Advanced UK Instrumentation Training 2024

Lab Techniques - 2

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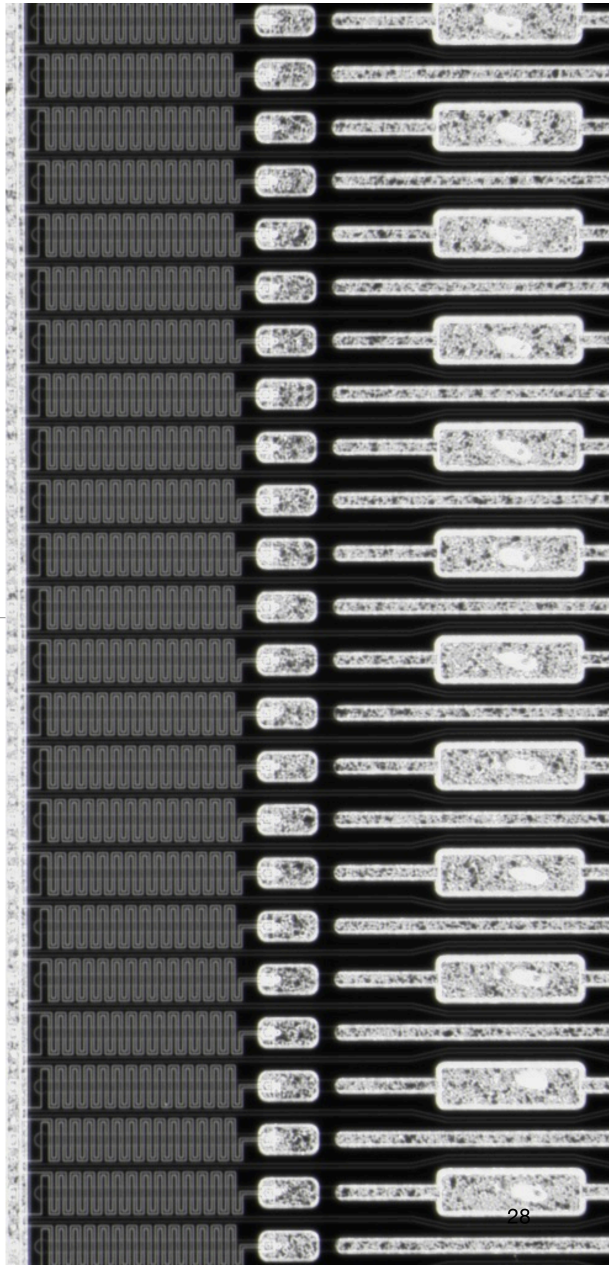
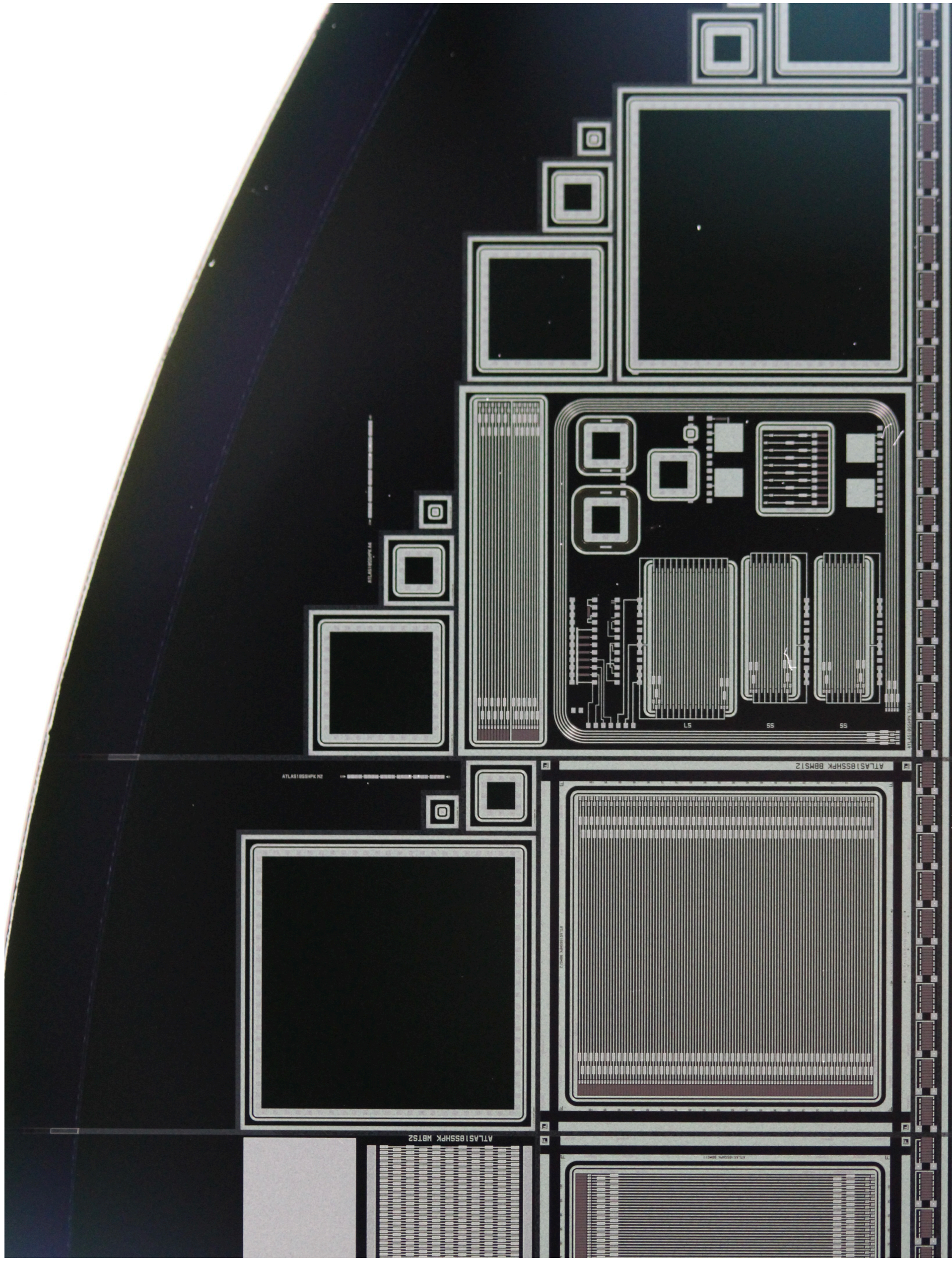


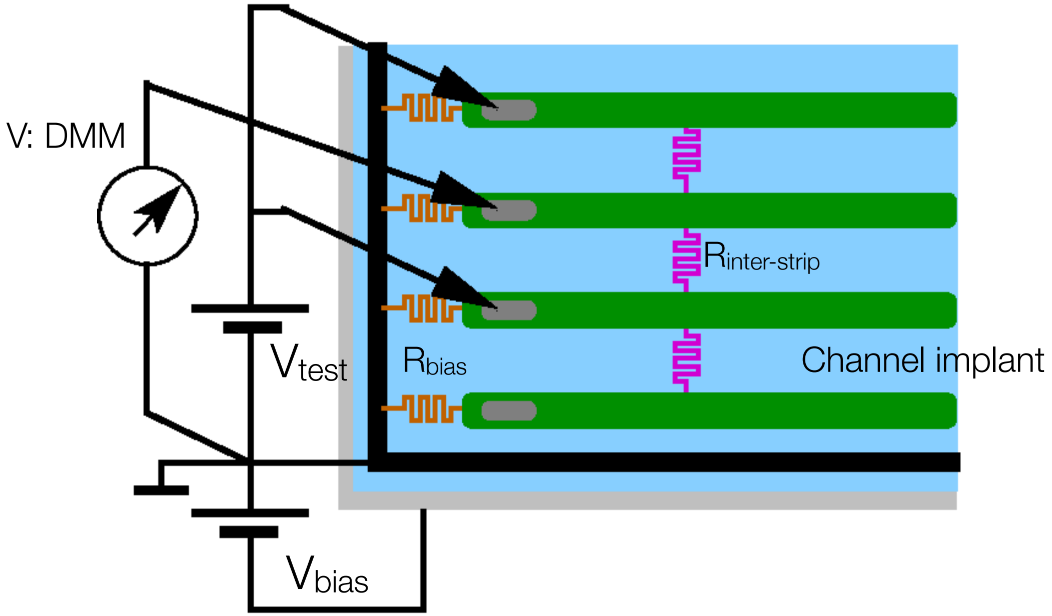
Inter-channel properties

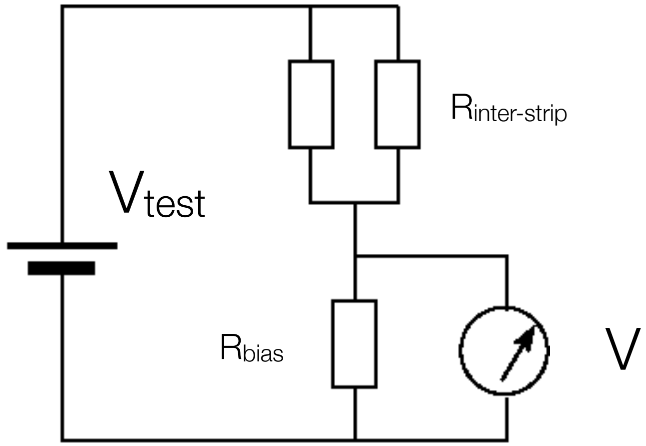
Inter-channel Resistance
Inter-channel Capacitance



