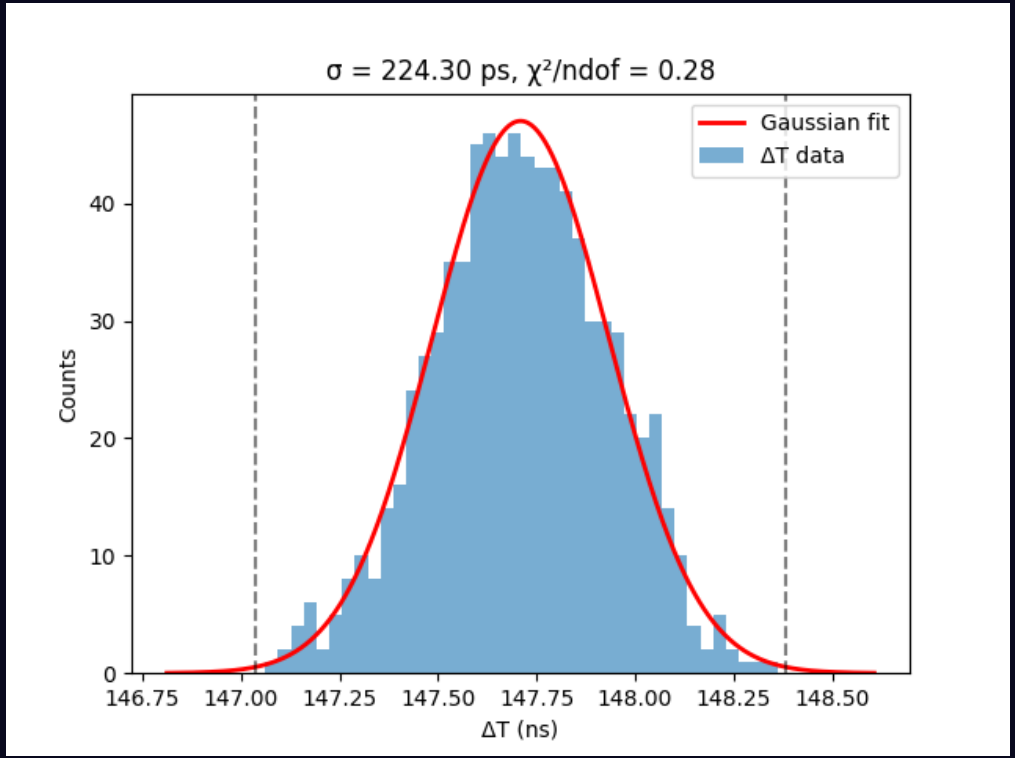
Time Resolution Measurements Setup





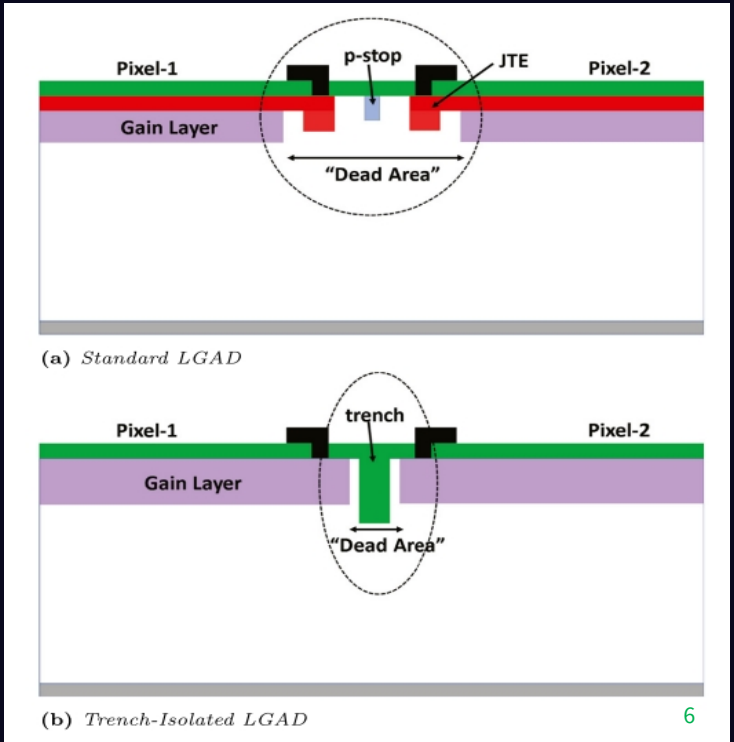
Early results – Time resolution (No calibration for optics)

- Code takes 1000 waveforms at full bandwidth
- Both pulses are attenuated to same amplitude
- CFD used for timestamp
- Delta-T plotted
- Need calibration for MM fibre



