Advanced UK Instrumentation Training 2024

Lab Techniques - 1

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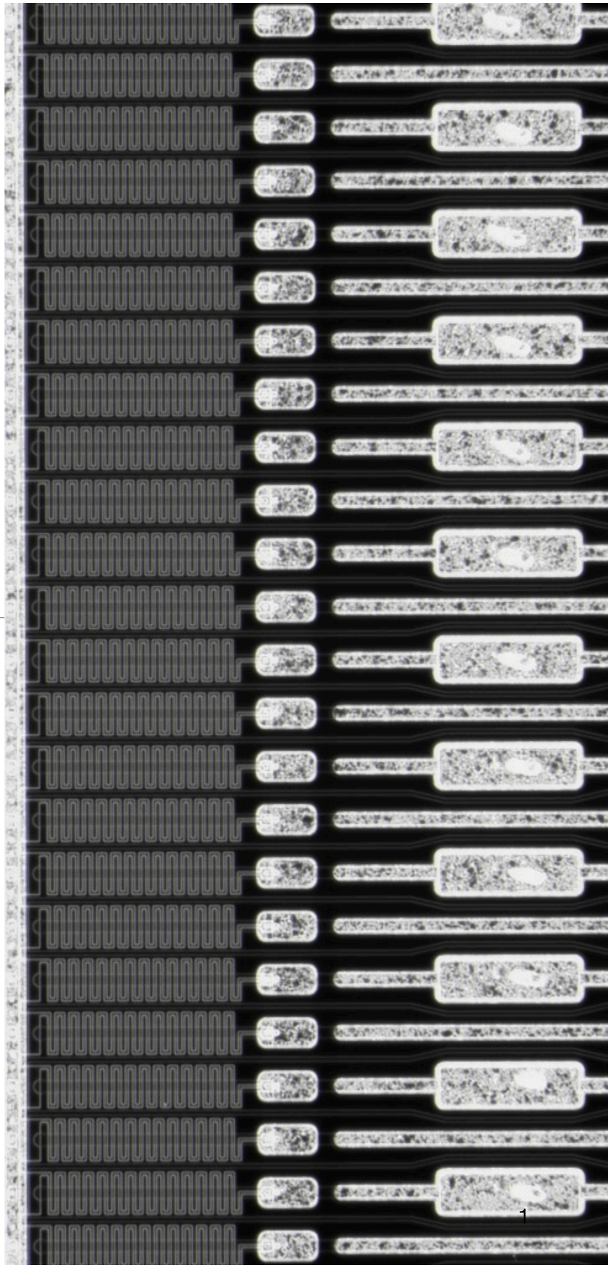
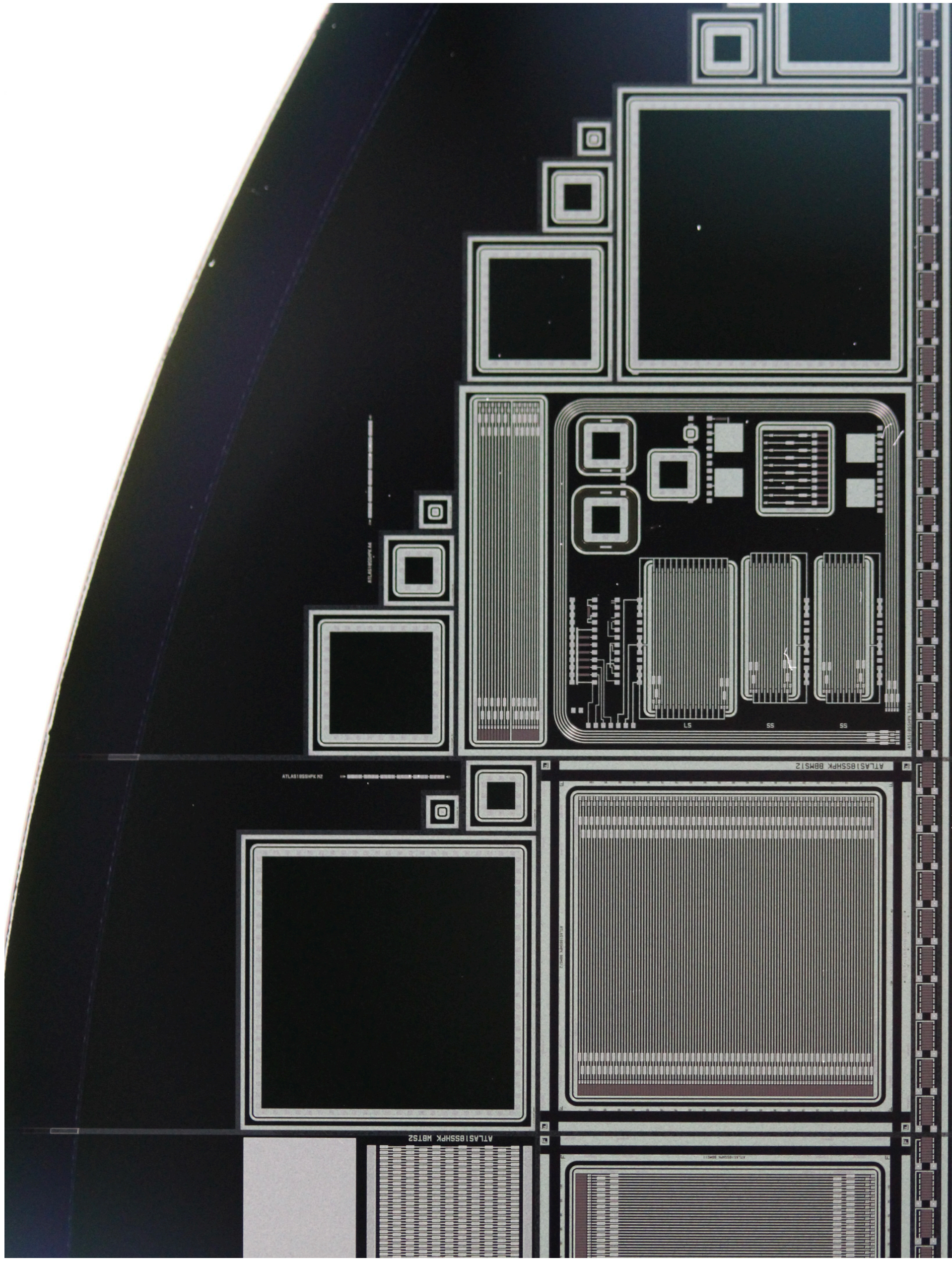