Inter-channel Resistance

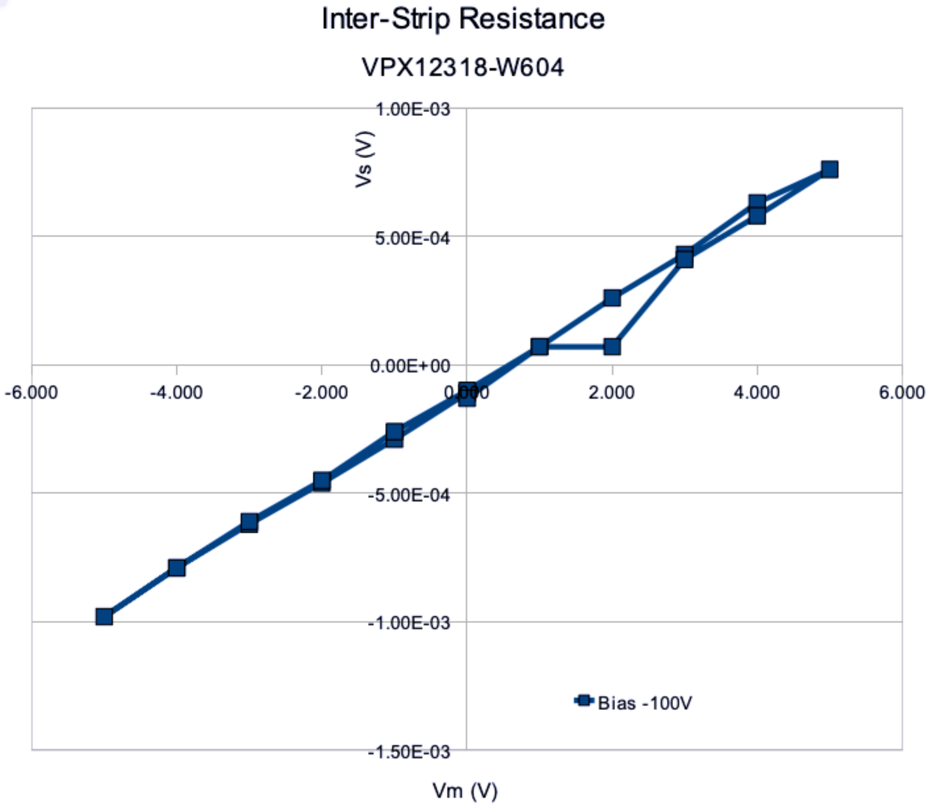
- Channel separation essential for tracking performance: $R_{ic} >> R_{bias}$ throughout detector lifetime
  - See lectures by Muñoz, Gonella
- R_{ic} measurement requires DC contact to channel implants
- $R_{ic} >> R_{bias}$, too high for LCR
- V_{test} to impose voltage across channels, introducing current through R_{ic}
  - R_{ic} in V divider with R_{bias}, limiting sensitivity
  - DMM $Z_{in} >> R_{bias}$, might require electrometer for small structures
  - Limit V_{test} not to burn out R_{bias}!





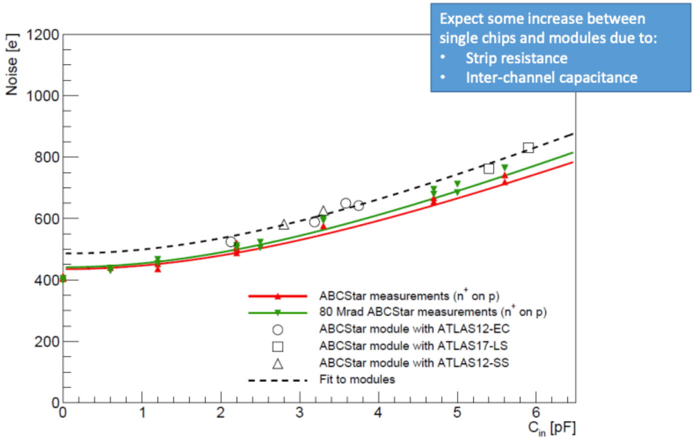
R_{is}: typical results

- Can’t just set DMM to Ohms and be done!
- Very low currents, and R_{is} measured across R_{bias} as shunt
- V_{test} sweeps from -5 to +5V and back to eliminate hysteresis
- Measured V in mV range
- Linear fit through data points gives slope = ratio of R_{is} and R_{bias}
- Note: the shorter the strip, the HIGHER the resistance. Keep this in mind when measuring test structures!



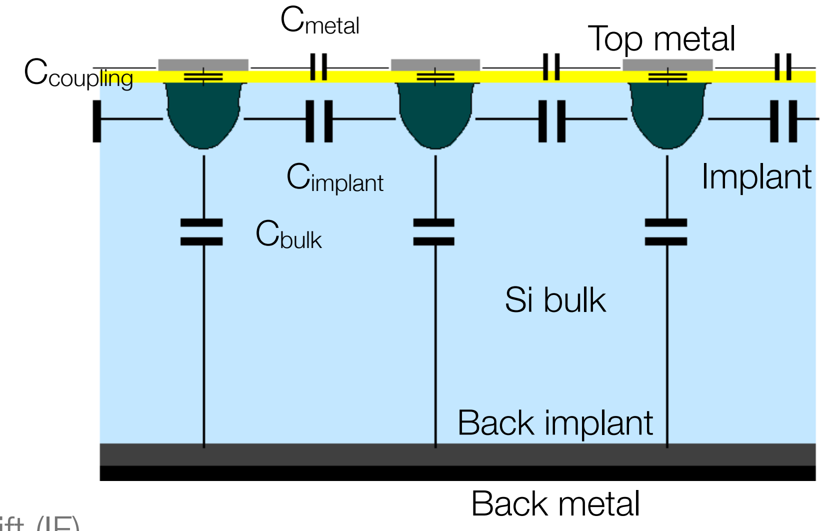
Inter-channel capacitance

- Semiconductor detector (& amplifier) noise sources: see lecture by Muñoz Sanchez
    - 2 contributing factors feature input capacitance C^2
- 2 main sources of capacitance: C_{bulk} and C_{is}/C_{ip}
    - $C_{is}/C_{ip} = C_{implant} + C_{metal}$, implant normally dominates
    - C_{bulk} and C_{is}/C_{ip} ratio depends on sensor thickness
- Backplane capacitance depends on depletion:
    - Can be used to probe detector noise slope: e- (eq) / Input
- Balance collecting volume vs capacitance
    - Monolithic Si (drift) detectors: very important
    - CMOS detectors: different trade-off since diffusion more important than drift (IF)



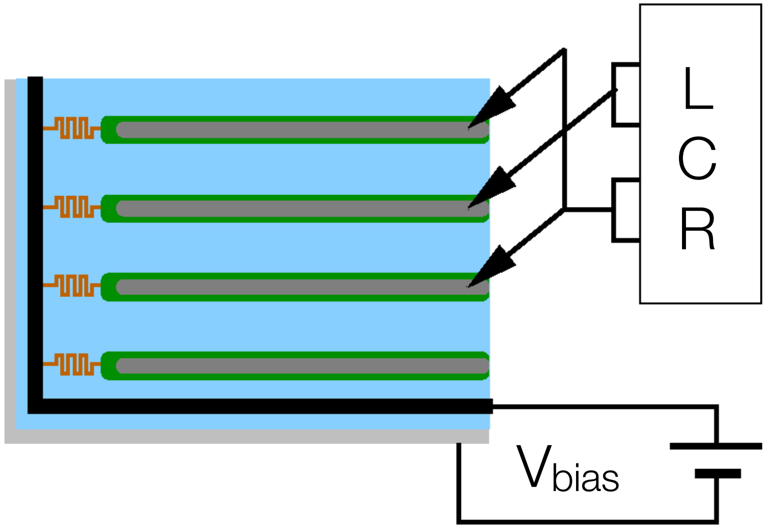
Expect some increase between single chips and modules due to:

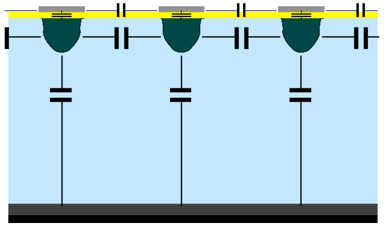
- Strip resistance
- Inter-channel capacitance

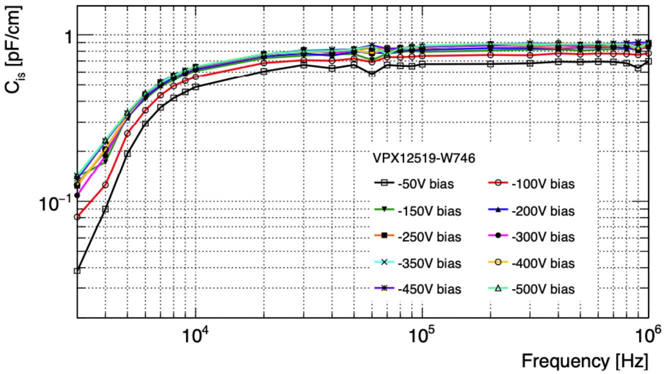


Cis/Cip measurement

- Usually, the implant capacitance dominates. Typical values:
  - $C_{is}/C_{ip} < 0.8$ pF/cm,
  - $C_{bulk} < 0.2$ pF/cm, estimated from full sensor CV result
- Contact 3 channels: use LCR
  - Next-neighbours contribute 10-20%
- Contacts can be AC or DC coupled
- Note that the LCR working parameters are (very) different than for CV
  - Irradiated sensors: different yet again
  - Measure dependence on *f* for every use case