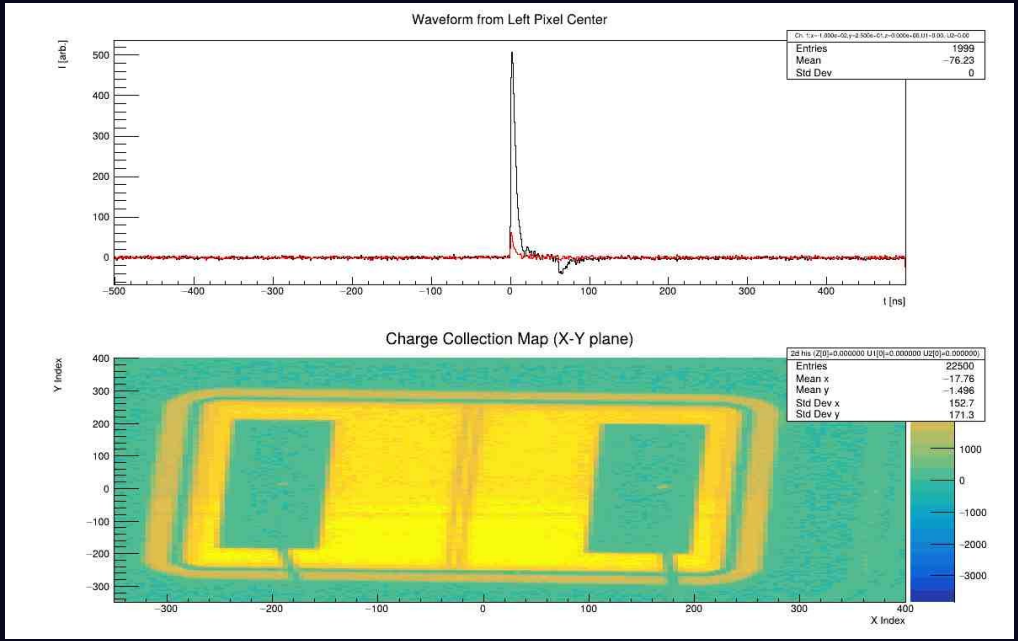
LGAD v TI-LGAD

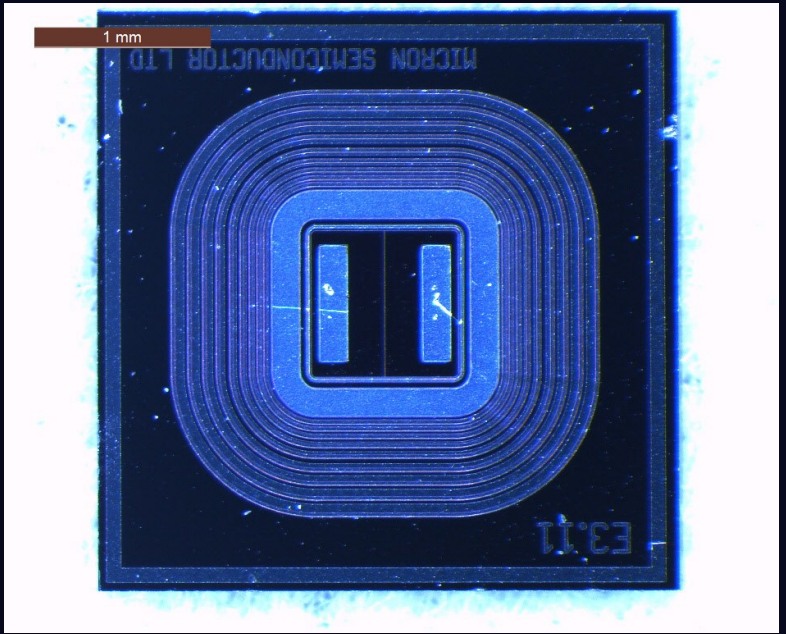
- Trench Isolation (TI) uses a physical trench to isolate pixels
- TI allows for expansion of active area (increased fill-factor)
- Decrease in interpixel distance