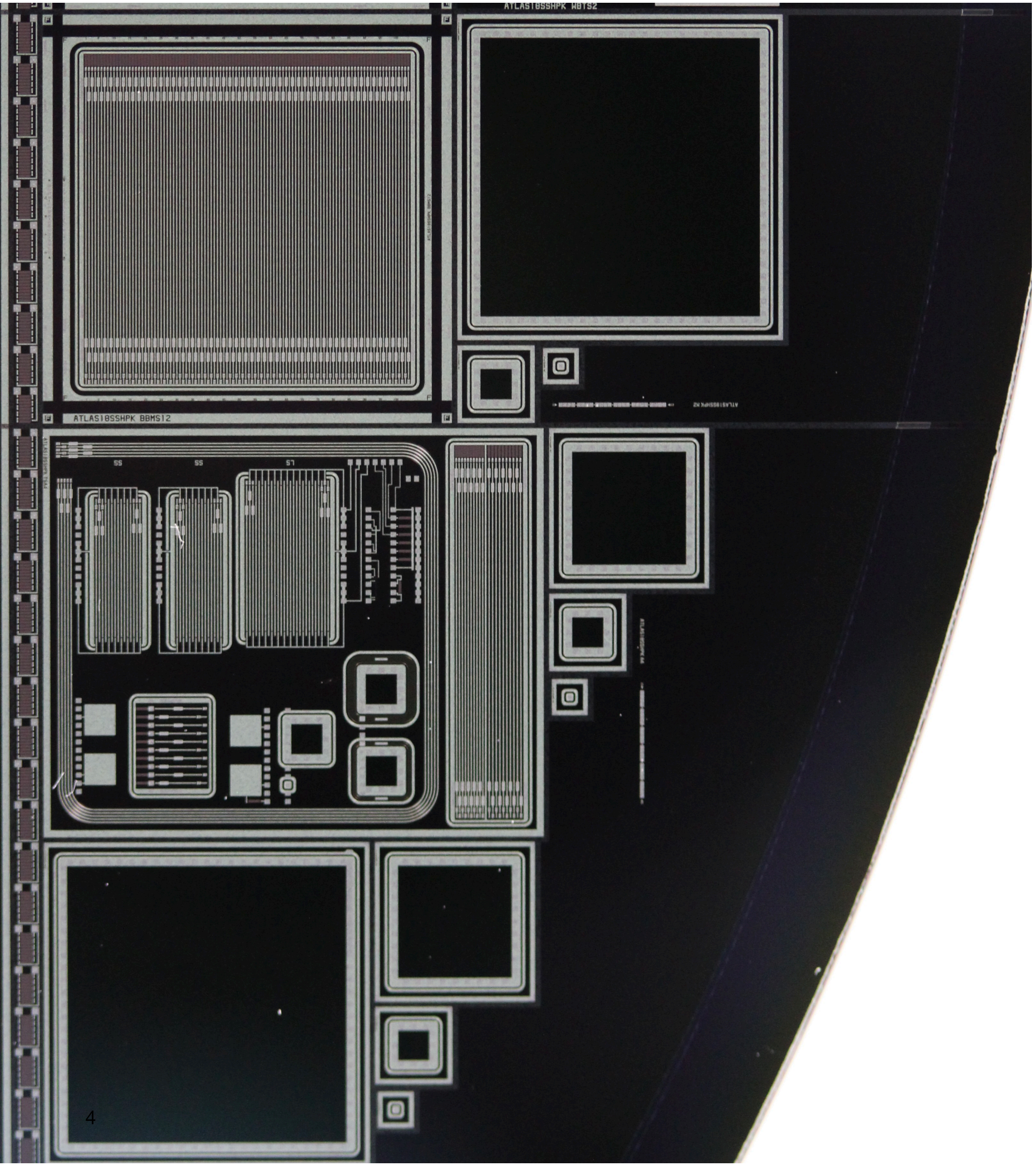
Preamble

- This session contains an overview of various “standard” measurements.
- It focuses on monolithic, planar Silicon, i.e. silicon detectors with conventional layouts and implants, to give you an idea on how to measure properties of the active medium.
- Techniques will vary (very) little for different types of devices (3D etc).
- For integrated detectors such as Active Pixel and/or CMOS devices, you will have to see how the measurements and techniques can be adapted to work with the particular device.
- I hope to give you an idea of how measurement techniques work to help you figure out how these can be applied to your project.

Contents

- Reverse bias leakage current (I-V)
- Leakage Current Stability
- Depletion depth / doping concentration (C-V)
- Inter-channel properties
  - Inter-channel resistance (R_{is})
  - Inter-channel capacitance (C_{is})

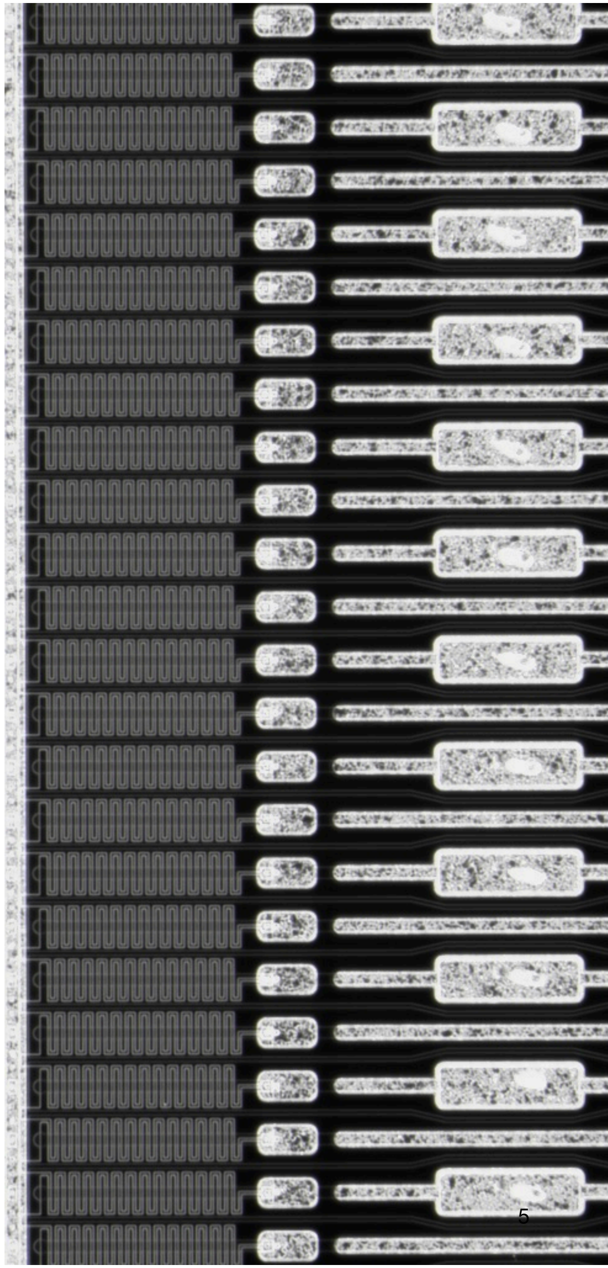




Contents - II

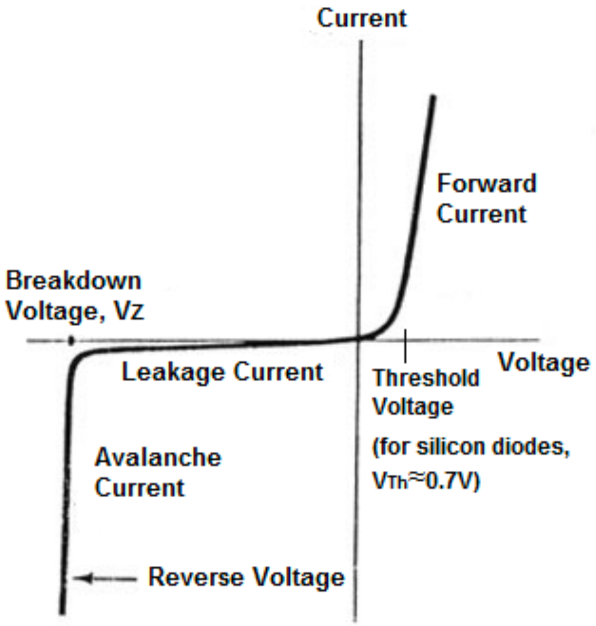
- Measurements on test structures
  - Flat-band voltage
  - Punch-through Protection
- Multi-channel characterization
  - Coupling Capacitance
  - Channel Test Protocols
- Advanced Imaging
- Measurement Equipment

I-V:
Current - Voltage measurement



Reverse Bias Leakage Current (I-V)

- Reverse bias: depletion zone in at least part of the silicon volume
- Leakage current: sum of bulk current and surface current



Reverse Bias Leakage Current (I-V): Bulk current

- **Bulk** leakage current: from (diffusion) recombination of e^- / h^+ pairs generated in the depleted region:

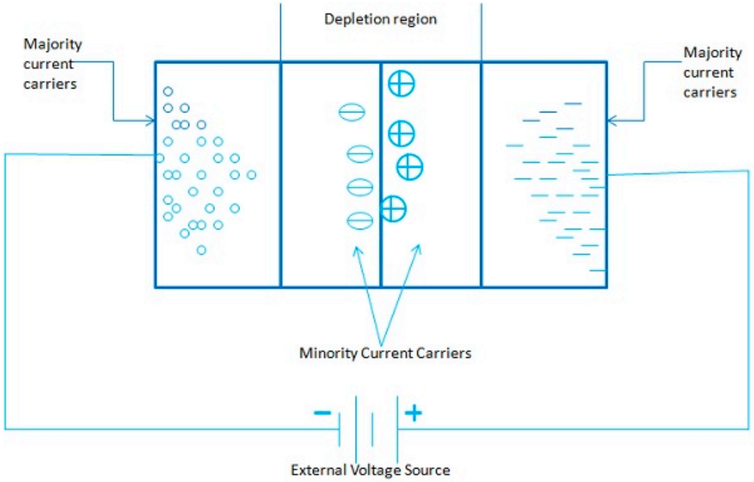
$$I_{bulk} \propto W \propto \sqrt{V}$$

- Depends on depleted volume, dopant type and concentration, and above all, temperature