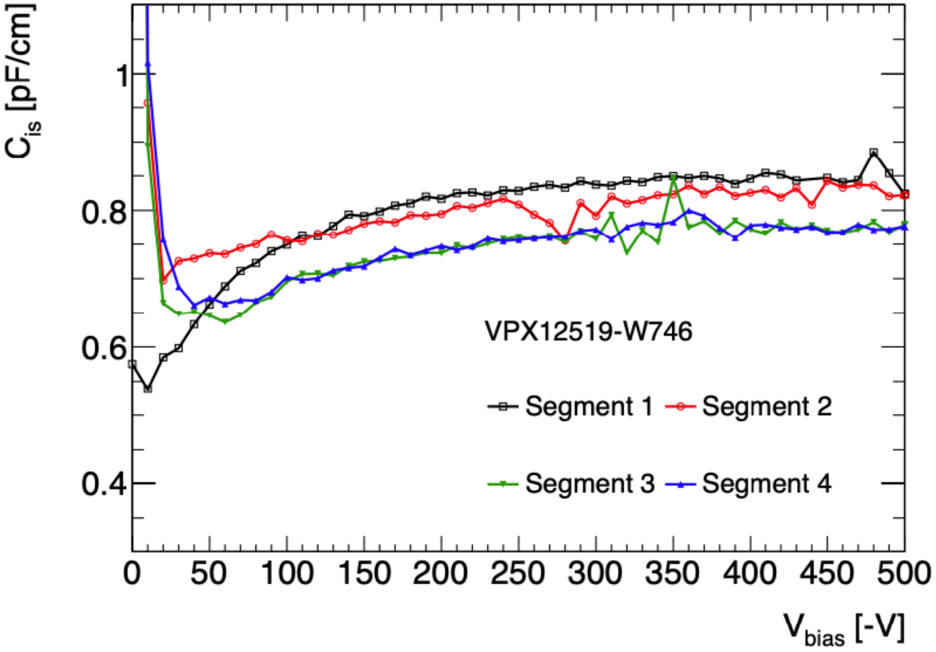




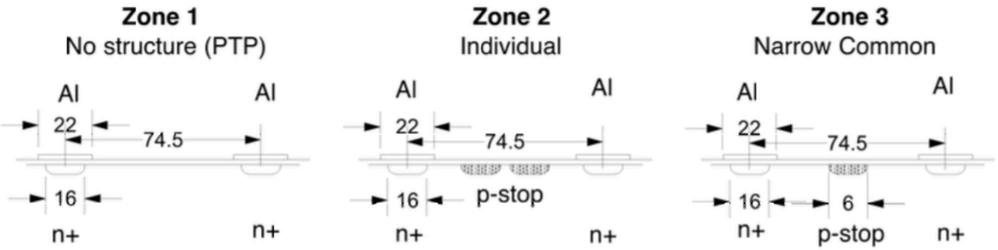


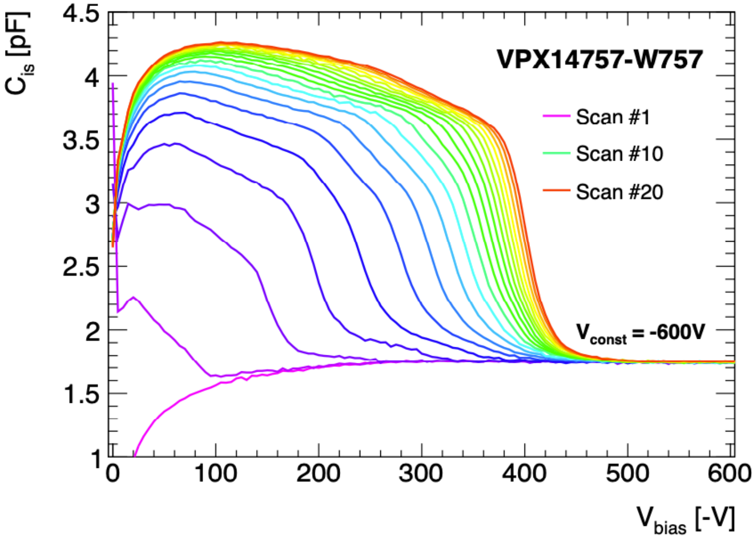
Cis/Cip measurement: typical results & considerations

- Grounding: could run setup floating
  - Depending on environment noise, central GND point close to DUT should be introduced
  - Delicate measurement *O(*pF*)* using long cables
  - Shielding very important
  - Contact quality to sensor very (very!) important
- Sub V_{FD} behaviour determined by inter-channel structures
- Settling behaviour over time…



Inter-channel capacitance: time evolution

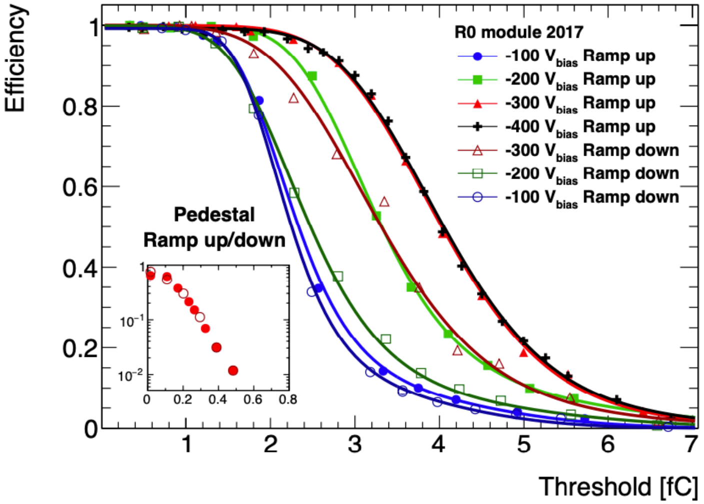




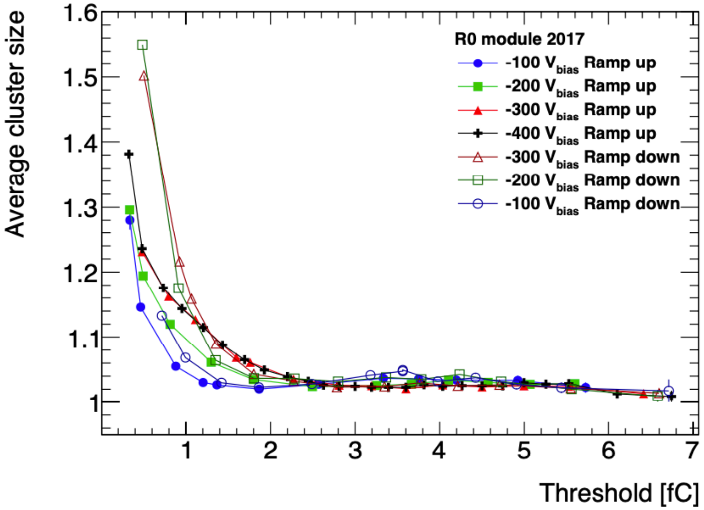
- Gives information about inter-channel structure properties
- Dependent on many things:
  - p-stop, p-spray details and concentrations
  - Insulation layers & interface with Silicon top surface
  - Layout & lay-up of top metal layers
  - Environment: T, RH and interaction with top passivation / insulation layers
- DLTS-like analysis of time series behaviour

Influence on detector operation

- Inter-channel structures determine tracking performance
  - Channel-channel isolation is crucial!
- C does not change much when detector at steady operating conditions
- When Vbias changes under operating conditions (<10% RH, -20°C):
  - Cluster size not as predicted
  - Higher noise
  - Could take hours/days to settle!

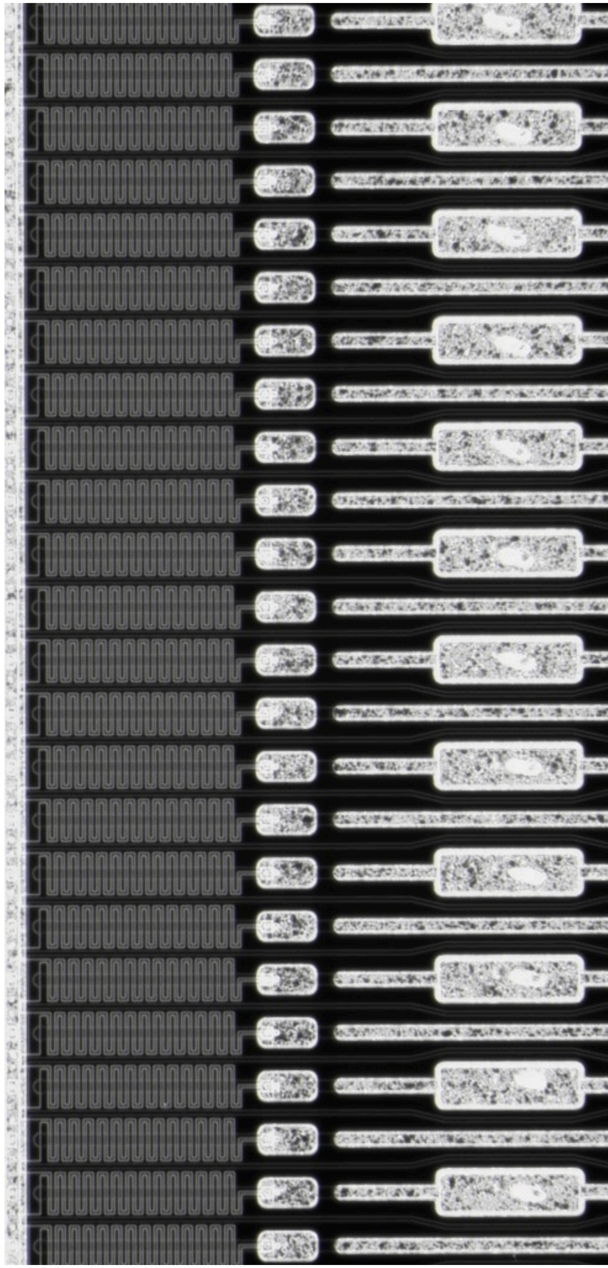


DESY testbeam data on ATLAS ITk strip modules



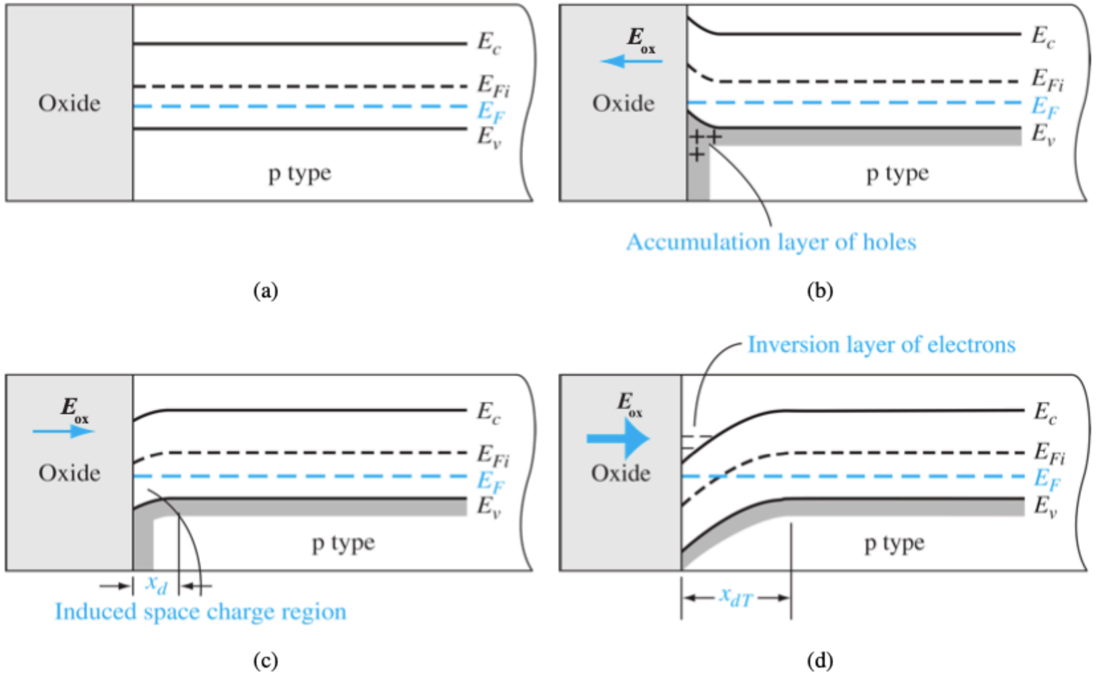
Test Structure Measurements

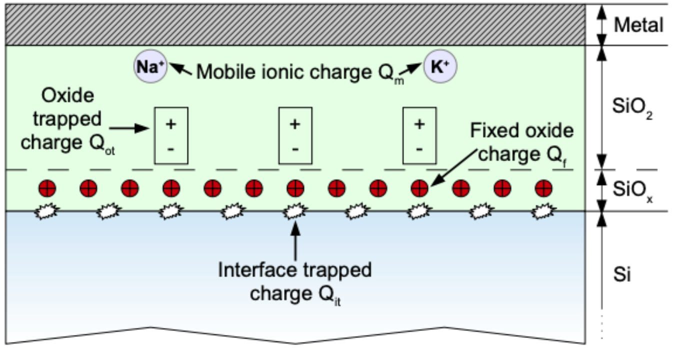
Flat-band Voltage
Punch-Through Protection

