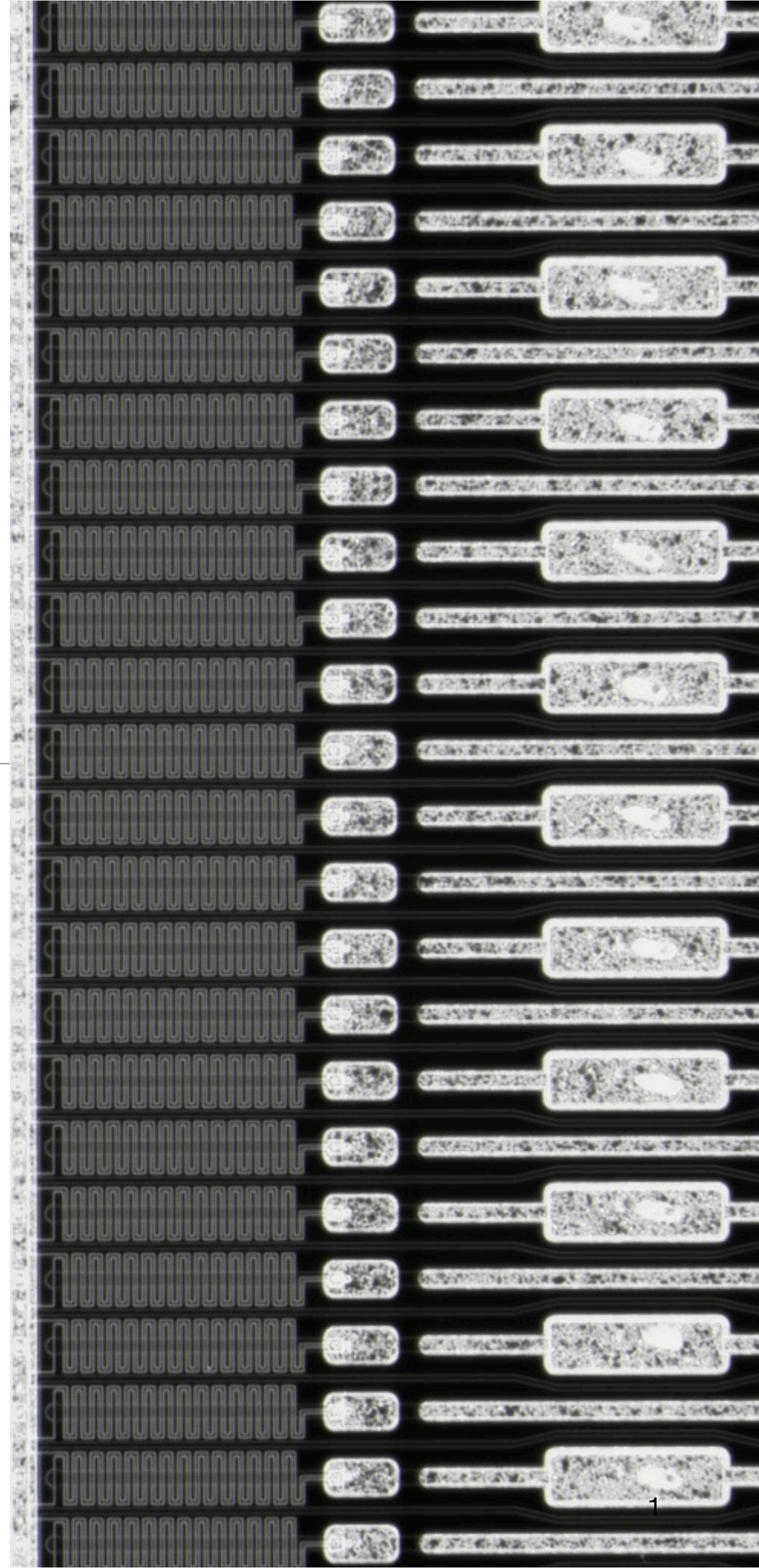# Advanced UK Instrumentation Training 2022
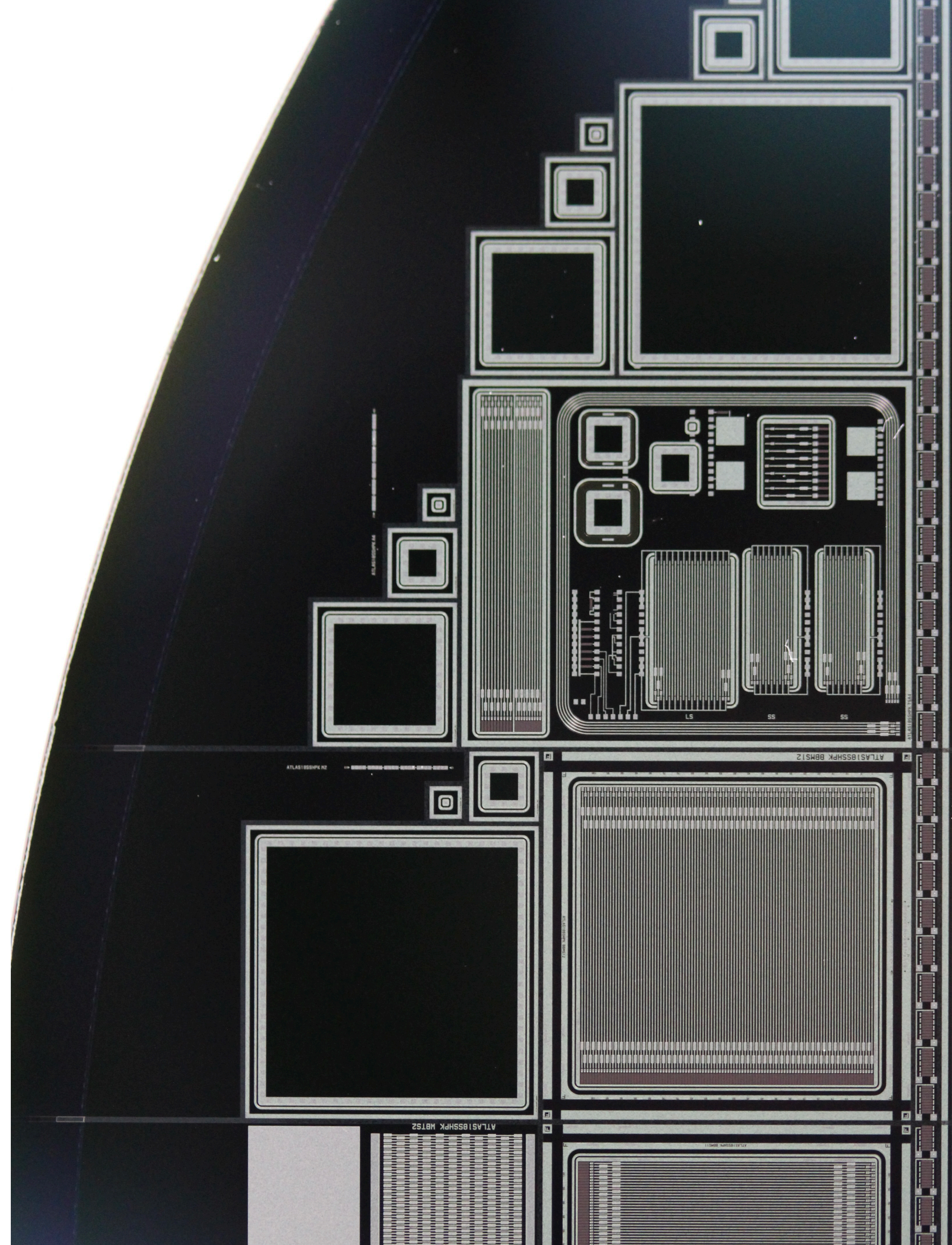
Lab Techniques - 2

Bart Hommels - Cavendish Laboratory
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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}!