- Comparing measurements requires T correction:

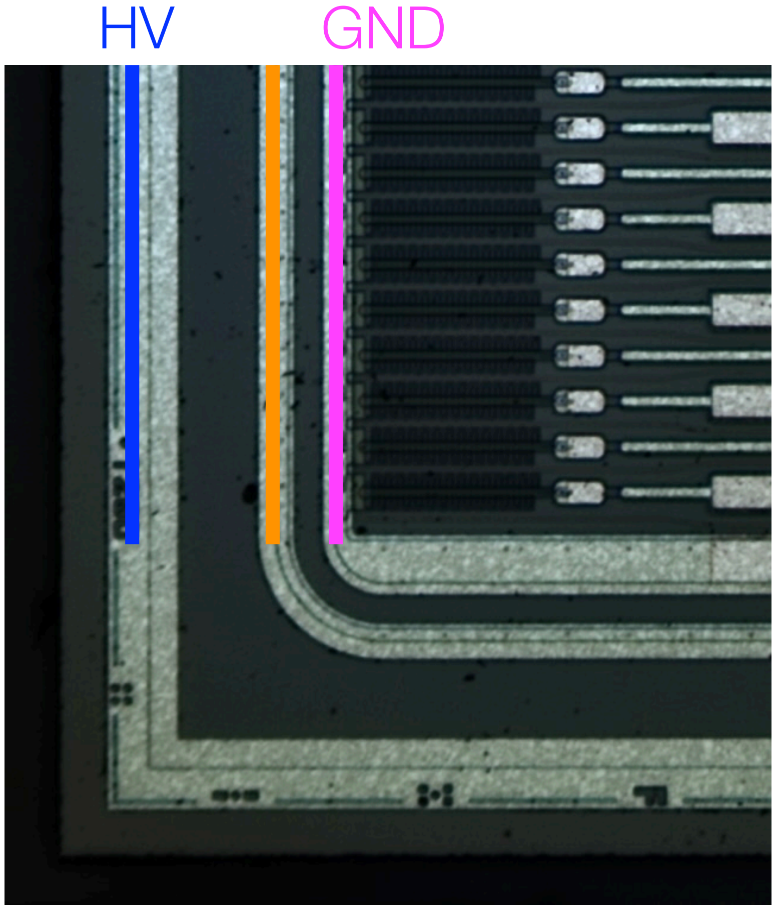
$$I(T_R) = I(T)\left(\frac{T_R}{T}\right)^2 \exp\left(-\frac{E_g}{2k_B}\left[\frac{1}{T_R}-\frac{1}{T}\right]\right),$$

with E_g=1.12 eV for Si

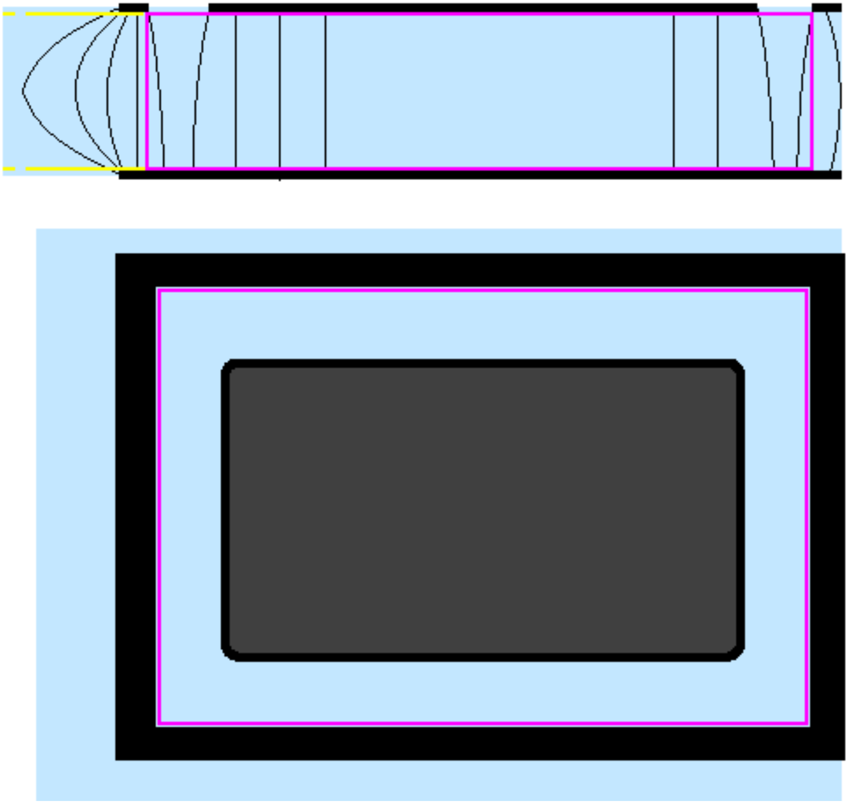


Reverse Bias Leakage Current (I-V): Surface currents

- **Surface** Currents:
  - Dependent on impurities, process or radiation induced defects
  - Edge structures: bias rail, guard rings, edge metal designs
    - O(10) difference in edge / bulk ratio for sample pieces vs. full size detectors
- Surface currents less T dependent than bulk current.
  - Charge depositions at the surface or insulation layers
  - Interface effects between Si/SiO2 interface at the top surface layers



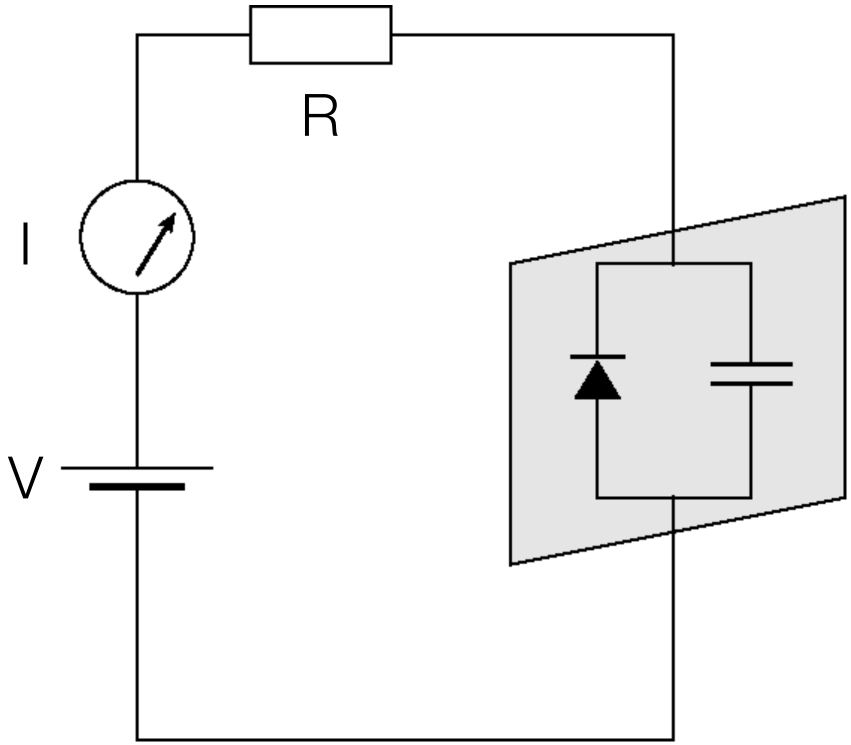
Reverse Bias Leakage Current (I-V): Measurement



- Structure perimeter determines active volume, or volume ‘seen’ by the measurement
- Guard rings provide well defined outline
- Particularly important when measuring (parts of) test structures
- Connect guard ring to same potential as central region but keep it out of the current measurement
- Equipotential gap: no surface currents