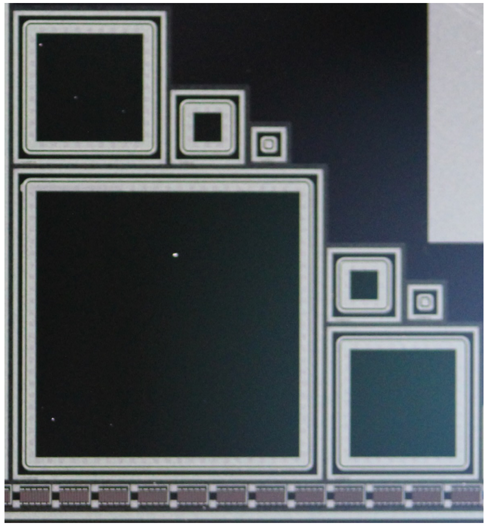


Flat-band voltage

- Silicon detector top surface: Si meets SiO_2
- Discontinuity in lattice structure: dangling bonds and/or surface states
- Band structures deviating from ideal
  A. Ideal case
  B. Negative oxide charge / ‘gate voltage’
  C. Positive oxide charge / ‘gate voltage’
  D. Stronger E field, as C) leading to inversion layer
- Study this using a MOS test structure







Measuring V_{FB}: MOS structures

- Gate capacitance:

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} A$$

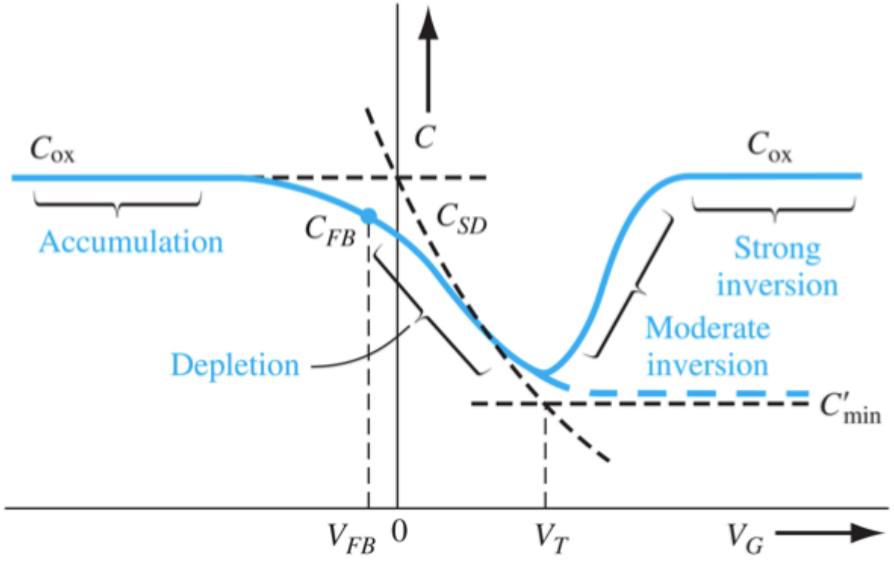
- At the flat band Voltage at the gate, the ideal band structure is restored:

$$V_{FB} = \Phi_M + \Phi_S$$

- Flatband Capacitance:

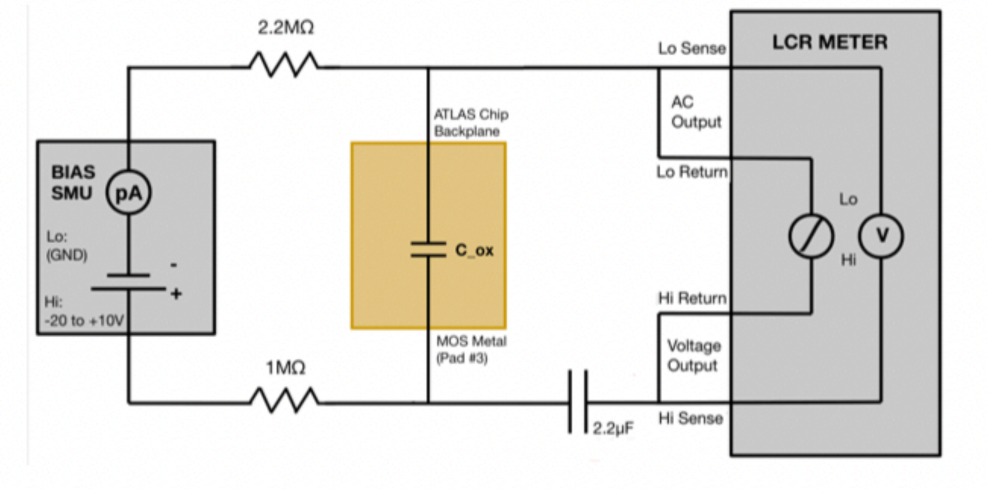
$$\frac{1}{C_{FB}} = \frac{1}{C_{ox}} + \frac{\lambda_d}{A\epsilon_{Si}} \; ; \lambda_d = \sqrt{\frac{\epsilon_{Si} kT}{q^2 N_A}}$$

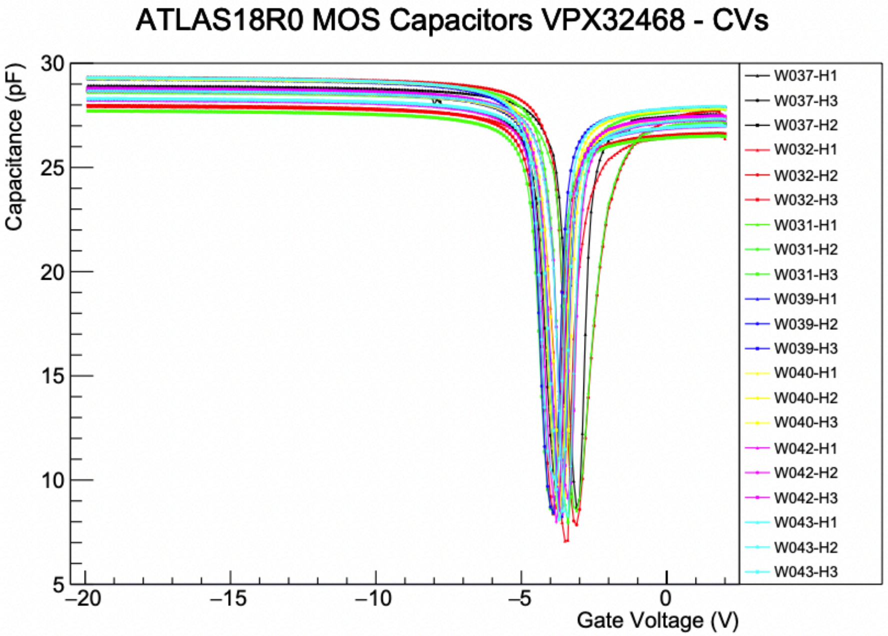
With λ_d the Debye length, and N_A the doping concentration (!)



MOS measurement & typical results

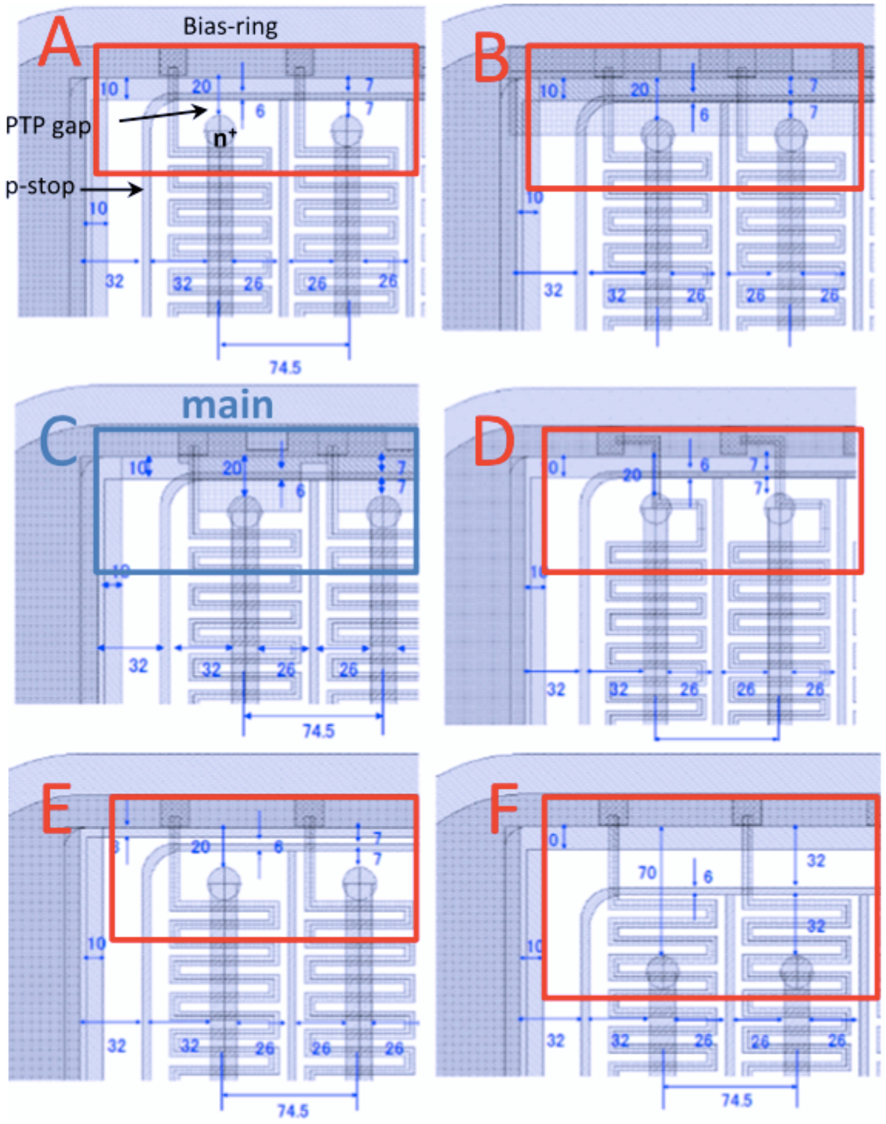
- Use LCR to measure capacitance while sweeping V_{gate}
- Resulting plot: easy to analyse
- Gives access to:
  - Details of the oxide growing process
  - Accumulated charges in the oxide layer
    - Pre-irradiation
    - Post-irradiation
  - Assess effectiveness of inter-channel isolation structures after irradiation