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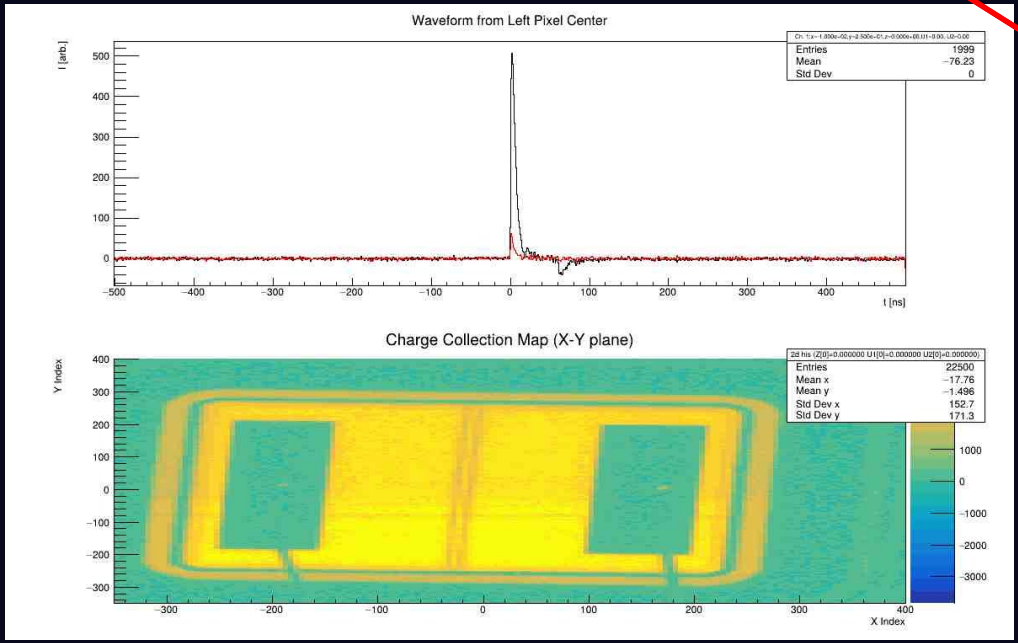
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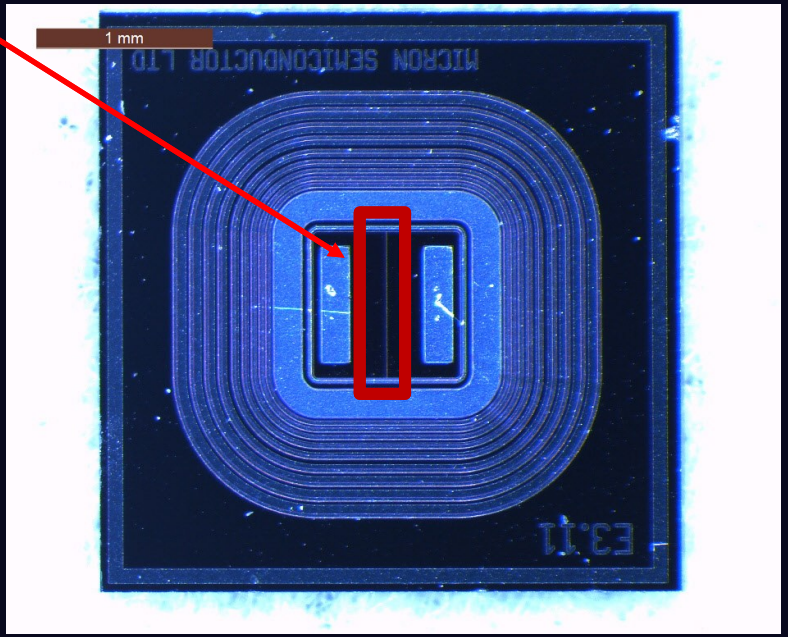