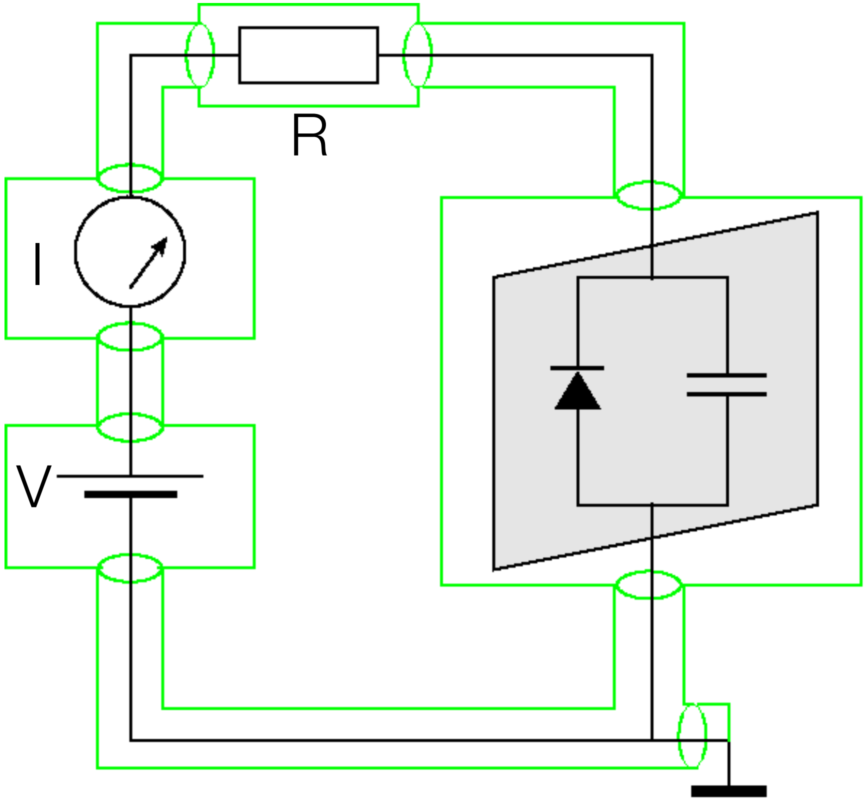
Reverse Bias Leakage Current (I-V): Measurement

- Equivalent circuit: rather simple
  - Sensor modeled by reverse bias diode & capacitor
  - Series resistor R to “extinguish” breakdown / avalanching. Order: 1 MΩ, depending on leakage current levels.
  - High side vs low side current measurement:
    - High side needs HV capable I meter
    - Low side more sensitive to grounding issues

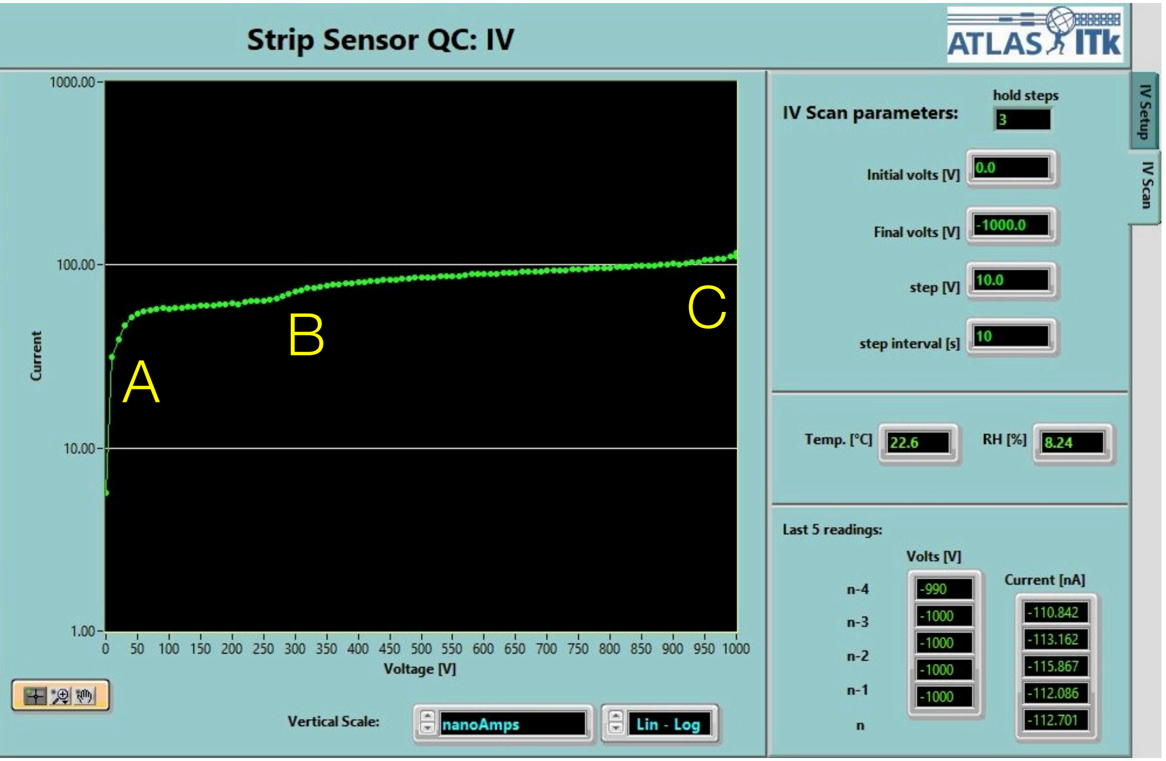


Reverse Bias Leakage Current (I-V): Measurement

- The smaller the currents, the more important grounding and shielding becomes
  - Lower than O(10 nA) is where it gets tricky
  - O(10 pA) is very difficult but can be done
- Contact points on sensor: contact quality important for sensing low currents accurately
  - Bond wires
  - Probestation manipulators with tungsten tips
- Best practice: fully floating design with central GND point near DUT and grounded shielding
  - Not always practically possible
  - Avoid ground loops!



Reverse Bias Leakage Current (I-V): Typical results



IV Scan parameters:

hold steps: 3

Initial volts [V]: 0.0

Final volts [V]: -1000.0

step [V]: 10.0

step interval [s]: 10

Temp. [°C]: 22.6

RH [%]: 8.24

Last 5 readings:

	Volts [V]	Current [nA]
n-4	-990	-110.842
n-3	-1000	-113.162
n-2	-1000	-115.867
n-1	-1000	-112.086
n	-1000	-112.701

Vertical Scale: nanoAmps Lin - Log

Remember $I_{bulk} \propto \sqrt{V}$, plotting $log(I) \propto log(V)$ will reveal exponential compound contributions better

Typical result:

A. Initial rapid rise towards full channel isolation

B. Full depletion bump: saturating the (heavily doped) back implant bumps up the leakage current

C. Onset of breakdown

This is a large, low leakage sensor: 1.1nA/cm^2 @ 1000V

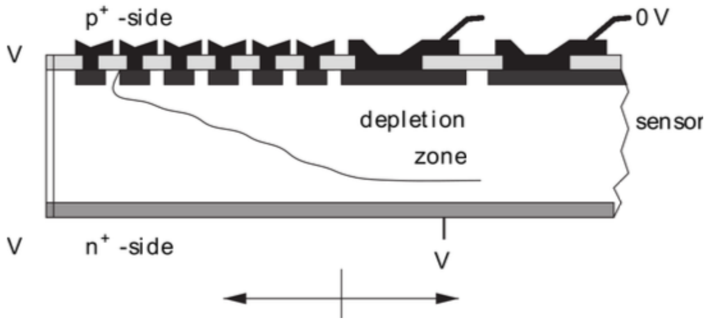
Higher leakage currents can hide subtle features

Reverse Bias Leakage Current (I-V): Measurement details

- Temperature measurement the limiting factor to accurately normalise currents
  - Sensor self-heating: thermal runaway for high current sensors, such as irradiated samples
- Settling behaviour: define interval between applying the voltage and sampling the current
- Sensor history can play a role, in particular in sensors with extremely low leakage currents and intricate top surface isolation layers
  - Repeated measurements influence the steep ramp towards channel isolation