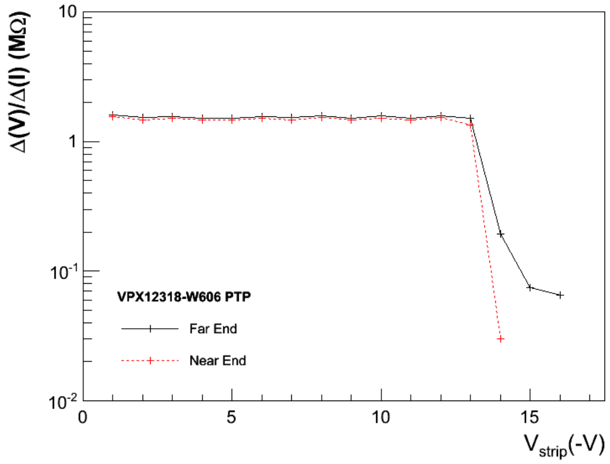
Punch-Through Protection

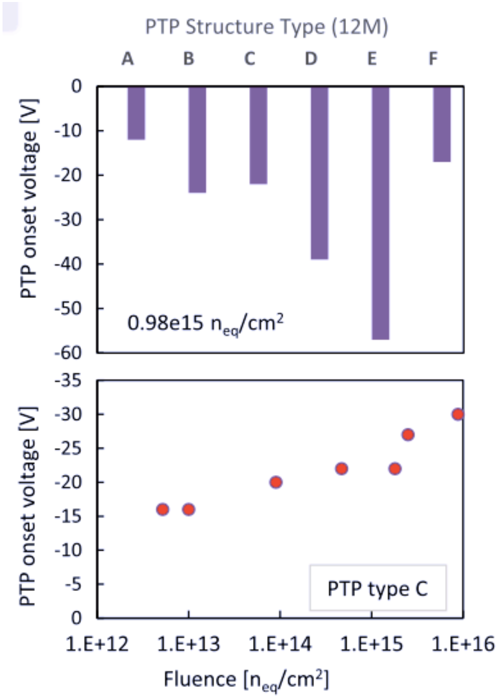
- Why? Beam splashes suddenly releasing large amounts of charge: substantial potential difference between strip and GND could burn out bias resistor and/or implant
- PTP structures: evolution from simple extension to fully gated design.
  - Reliable and repeatable breakthrough potential
  - Sufficient current draining capability
- Practical measurements:
  - DC equivalent
  - Dynamic measurement using external stimulation (laser)
- Recovery behaviour



Study of surface properties of ATLAS12 strip sensors and their radiation resistance

M. Mikestikova, for the ATLAS ITk collaboration



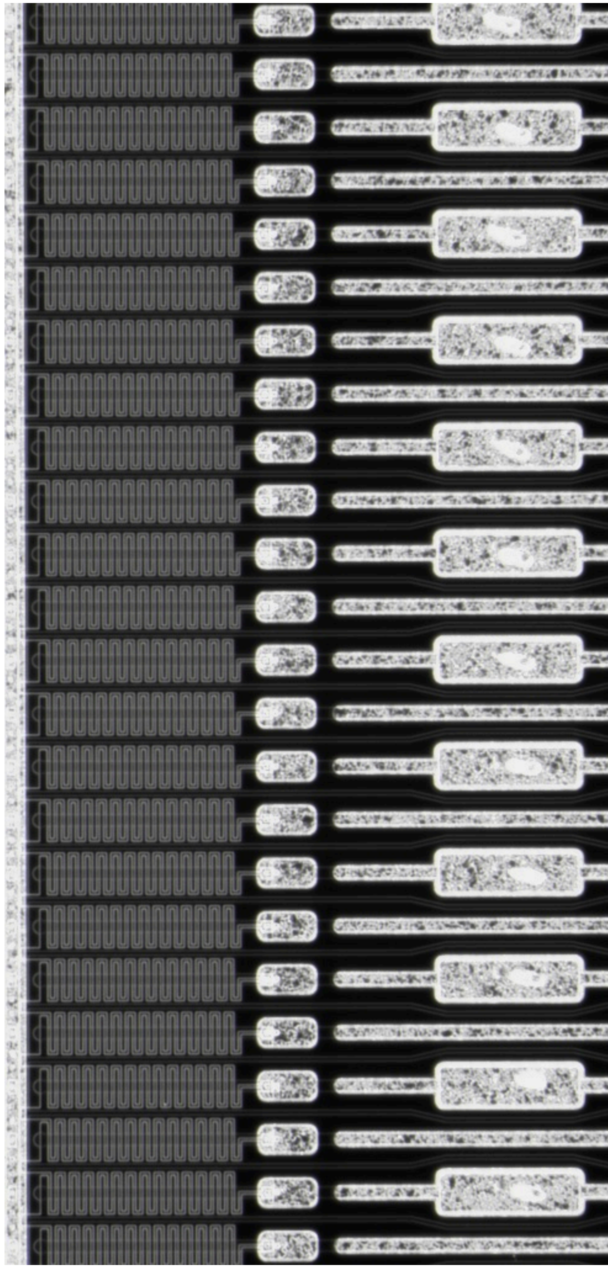


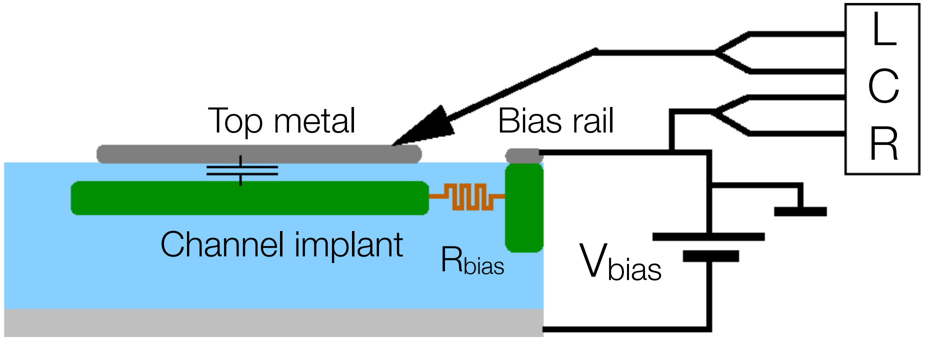
R_{IS}: typical results for DC measurement

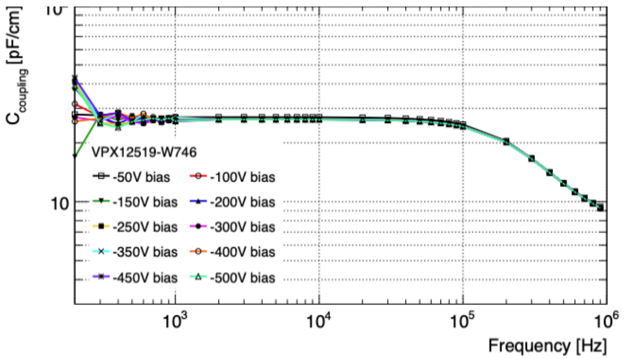
- Before PTP gap acts: measurement sees R_{bias}
  - PTP breakdown changes R to O(10kΩ)
  - Implant resistance O(1kΩ)
- Surface structure: altered by charged particle flux
  - Need to make sure PTP performs well towards end of detector lifetime

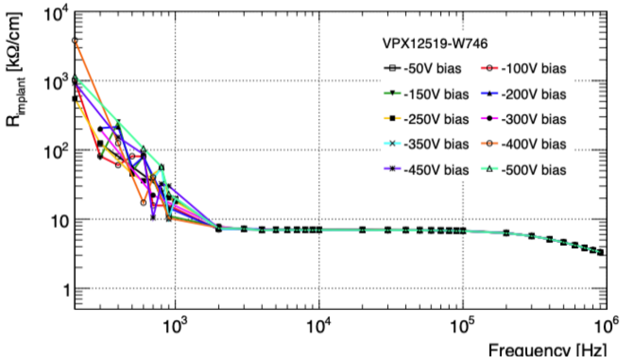
Multi-channel characterisation

Coupling Capacitance
Strip test protocols







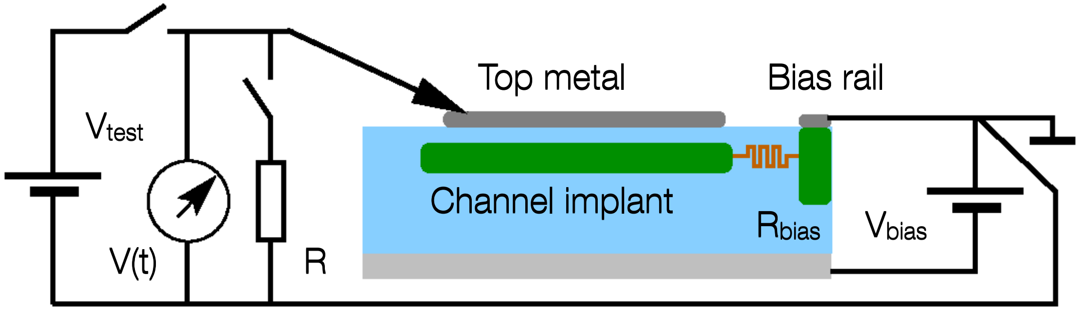


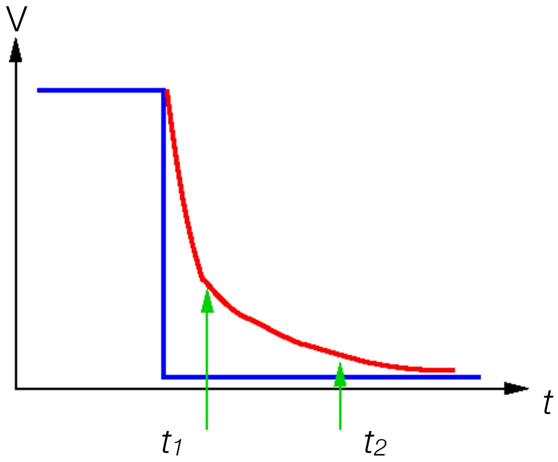
AC coupled channels

- Coupling capacitance between implant and top metal
- $C_{\text{coupling}} >> C_{\text{is}}$
- Resistive implant and coupling capacitance form lossy transmission line: high *f* drop-off
- Bond pads and other structures add capacitance
- LCR: measure R_{bias} - C_{coupling} network in one go
  - Determine suitable *f*
- Gives access to
  - insulation thickness,
  - uniformity across wafer
  - R_{bias} / Poly-Si process monitoring