LGAD v TI-LGAD

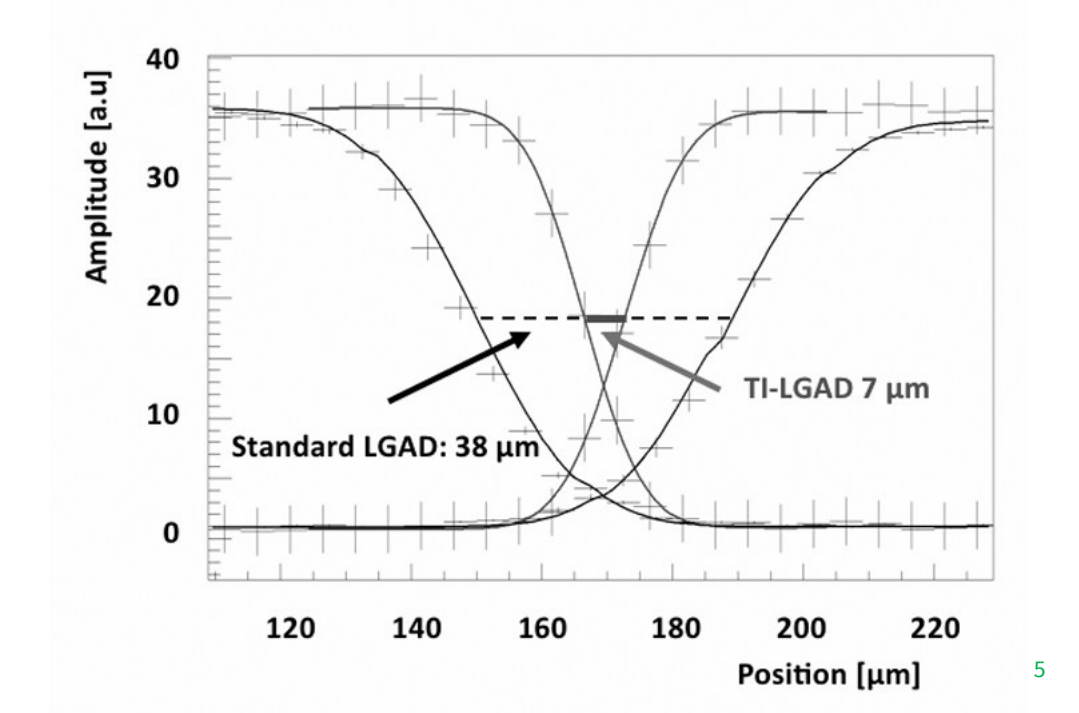
Trench





Using TCT to Test IPD

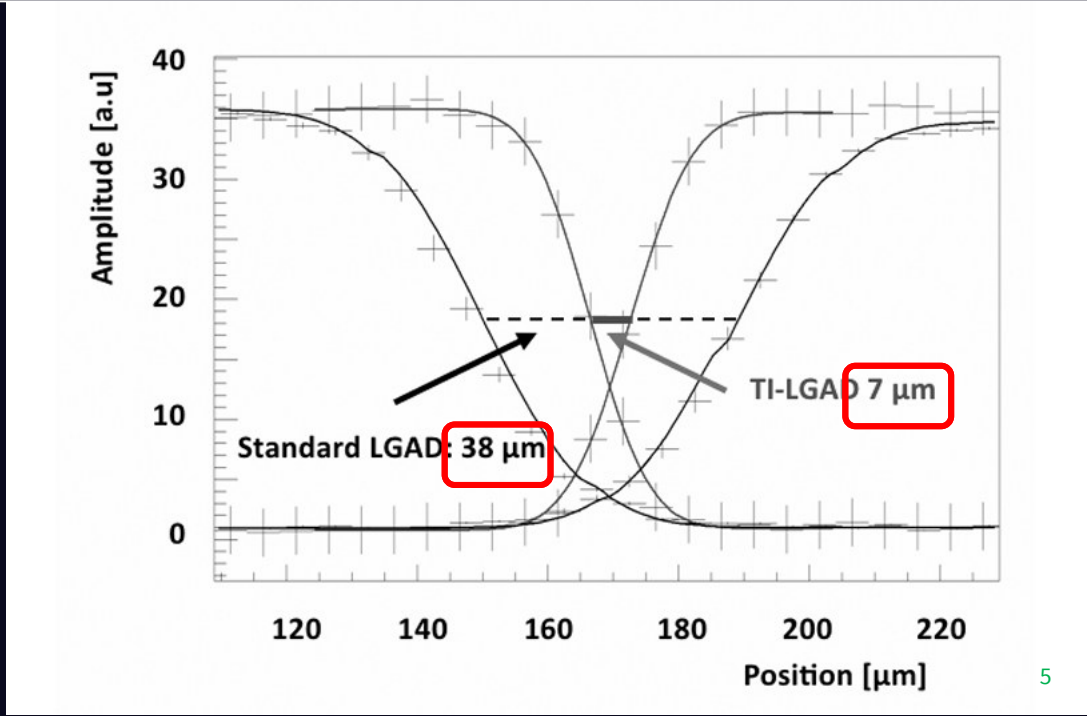
- By scanning across trench, CC profile can be obtained
- From charge collection profile inter-pixel distance (IPD) is determined



Using TCT to Test IPD

- By scanning across trench, CC profile can be obtained
- From charge collection profile inter-pixel distance (IPD) is determined
- Ideally :

$IPD_{TI\text{-}LGAD} < IPD_{LGAD}$



Next Steps!

- Increase CV range capabilities
- Calibrate TCT timing
- Measure photon injection of TCT
- Measure more devices IV/CV/TCT
- Measure IPD for Trenched Devices

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Thank you !



Lab= Happiness



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Citations

[1] https://commons.wikimedia.org/wiki/File:Pn-junction-equilibrium-graph.svg

[2] Yang, Tao, et al. “Leakage current simulations of low gain avalanche diode with improved radiation damage modeling.” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 1040, 2022, p. 167111, https://doi.org/10.1016/j.nima.2022.167111

[3] Friday, David. “Simulation of Low Gain Avalanche Detectors(LGAD) for LHCb Operation in Run 5.” University of Glasgow, 1 Apr. 2022.

[4] https://www.allaboutcircuits.com/technical-articles/understanding-i-v-curves-of-non-linear-devices/

[5] Ferrero, Marco. *An Introduction to Ultra-Fast Silicon Detectors*. CRC Press, 2021.