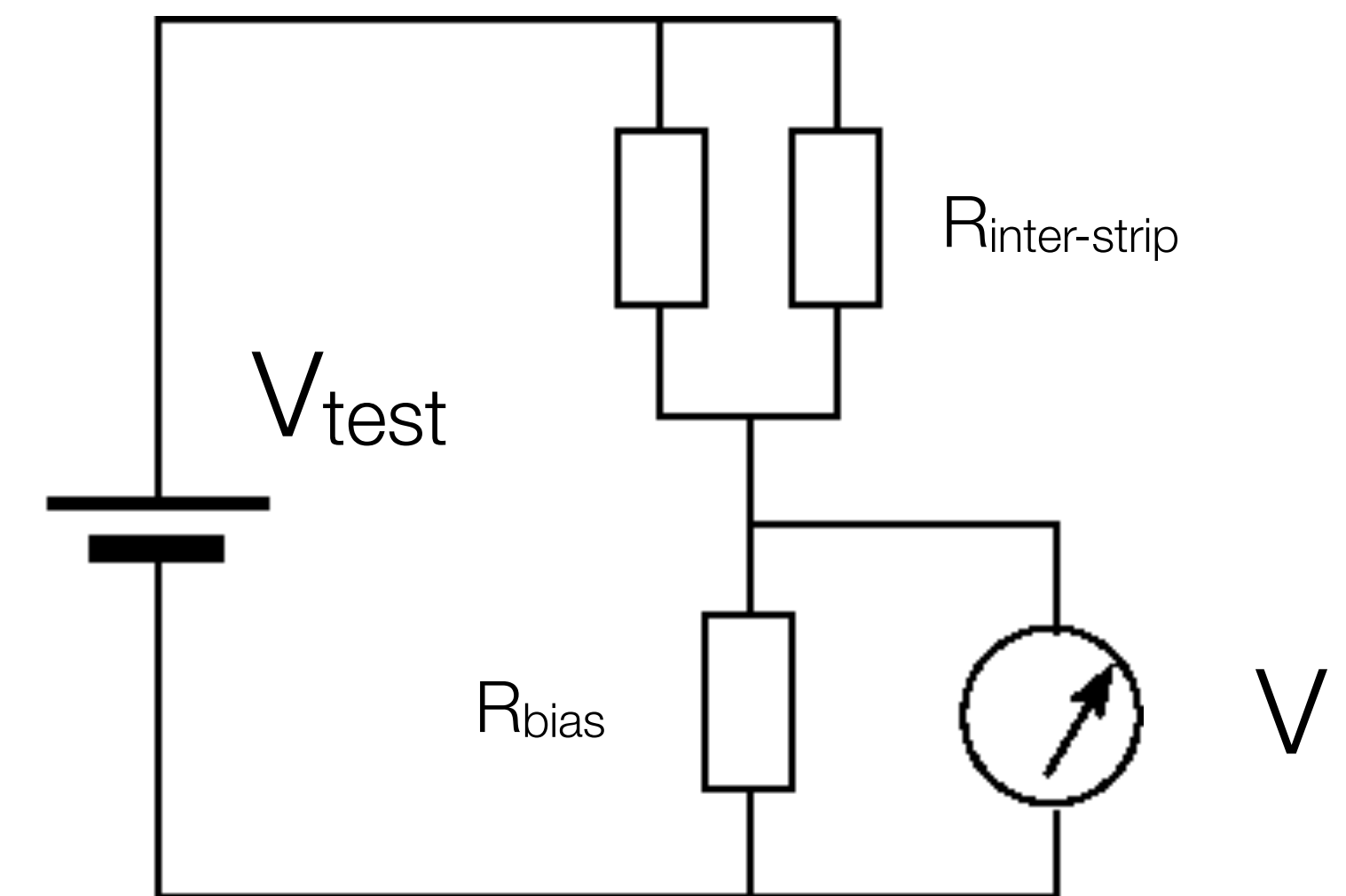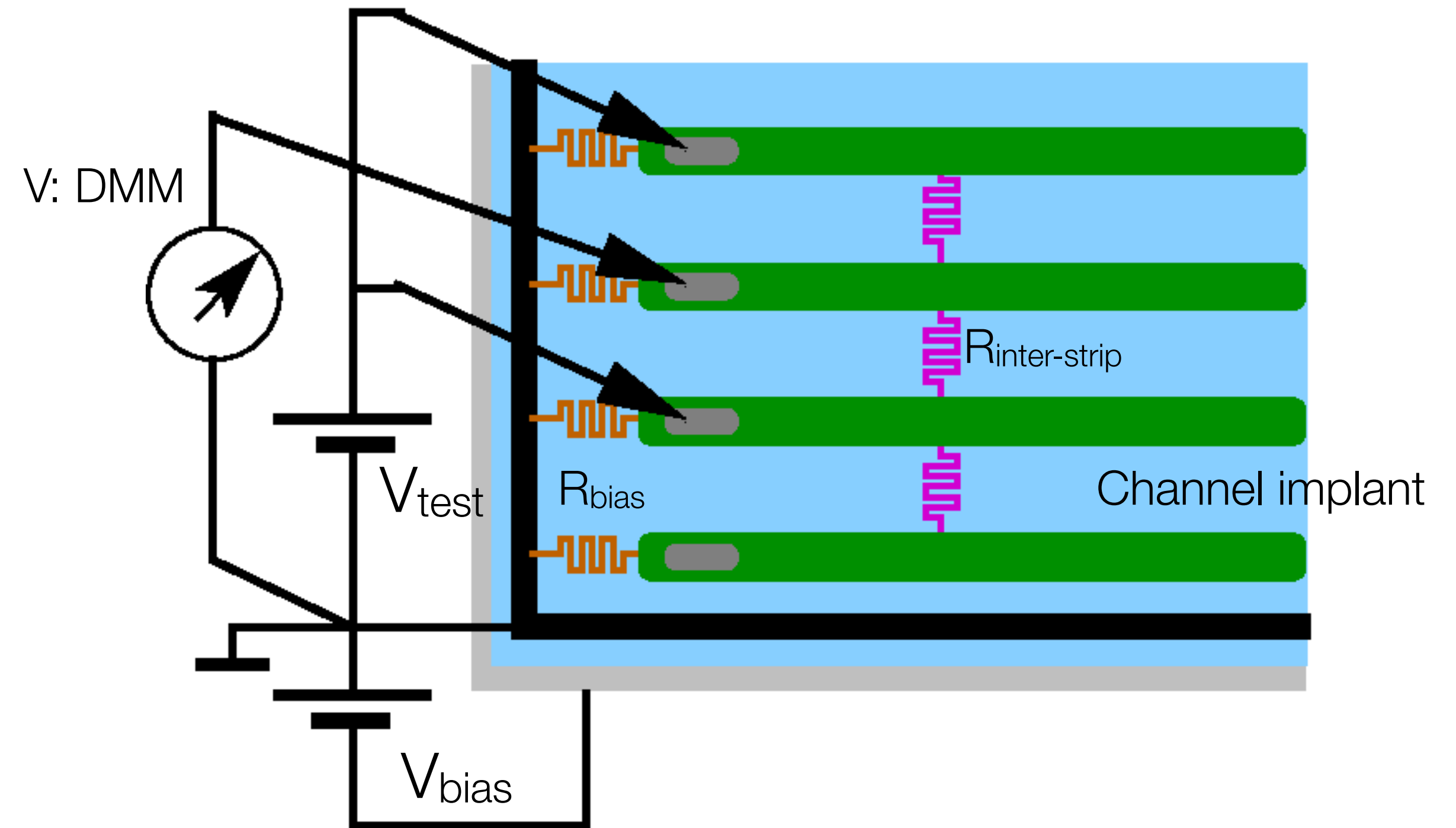
R_{is}: typical results

- 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