Reverse Bias Leakage Current (I-V): Measurement details

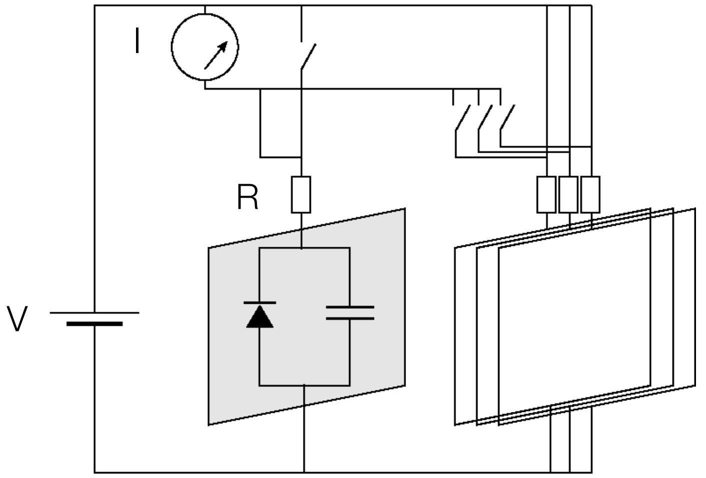
- In diced detectors, (multi) guard ring potential measurement gives insight in E field configuration
  - Important to mitigate highest E field spots to avoid breakdown
    - Does the structure work as designed? Are there unforeseen breakdown issues?
  - Example: 1cm^2 sample detector 1nA @ 1000V ~ 1 TΩ
  - Measurement device needs input impedance much larger than this.
    - A good multimeter can do O(10 GΩ): not enough.
    - Electrometer: O(100 TΩ): Keithley 6517, for example.

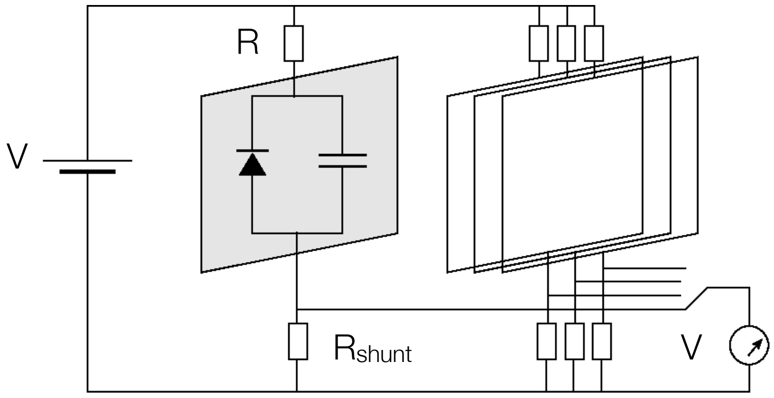


Reverse Bias Leakage Current Stability

- Longer term stress test of sensor top surface and/or edge structures
  - **Bulk leakage** dependent on intrinsic properties, not influenced by dynamic behaviour
  - Variations in leakage current caused by **surface effects**:
    - Interactions between Si/SiO2 layers and other insulation layers at the top surface
    - High voltage gap, guard ring, bias rail design and implementation
  - The E field causes any charge at the top layers to move around.
    - Mobility depends strongly on T, and, potentially, (Relative) Humidity (RH)
    - Low I sensors with intricate top isolation layers more affected
    - Edge structures where bias gaps appear can take a long time to settle

Reverse Bias Leakage Current Stability: measurement



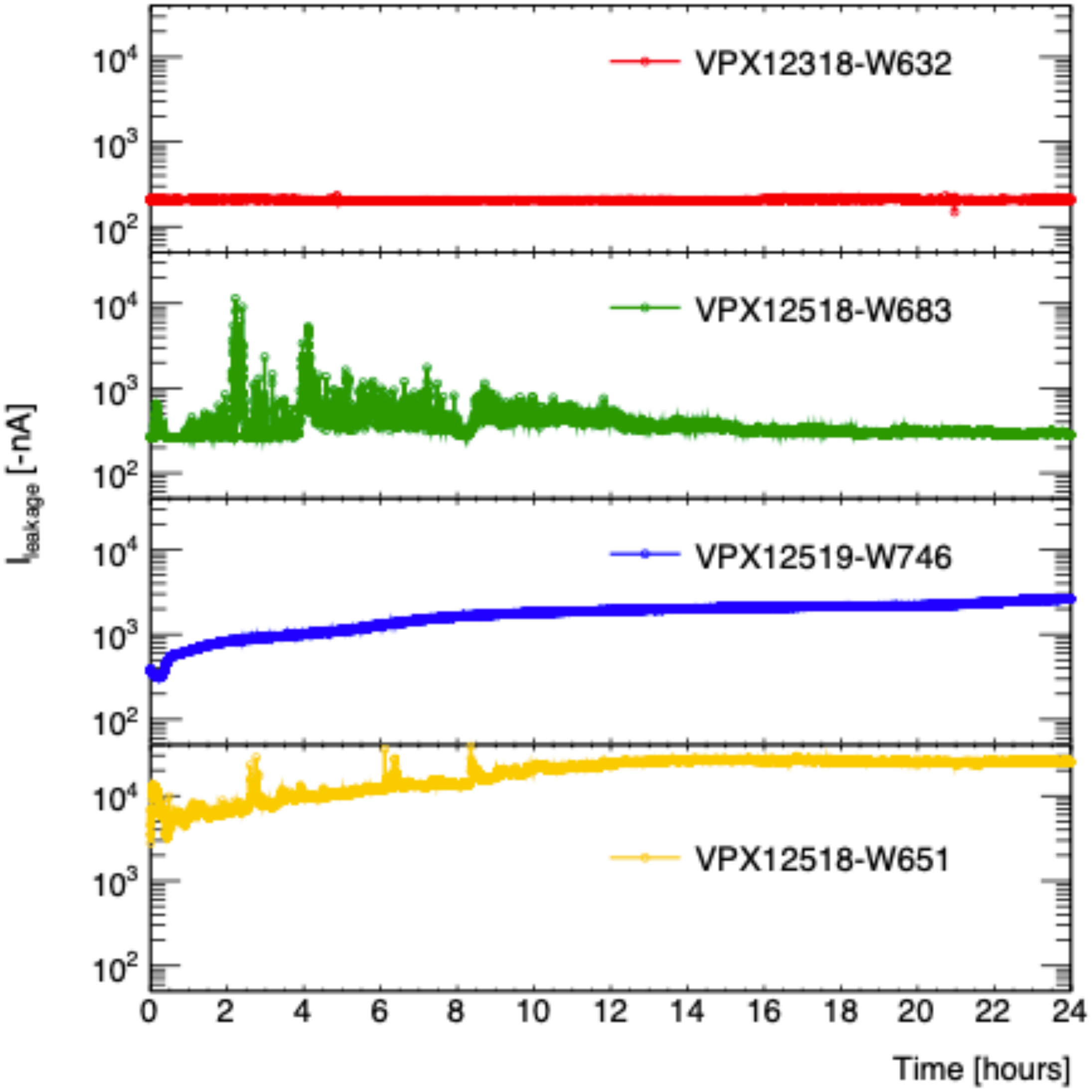


- Requires independent HV supply and measurement instrument
    - Direct current measurement, or
    - Voltage across shunt resistor
- Contact quality and stability must be excellent
- This measurement takes a long time: multiple sensors simultaneously
    - Needs matrix (direct I) or multiplexer (shunt V).
    - Consider switch leakage, noise, controls and grounding
- Current normalisation by temperature compensation. Requires T sensor coupled to similar thermal mass as sensors

Reverse Bias Leakage Current Stability: atypical results

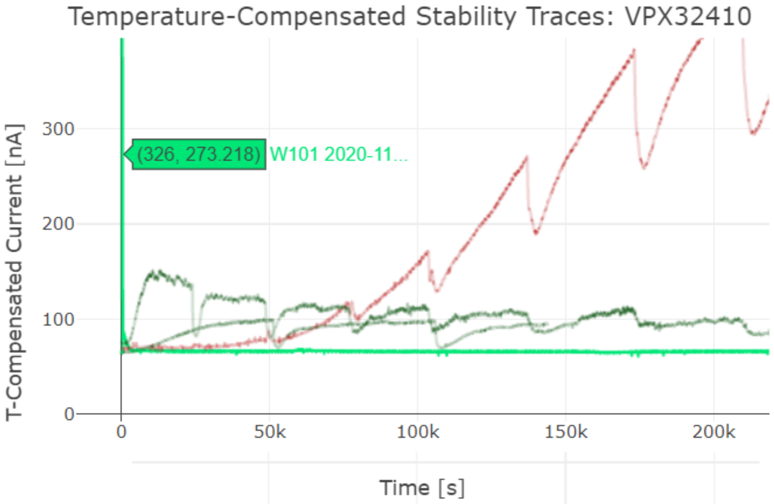
- Stable leakage : good
- Quick fluctuations
- Rising current
- Combinations of the above