Coupling capacitance: V step function

- LCR meter really convenient here, measures R, C in a single shot at high rate
  - Non R-C like behaviour detected by R, C values deviating from expectations
- V Step function is tricky to implement and data analysis is more complicated
  - Needs device to record *V(t):* oscilloscope
  - Data compression by measuring at discrete time intervals
  - Can provide more information in case of ‘bad’ channels

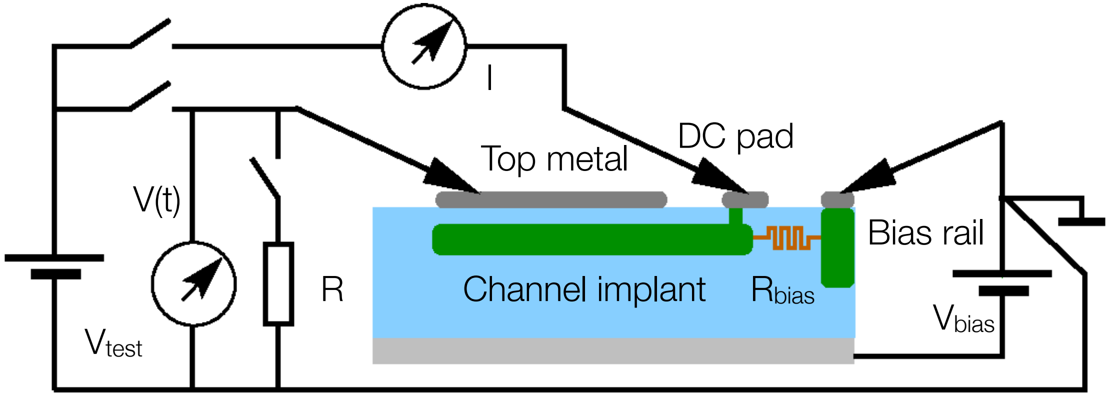


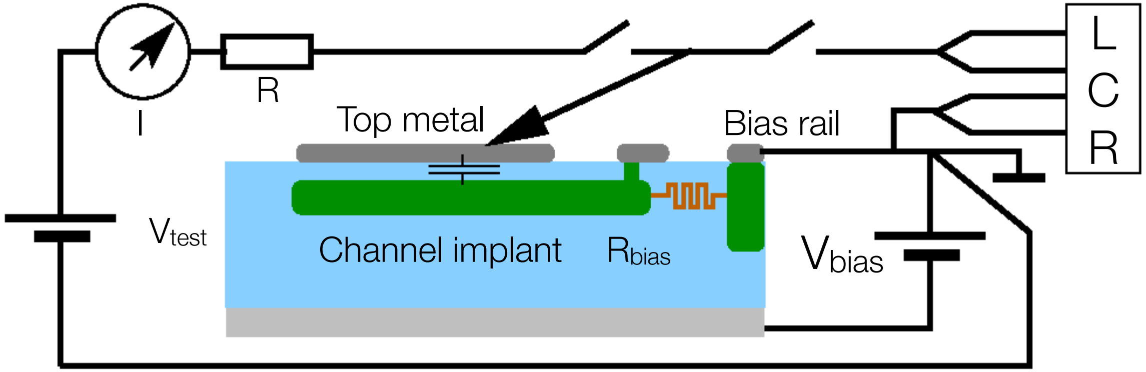


Biased AC coupled structures

- Access to more failure modes

Strip test protocols

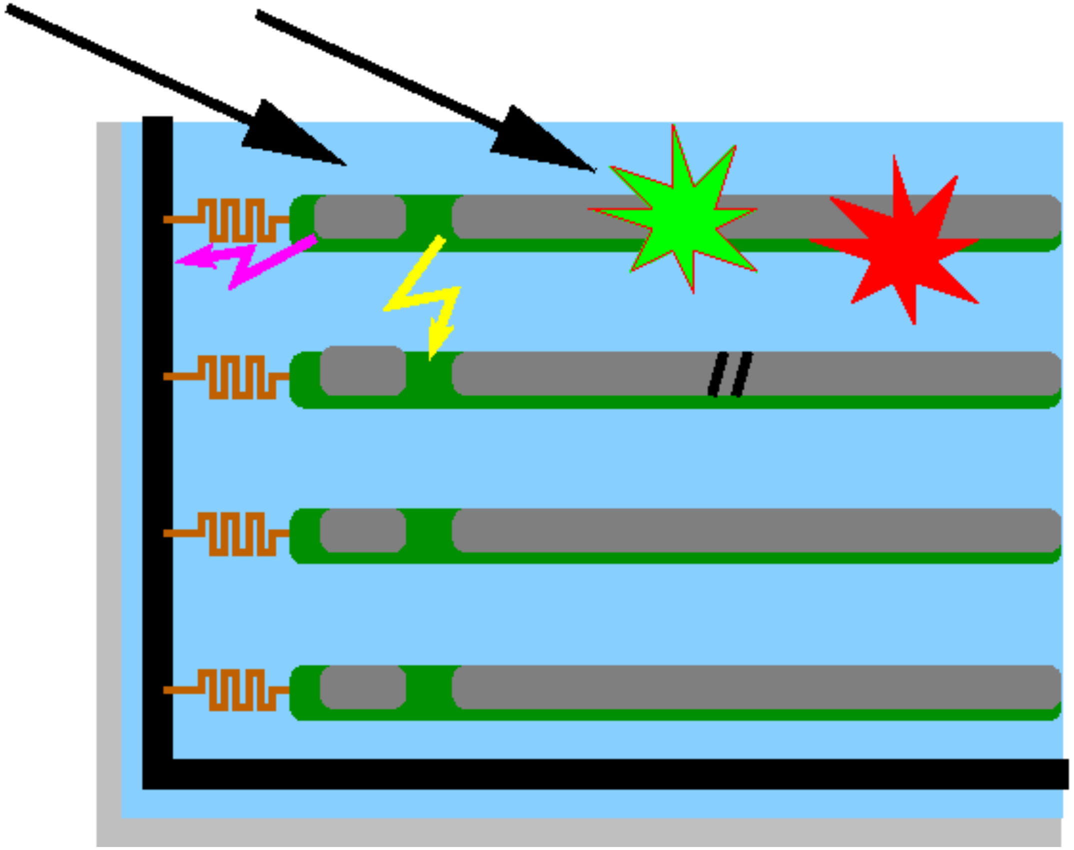


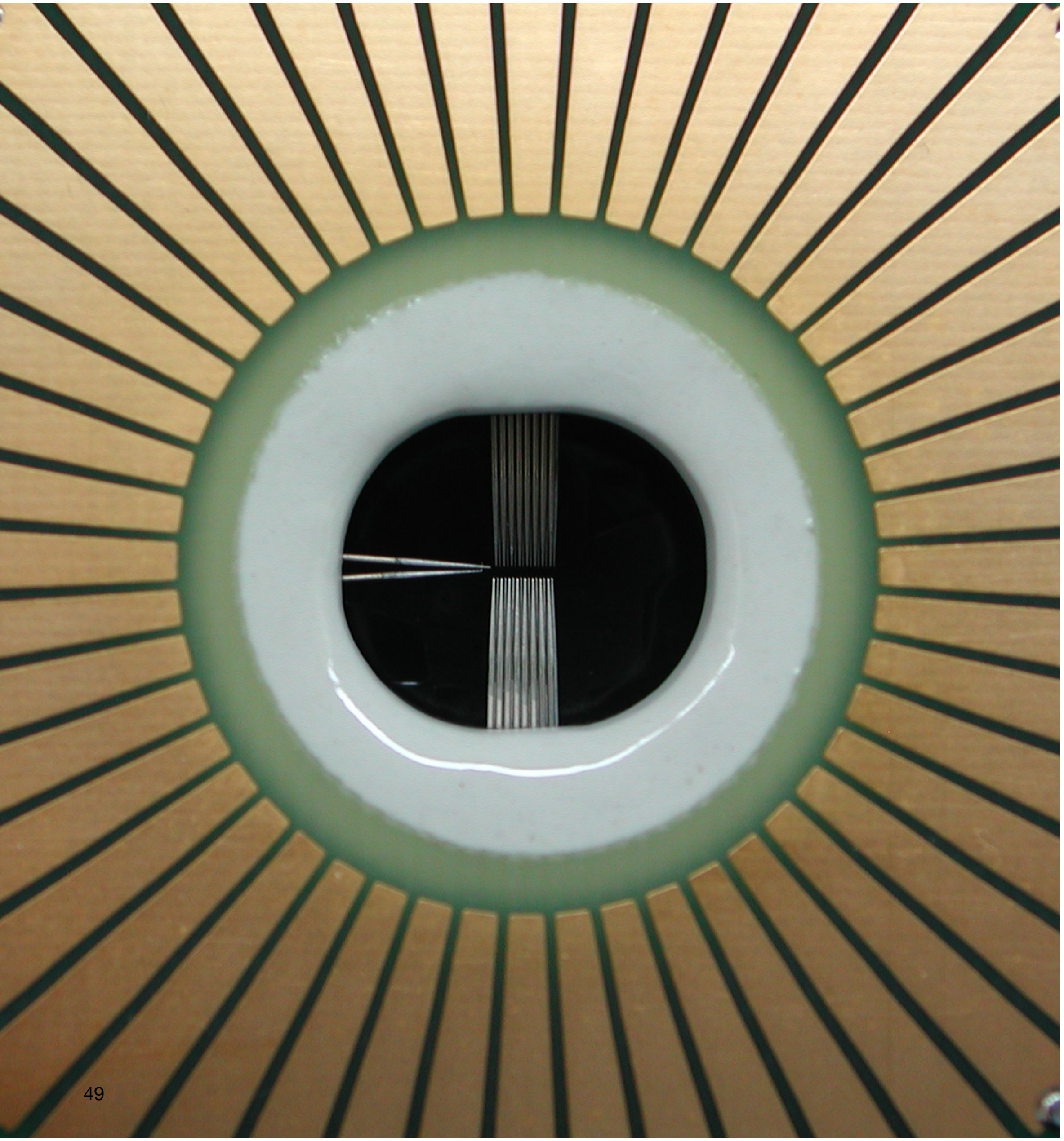


- Different contact mode: AC & DC pad, or AC only
  - Either method can:
    - Measure R_{bias} (direct vs LCR)
    - Measure C_{coupling} (V_{step} or LCR)
  - Assess failure modes
- Option to contact multiple strips simultaneously:
  - Allows for C_{is} / R_{is} measurement
- If DC pad sits at “far end” of the strip, implant continuity/resistance can be measured