-Strip Resistance
VPX12318-W604

Inter-channel capacitance
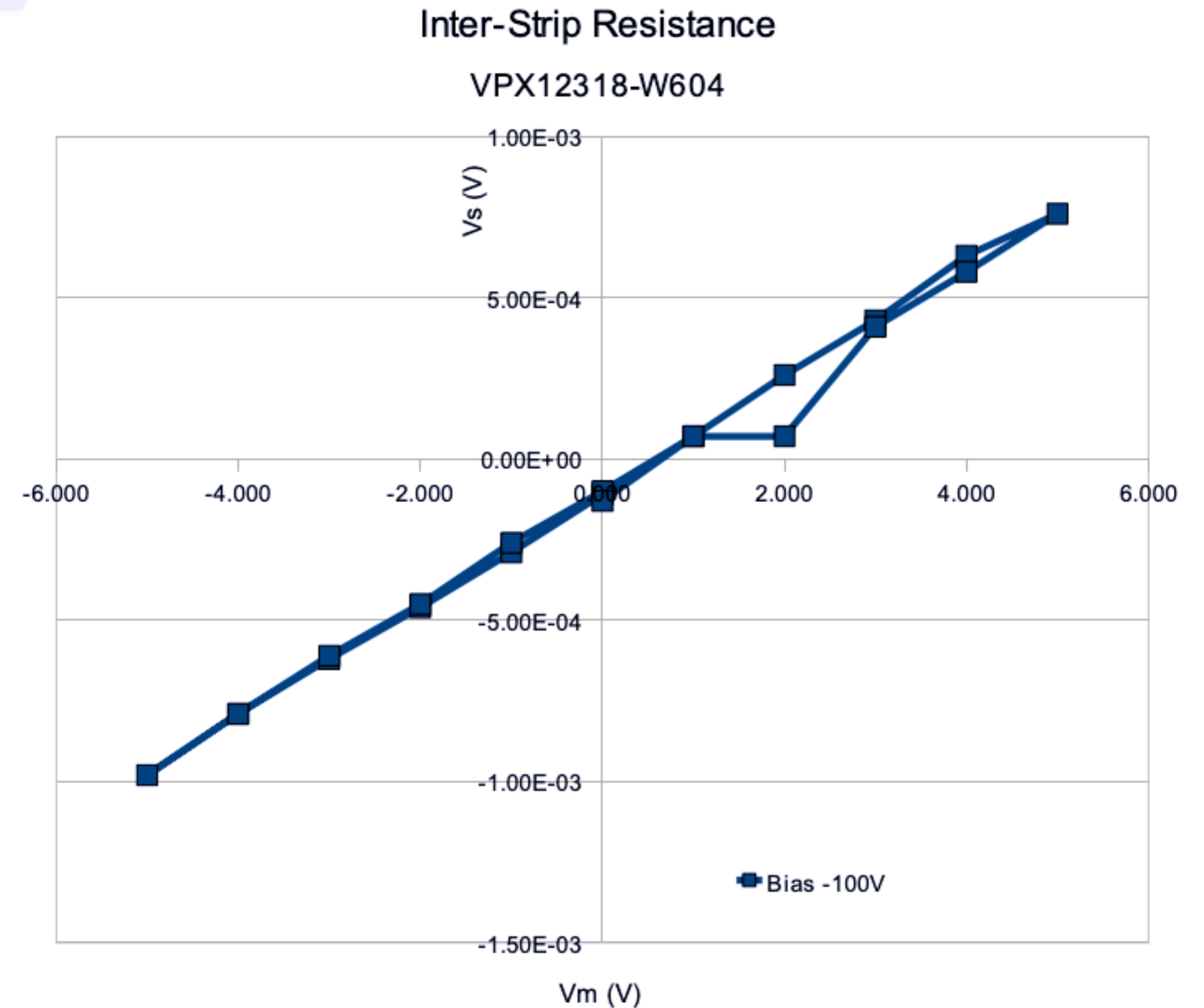