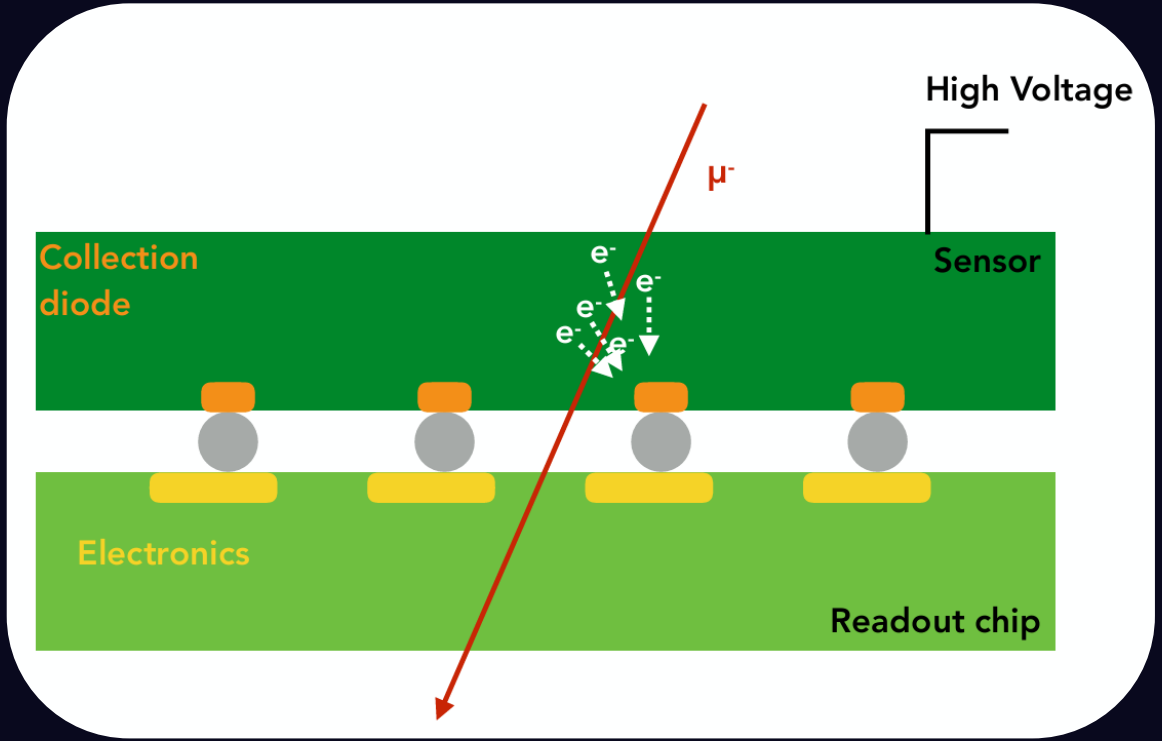
[6] Ashish Bisht and et al. Characterization of novel trench-isolated lgads for 4d tracking. Nuclear Instruments and Methods in Physics Research Section A: Accelerators,Spectrometers, Detectors and Associated Equipment, 1048:167929, 2023.

BACKUP

Silicon Detectors- Working Principle

- This is a hybrid pixel detector (readout decoupled from sensor)
- Working principle the same for all silicon detectors:

  -charge generation

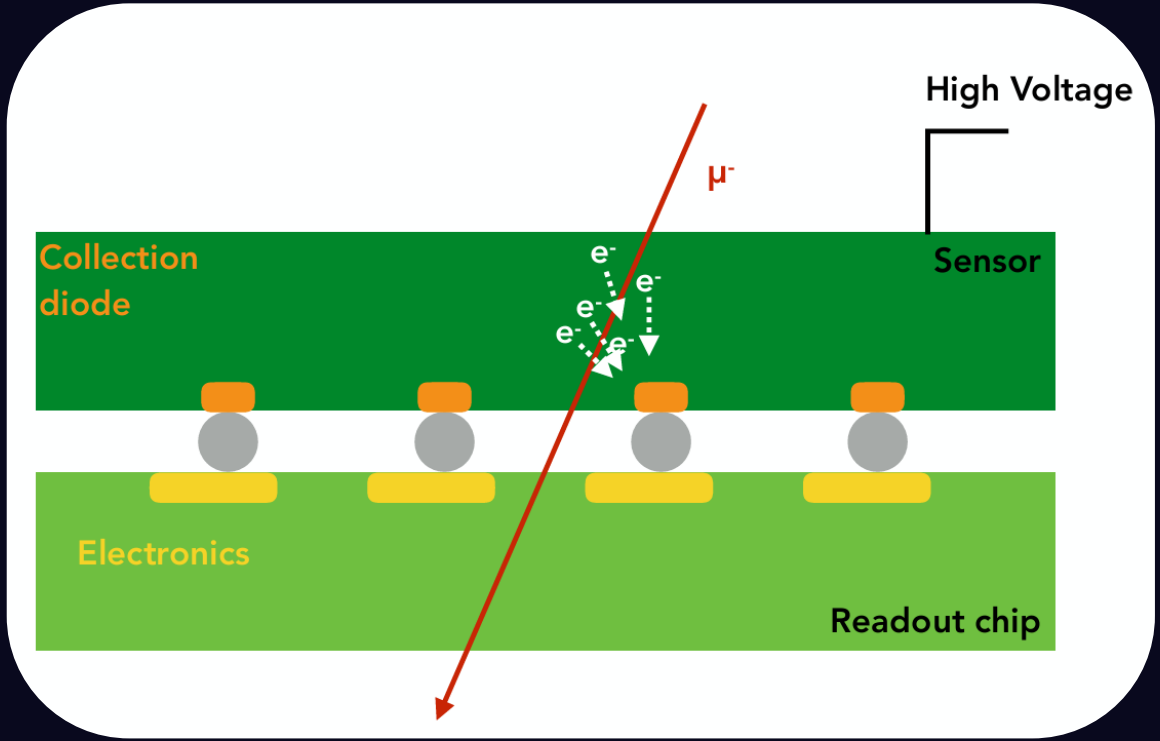


Diagrams by Daniel Hynds

Silicon Detectors- Working Principle

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  -charge movement

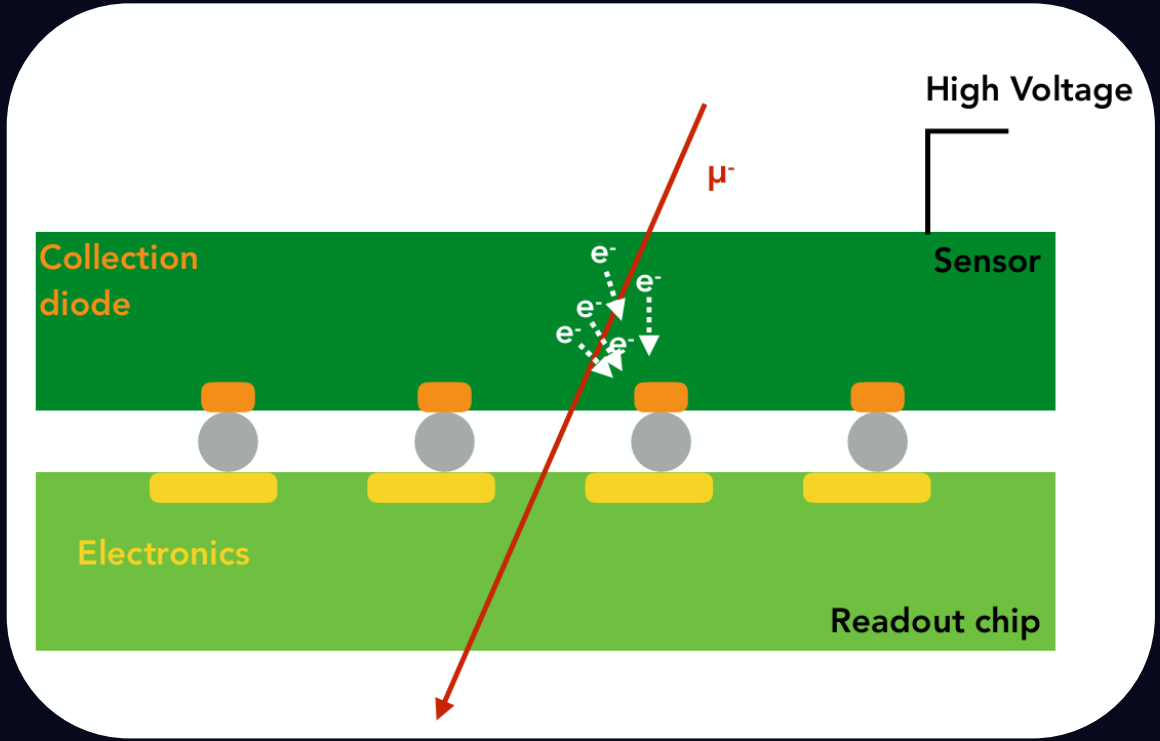


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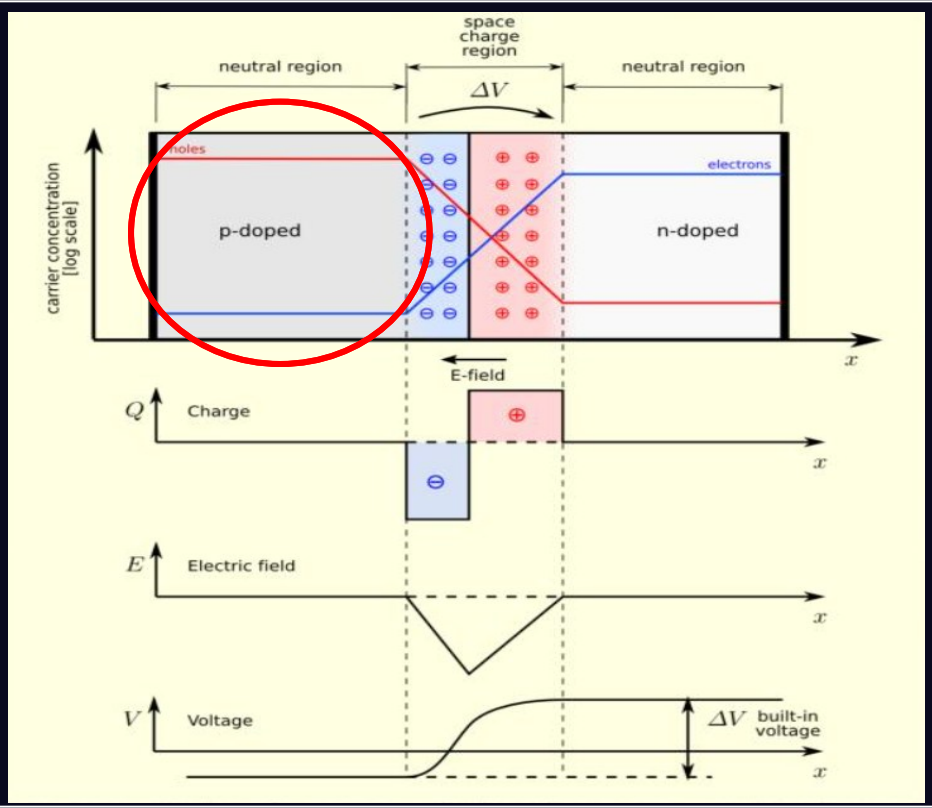
  -charge generation
  -charge movement
  -charge collection