Strip test protocols

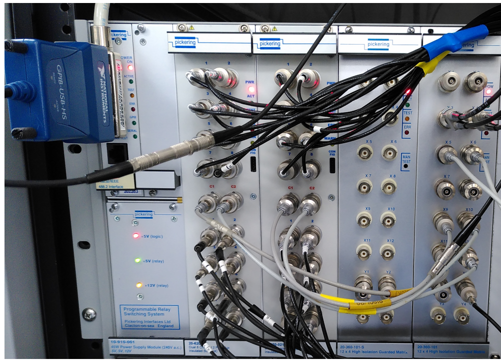
- Failure mode detection
  - **Short**: high current at low V between top metal and implant
  - **Pinhole**: high current at higher V between metal and implant
  - R_{bias} out of specification: short, open, short to neighbour
  - $C_{coupling}$ out of specification: metal break / Implant break, isolation layer thickness
- Single/dual needle vs multichannel operation





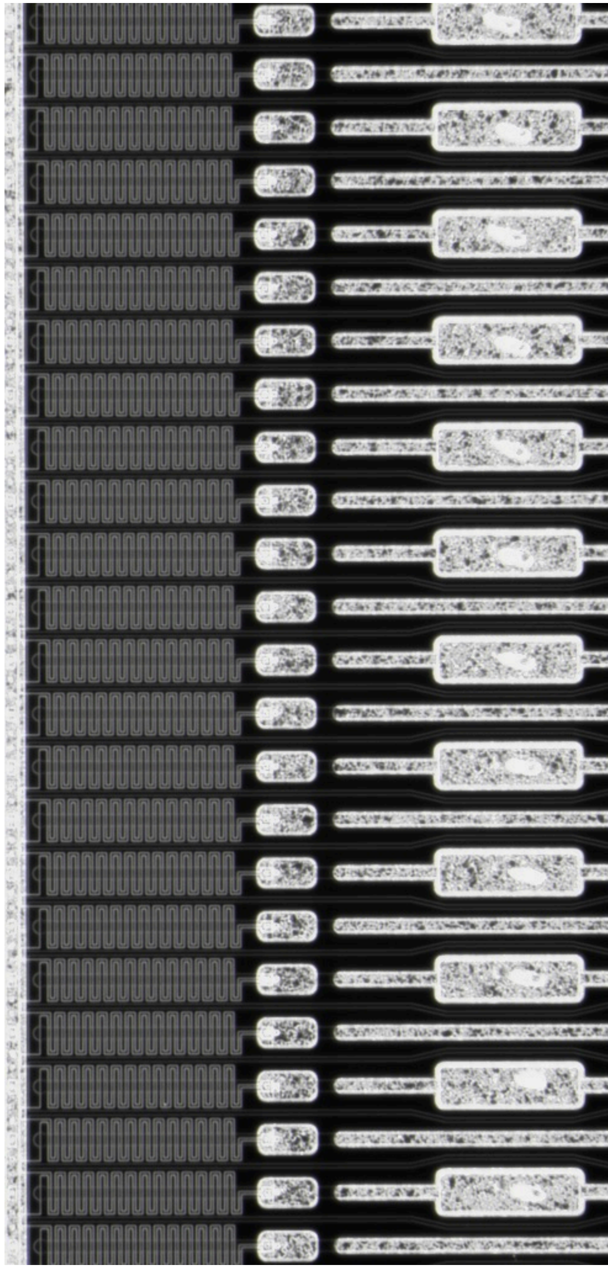
Probecard

- Off-the-shelf PCB with precision placed needle in a low-leakage epoxy insert
- Quick multichannel sequencing of tests
- Probestation: platen mounted vs chuck mounted
- Touchdown needles
- Parasitic capacitance
- Switching equipment
- Controls
- Cleaning



Advanced Imaging

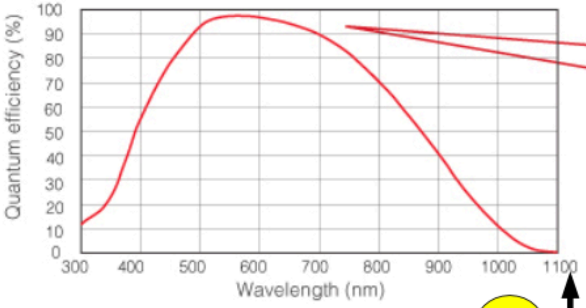
Pinpointing breakdown in Silicon sensors



Advanced Imaging: pinpointing sensor breakdown

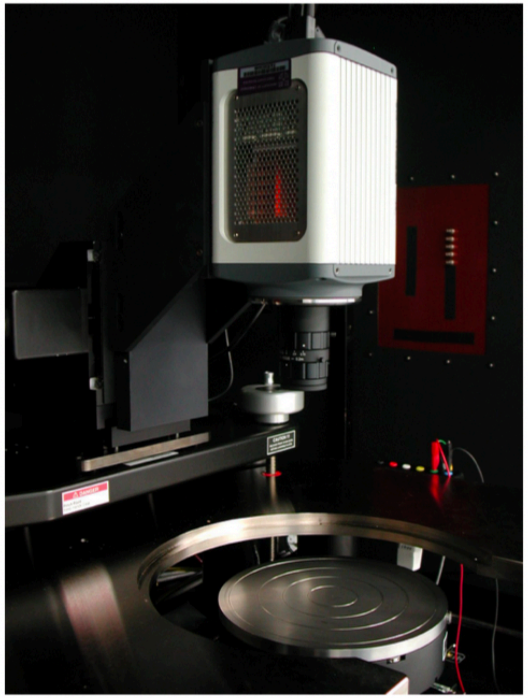
- SW-IR to image Si bandgap emissions
- Using Si to detect Si photons - really?
    - 1.12eV ~ 1107nm
- Back-thinned EM-CCD at -50°C helps!
- Low QE, also very low noise

- More elaborate semiconductor analysis kit has this built-in (HPK PHEMOS)
- Alternative methods exist:
    - Lock-in thermography (destructive)

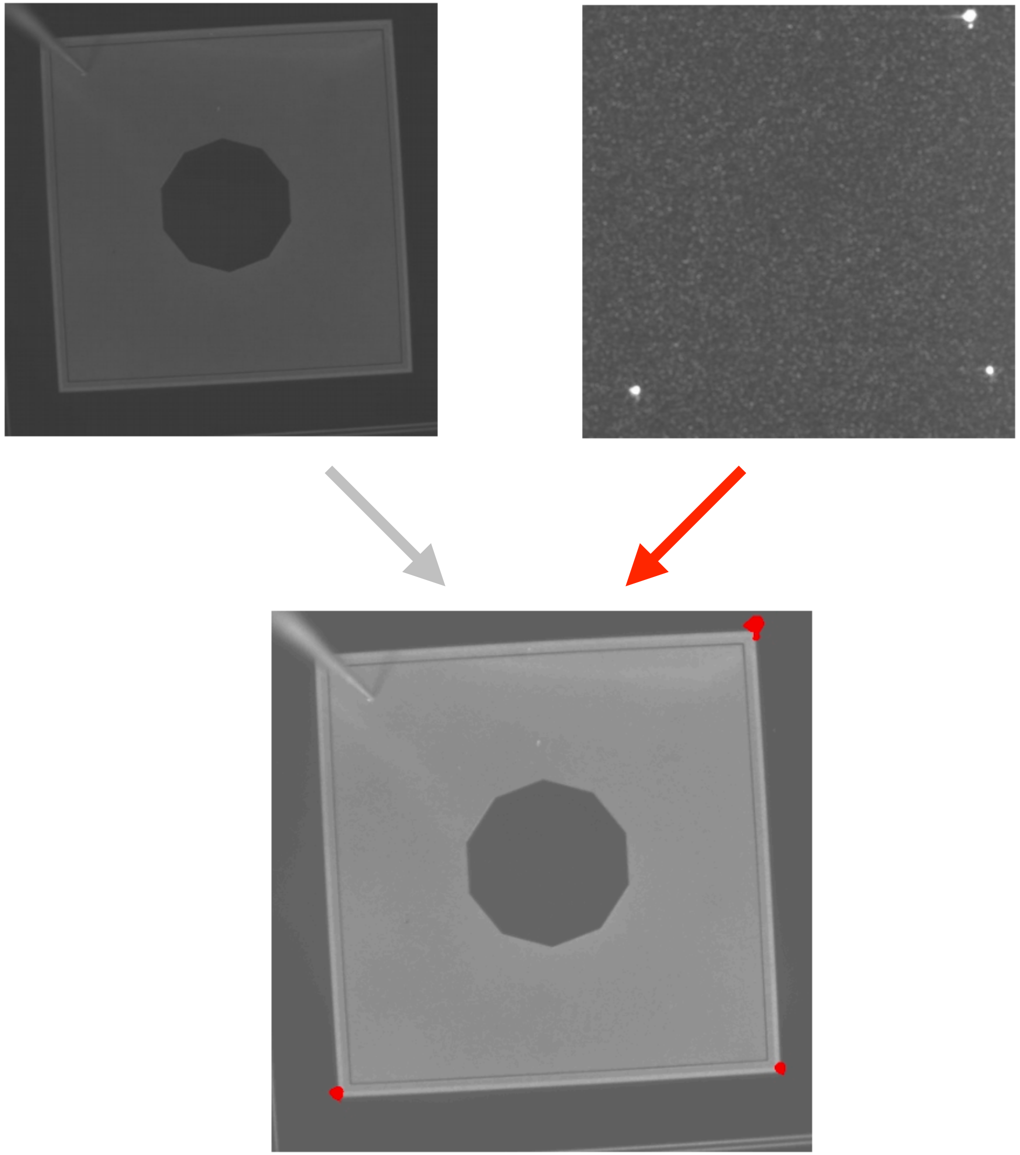


The beloved EM-CCD sensor provides over 90 % peak QE.