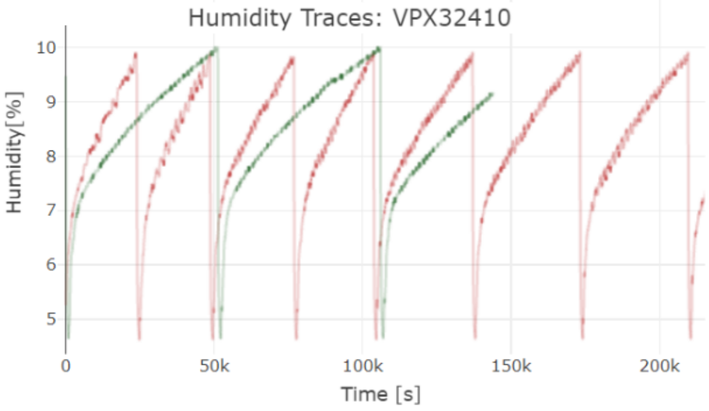
- Eyeballing the data is pretty straightforward
- Tricky to design algorithm that catches all

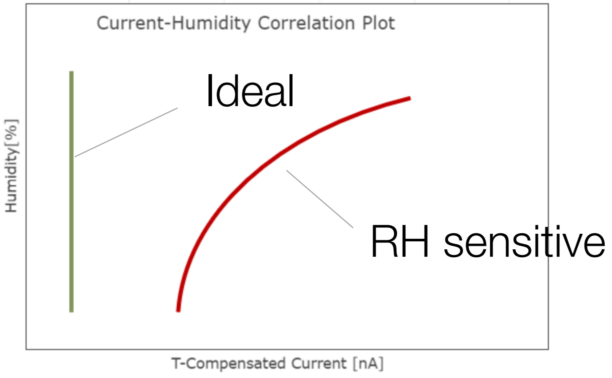


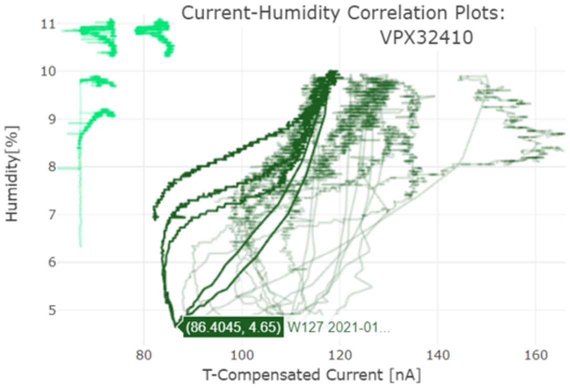
Reverse Bias Leakage Current Stability: atypical results & analysis example

- Top plot: various non-ideal behaviours
    - T compensated currents
- “Sawtooth” pattern correlates with dry cabinet letting in nitrogen: humidity sensitivity





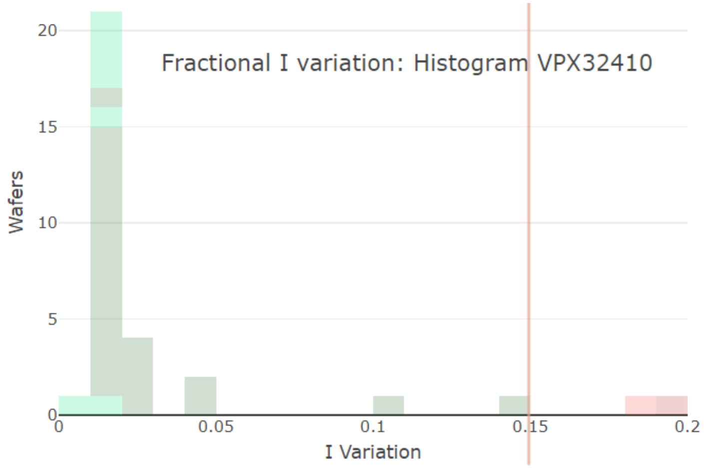


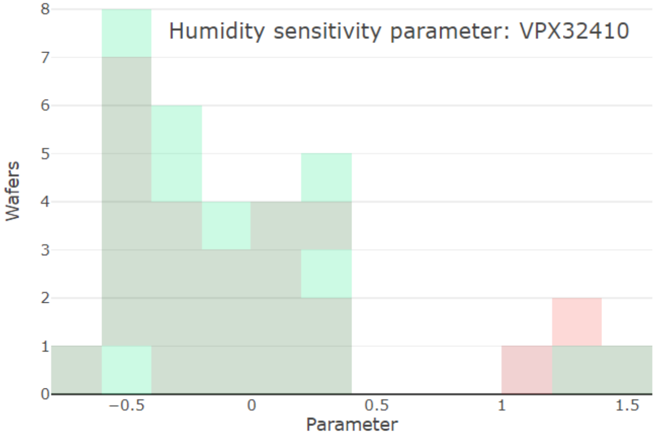


Composite analysis: example

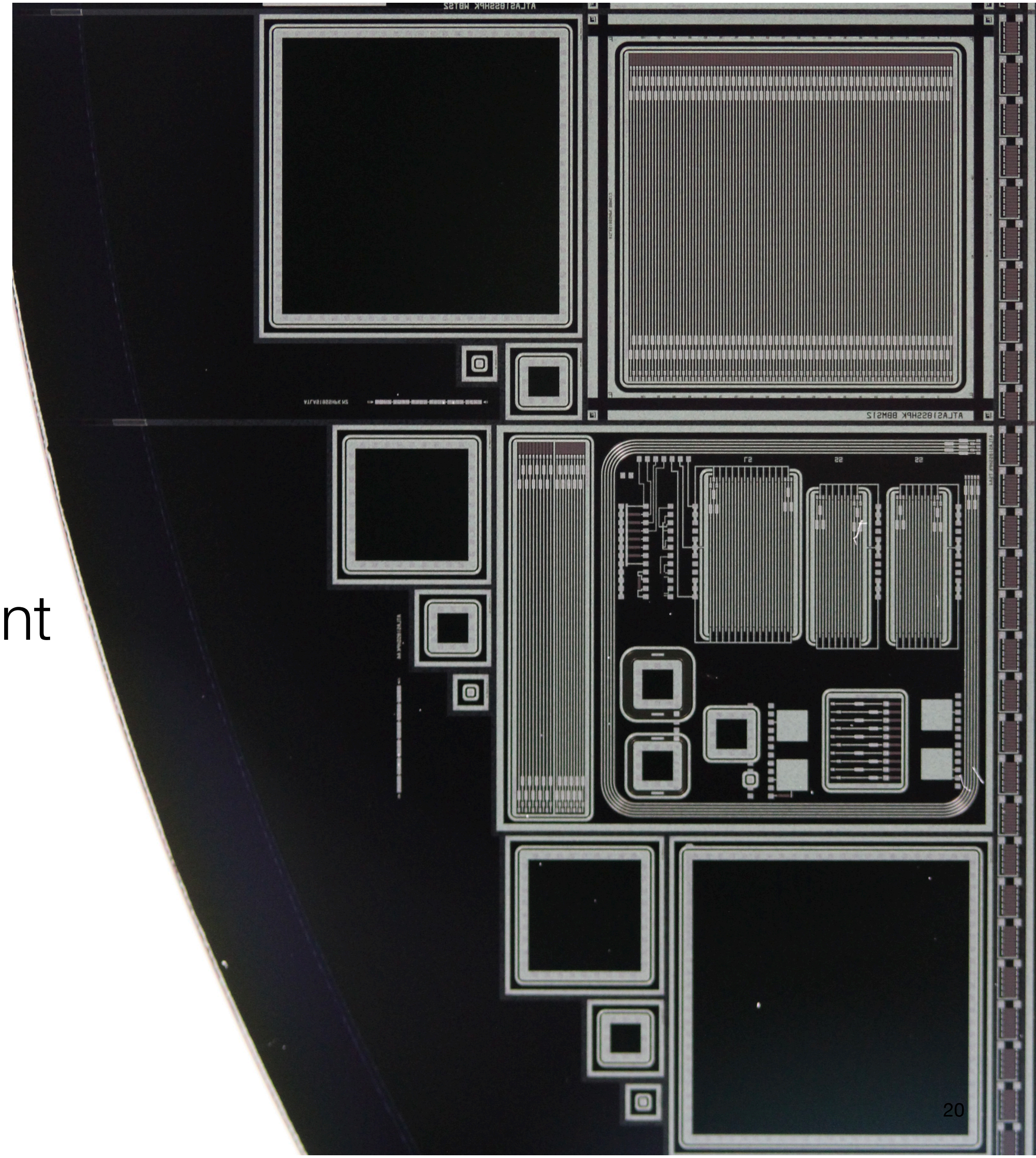
- Simple (running) avg/stdev will not catch all
- Use more advanced tools to try and catch all in a single “quality” parameter C_i:
  - (Pearson) correlation coefficient
  - Spearman (monotonic function) correlation coefficient
  - Linear regression (“straight line fit”)
  - Standard deviation