Diagrams by Daniel Hynds

P-N Junction

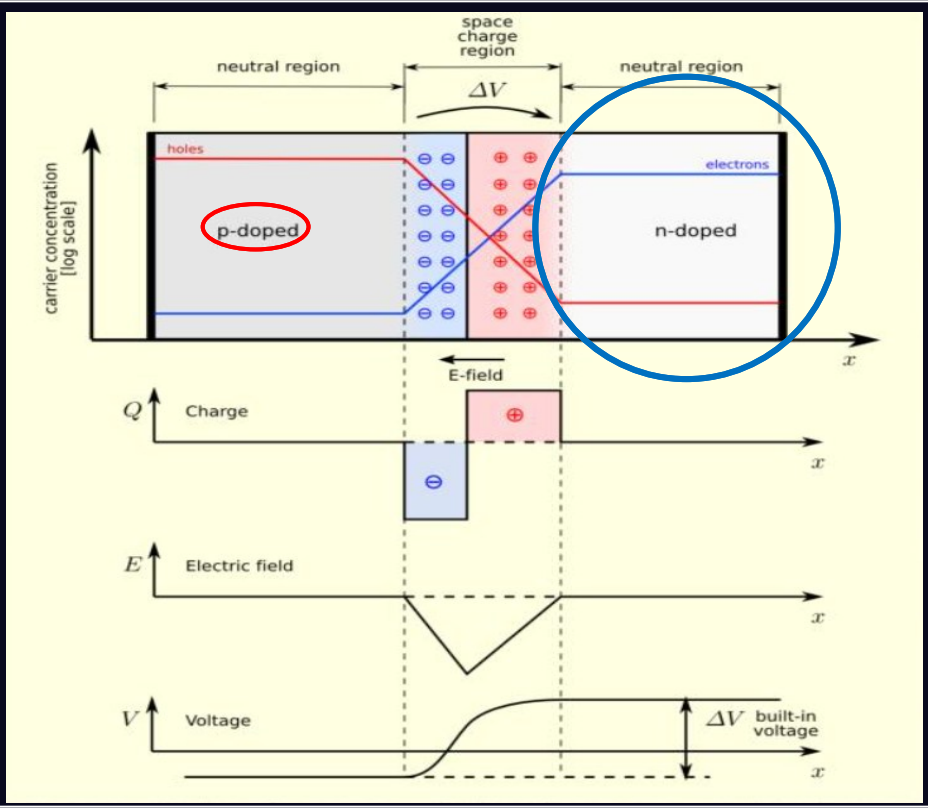
- The P-N junction is the simplest silicon detector geometry
- P-type has ‘too few electrons’



Diagrams by Wikimedia Commons [1]

P-N Junction

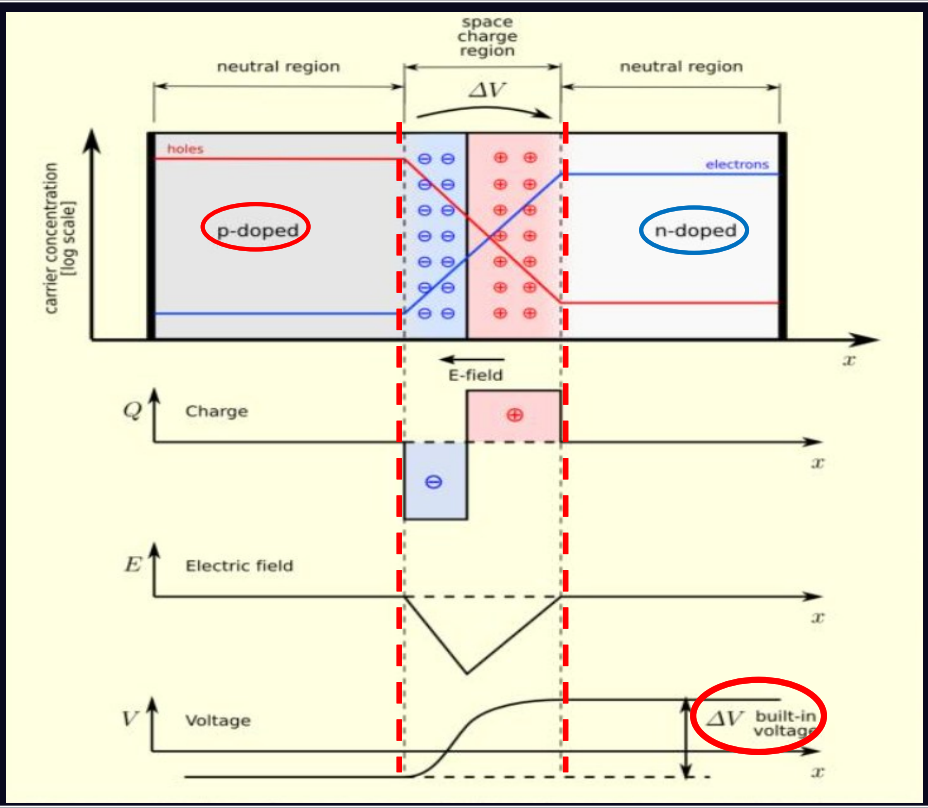
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Diagrams by Wikimedia Commons [1]