We want to be measuring here: 1.12eV Si bandgap



CC126MU

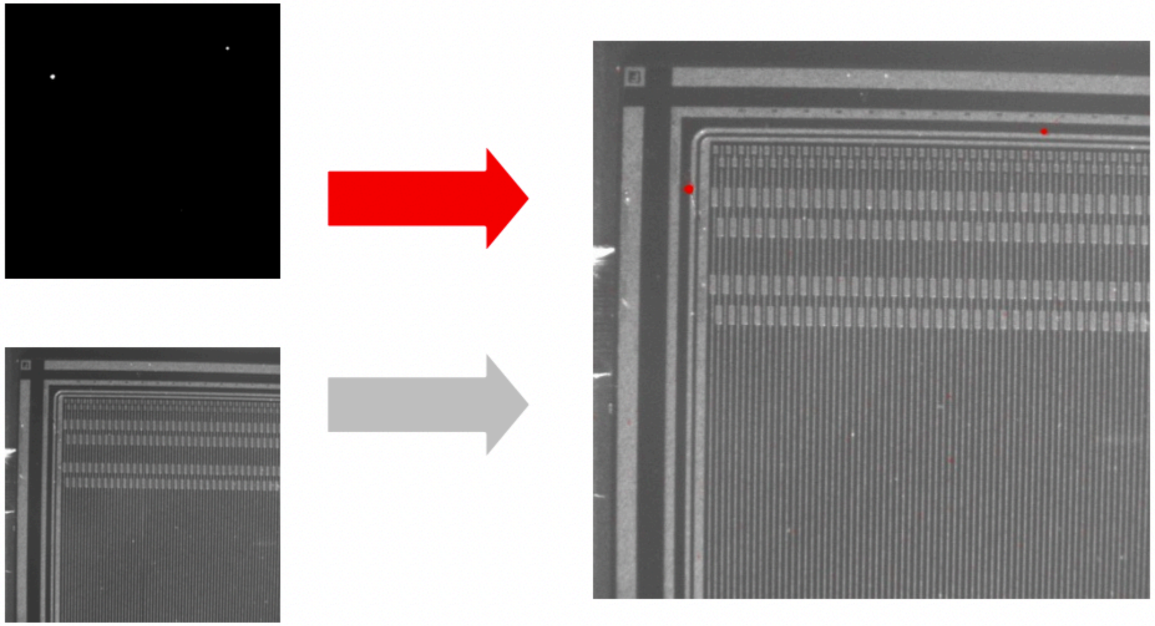


Breakdown imaging

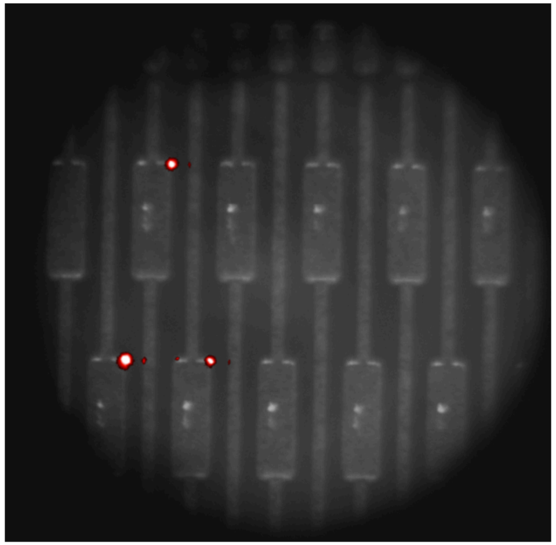
- Test structure: simple square diode
- Take image in low light conditions
- Push into breakdown
  - No current limiting resistor
  - Rely on HV source current compliance instead
- Overlay both images

Imaging: features

- Bias current has to go to high levels
  - Potentially damaging the device
- Imaging of scratches, breakdown points
  - Reveal high E-field concentrations



- Metal-implant E-field concentrations



- SW-IR cameras used for many other semiconductor debugging tasks
  - MAPS/CMOS….

Source measurements

- Different emitters to establish detector performance:
  - 55Fe: 5.6 keV X-rays
  - 137Cs: 0.51 MeV ß-
  - 90Sr: 0.9336 MeV ß- (avg)
  - 241Am: 5.486 MeV α
  - 22Na: 0.543 MeV ß+

X-ray tubes

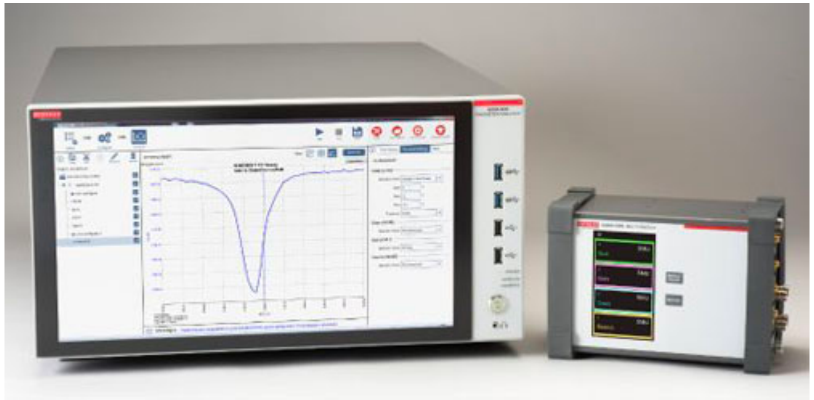
- X-rays: spot ionisations
- Rate capability / detector current
- Resolve muons (comics) whilst being irradiated with X-rays
-

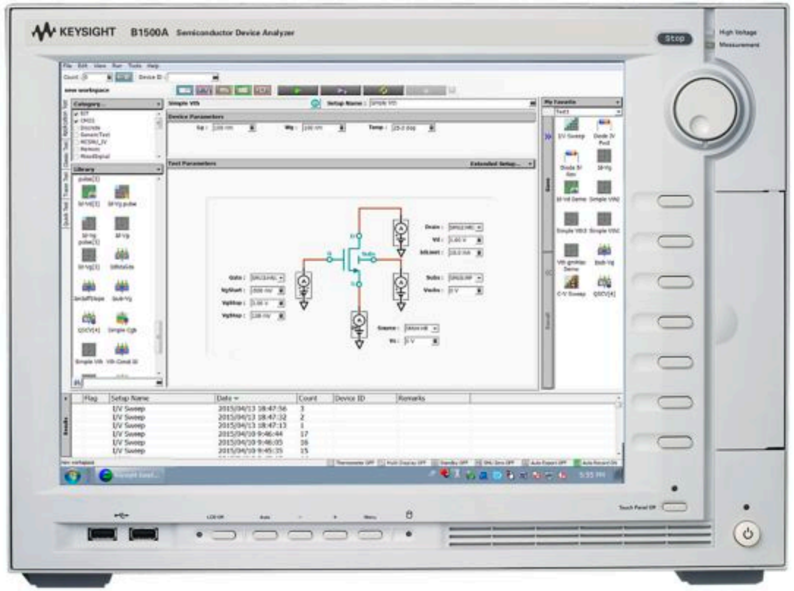
Measurement Equipment

A few examples

Semiconductor Analyzers

- All-in-one unit. Pros:
  - DC, AC and pulsed measurement
  - Automated parameter extraction
  - Very fast & efficient
- Cons:
  - Might not have all desired tests on board
  - High-Voltage capabilities
  - Channel by channel tests
  - Test integration



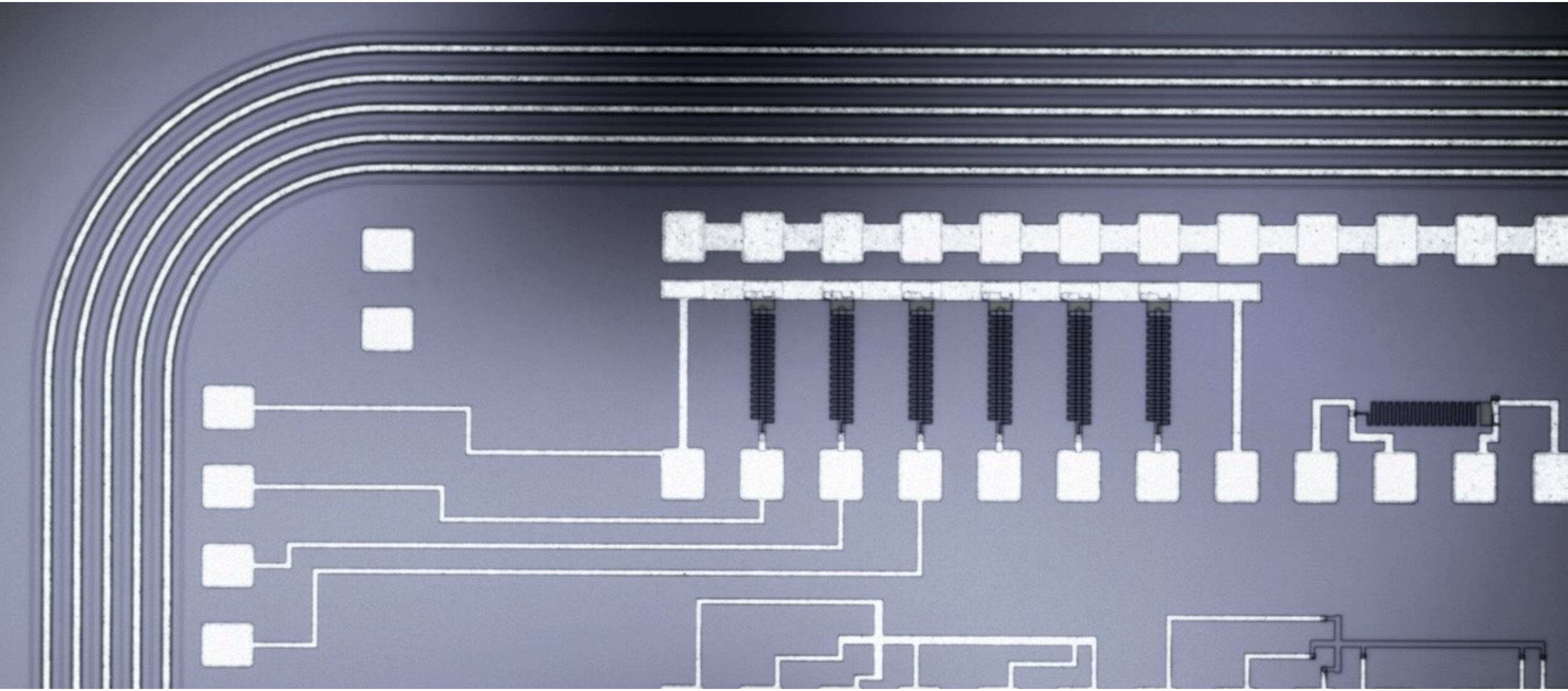


Discrete instruments

- Source Measure Units (SMU)
    - Full floating V or I sources with V, I, R measurement built in
- Current Meters
    - More sensitive than SMUs. I measurement only
    - Built-in voltage source, entirely stand-alone.
- Switch equipment
    - Matrix, multiplexers, switch banks
- Multimeters
    - Input impedance, accuracy
- Many connectors -> potential points of failure
- Software control: lots needed to compete with Semi Analyzers

Electrical measurements: instruments & controls

- Computer control:
  - GPIB/IEEE 488.2: slow, expensive, clunky cables, limited cable length, bombproof
  - USB: up to 128 devices on single bus. Very versatile, difficult to debug
  - Ethernet: very fast, very versatile, well supported. High reliability, cheap-ish
  - RS-232: point-to-point, slow



Thank you !

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