$$C_i = a_1 R_{Pearson} + a_2 R_{Spearman} + a_3 \beta + a_4 I_{var}$$





C-V:
Capacitance - Voltage measurement



Depletion Depth - Doping Concentration (C-V)

- Definition of capacitance at given voltage V_0 and depletion depth w:

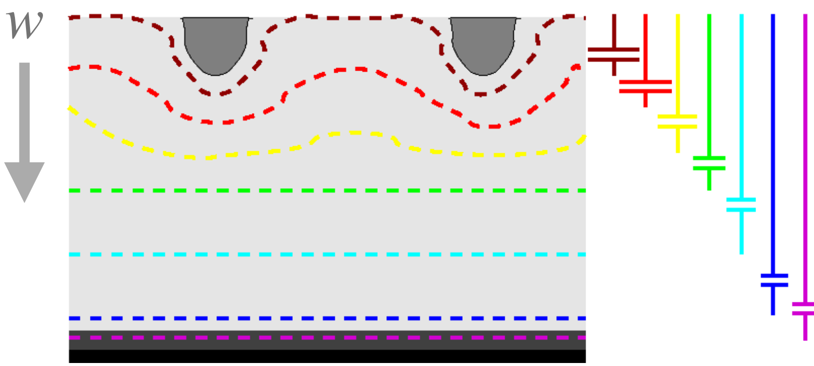
$$C(V_0) = \left.\frac{dQ}{dV}\right|_{V=V_0} = \left.\frac{dQ}{dw}\frac{dw}{dV}\right|_{V=V_0}$$

- With w depending on the effective doping concentration N_{eff}:

$$\frac{dw}{dV} = \sqrt{\frac{e\epsilon_r\epsilon_0}{2eN_{eff}V}}$$

- The above only applies when $V < V_{FD}$, or alternatively with $w < d_{eff}$, the distance less than the active thickness

- Planar sensors can be reliably modelled by parallel plate capacitors

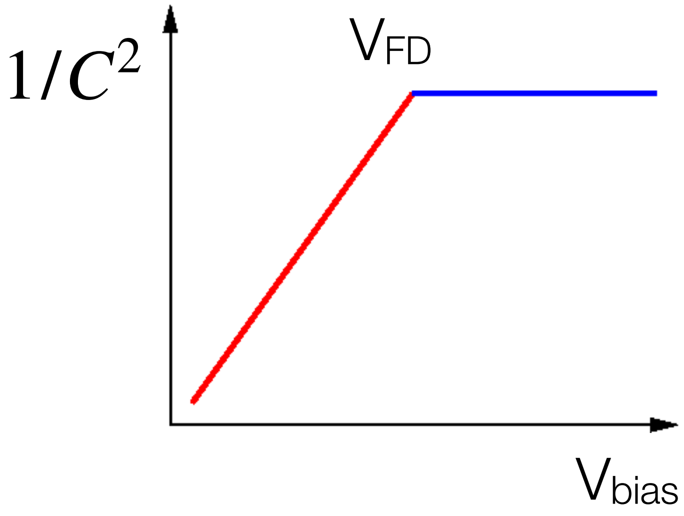


Capacitance - Voltage measurement

$$C(V) = \begin{cases} \sqrt{\dfrac{e\epsilon_r\epsilon_0 N_{eff}}{2V}}A, V < V_{FD} \\ \dfrac{e\epsilon_r\epsilon_0 A}{D}, V \geq V_{FD} \end{cases}$$

Plot $\dfrac{1}{C^2}$ for against V_{bias} for straight line

- With A the area enclosed by the bias rail, the effective depth D can be calculated for $V \geq V_{FD}$
- For $V < V_{FD}$, N_{eff} can be determined, even for $N_{eff}(w)$

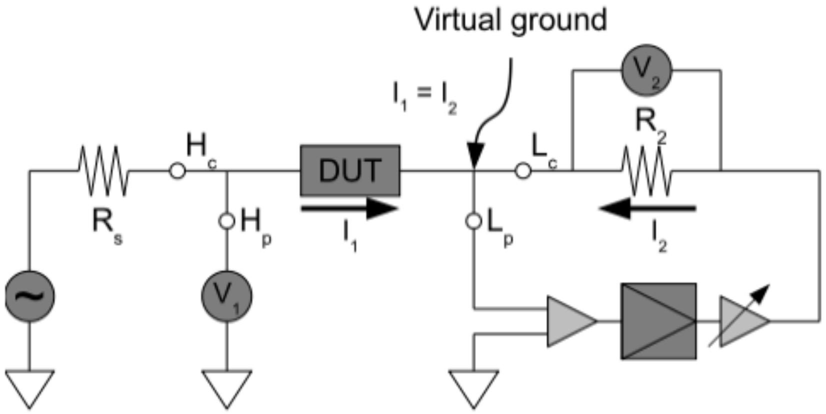


Capacitance measurement: LCR meters

- Sensor capacitance is derived from determining complex impedance *Z* using an AC test voltage with frequency *f*:

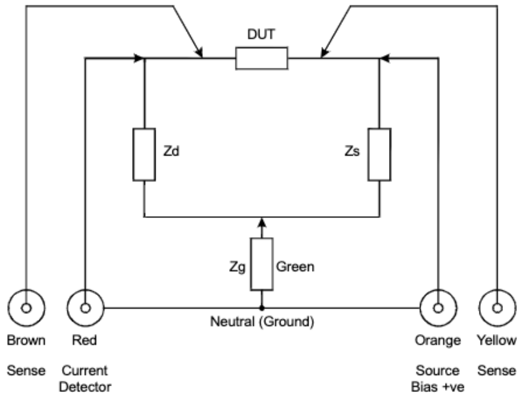
$$Z = R + i\left(2\pi f L - \frac{1}{2\pi f C}\right)$$

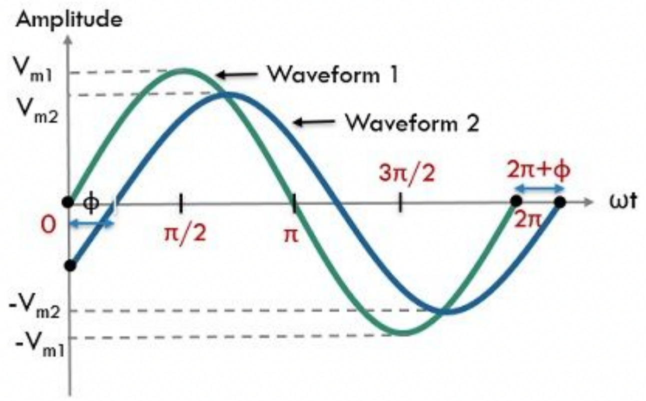
- LCR meter: contains an auto balancing bridge to measure impedance of simple R/L/C networks