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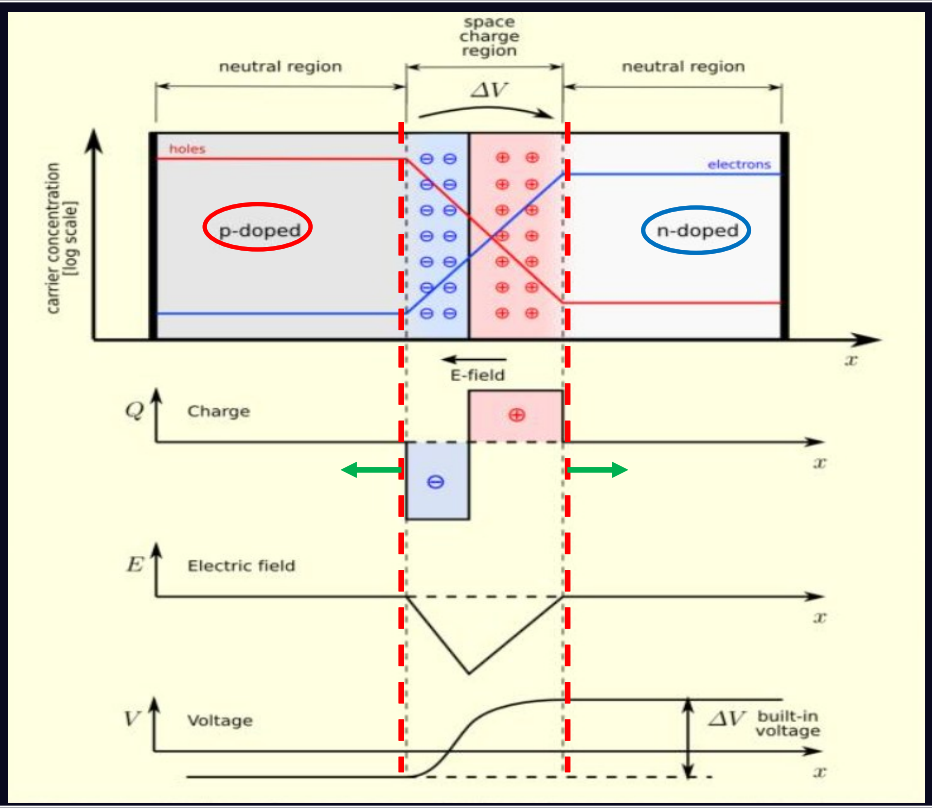
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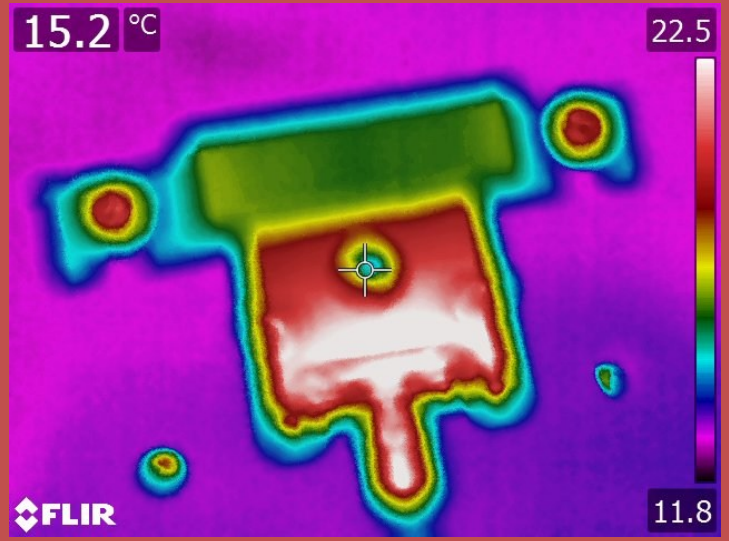
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- When a junction is created, diffusion occurs creating a built-in potential and a depletion region
- Depletion region (no charge carriers) can be extended by external bias



Diagrams by Wikimedia Commons [1]

PT100 Validation Test



PT100 reading 15C
Outside of laser/peltier on



PT100 reading 9C
Outside of laser/peltier on