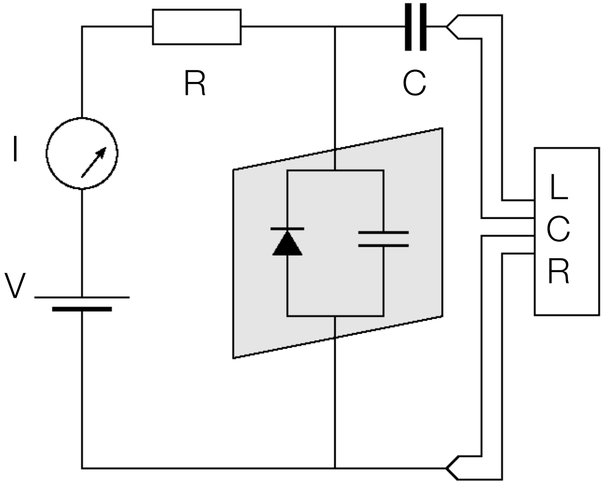


H_c: Signal source
H_p: Potential meter
L_c: Current meter
L_p: Potential meter to Lock the phase of measurement signal

LCR meters: measurement principle



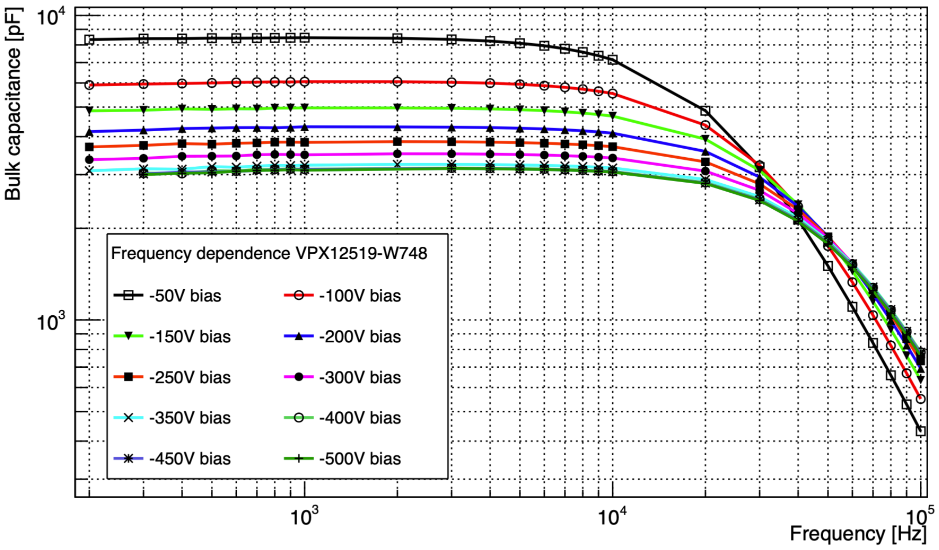




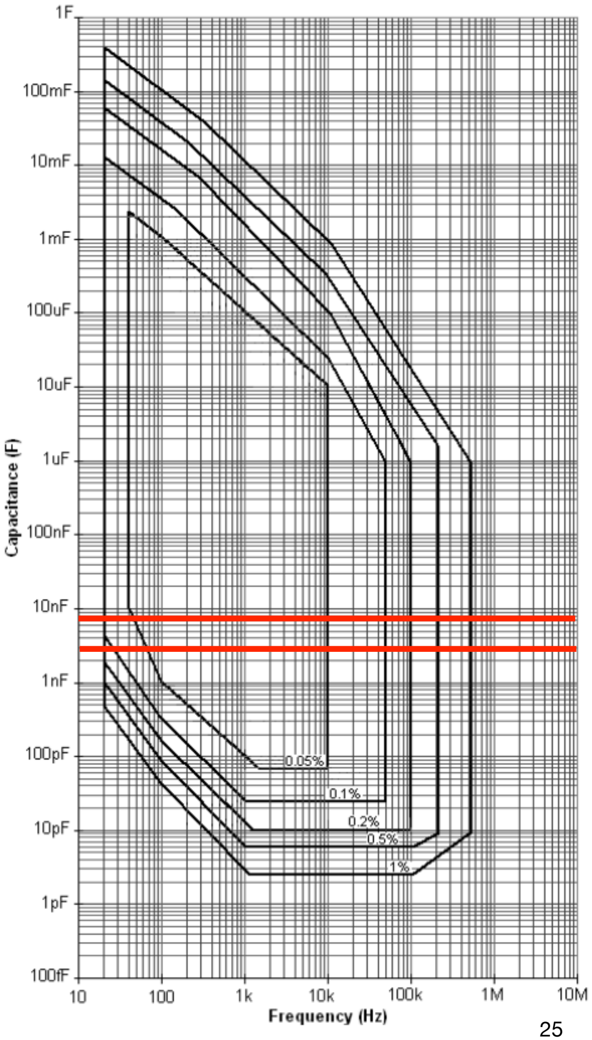
- Insert AC waveform, measure relative amplitude and phase shift of response
- Extract complex impedance of known network: R-C series, R-C parallel, etc.
- LCR is most accurate when $Z(R)$ and $Z(C)$ are comparable: $R \sim 1/jwC$, and parasitic impedances are low
- R-C network formed by $R_{bias} + R_{bulk}$ and C_{bulk}, L negligible
- Practical implementation: DC-blocking C, LCR protection circuits

LCR / CV measurement limitations

- LCRs cannot be asked to perform the impossible
- Frequency dependence of R-C network formed by detector
  - C should correspond to parallel plate capacitor for planar sensors
  - R should be roughly all R_{bias} in parallel

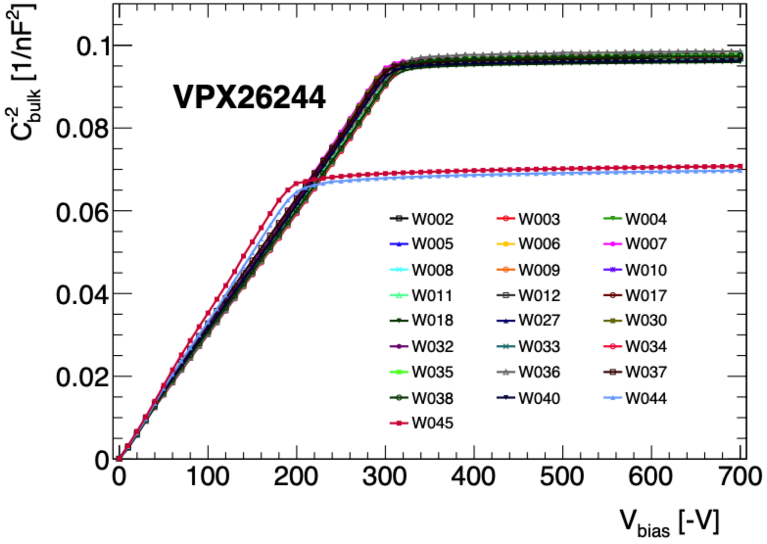


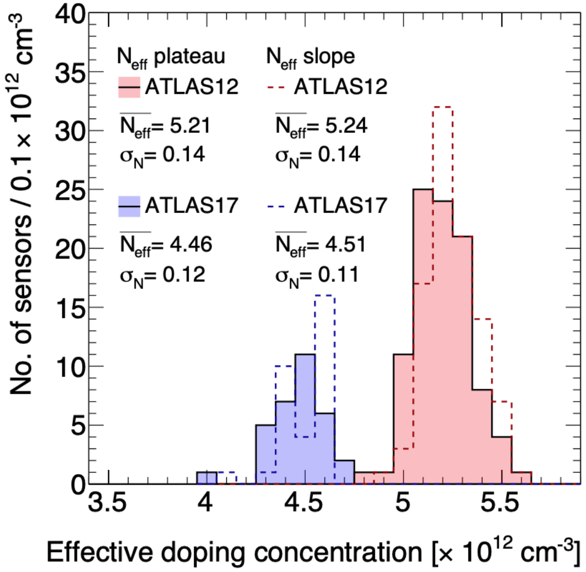
7.9.2 C Accuracy



Typical results: V_{FD}, D, N_{eff}

- Plot shows results for single batch of sensors, of which 2 have a different active thickness
  - Linear slope for $V<V_{FD}$ implies a homogenous doping profile
- Methods for extracting V(FD):
  - Intersection of linear fit to the 2 regions
  - Slope change: find peak on curve derivative





C-V for irradiated sensors

- Where is VFD?
- Note the O(10^5) higher leakage current:
  - V_{bias} needs correcting for drop across R_{series}
  - Avoid using top metal contact for HV, use backplane instead: irradiation potentially changes resistance of detector edges
- Note the very different behaviour vs *f*
  - Small operating window