Expect some increase between single chips and modules due to:
• Strip resistance
• Inter-channel capacitance

- 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

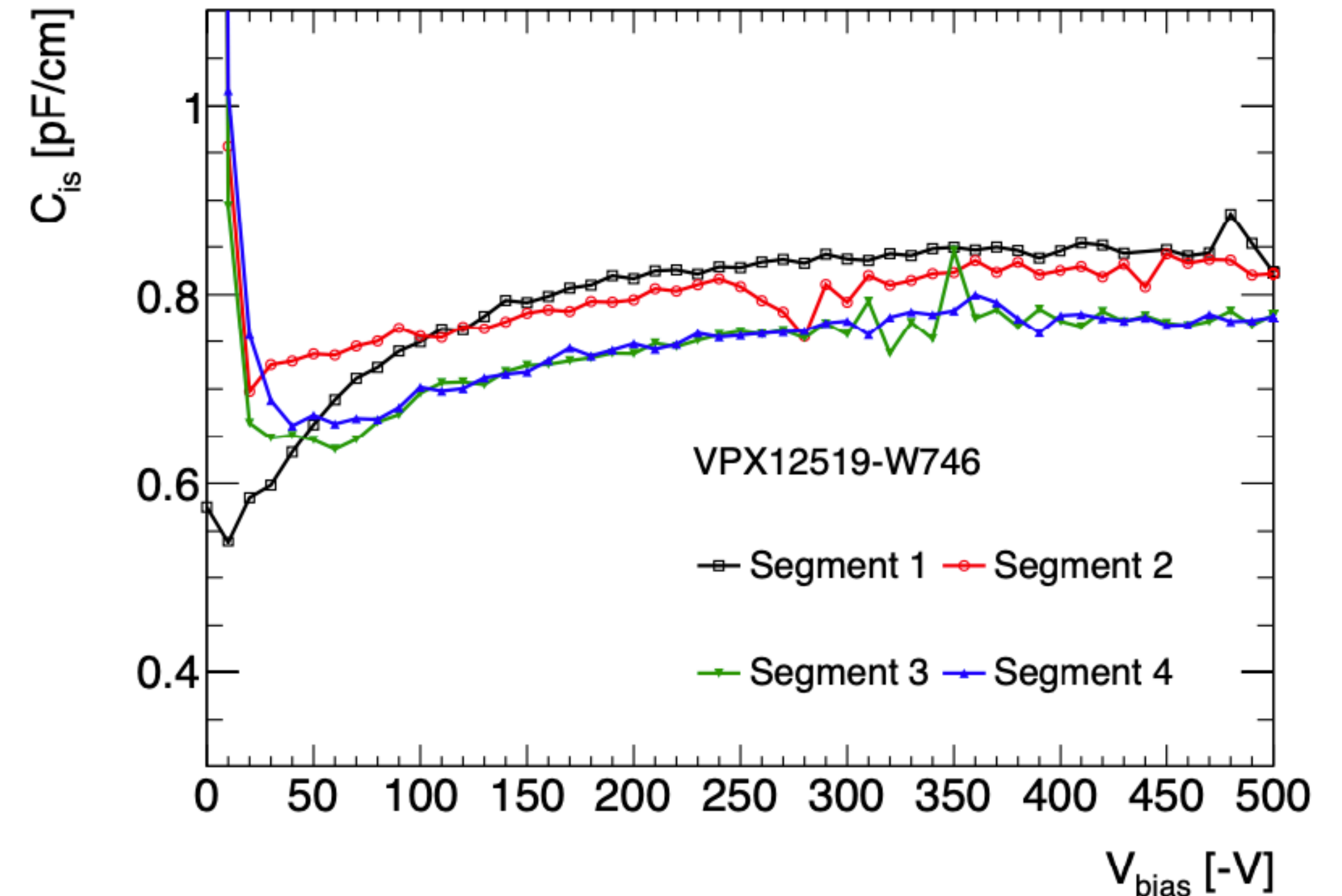 - CMOS detectors: different trade-off since diffusion more important than drift (IF)
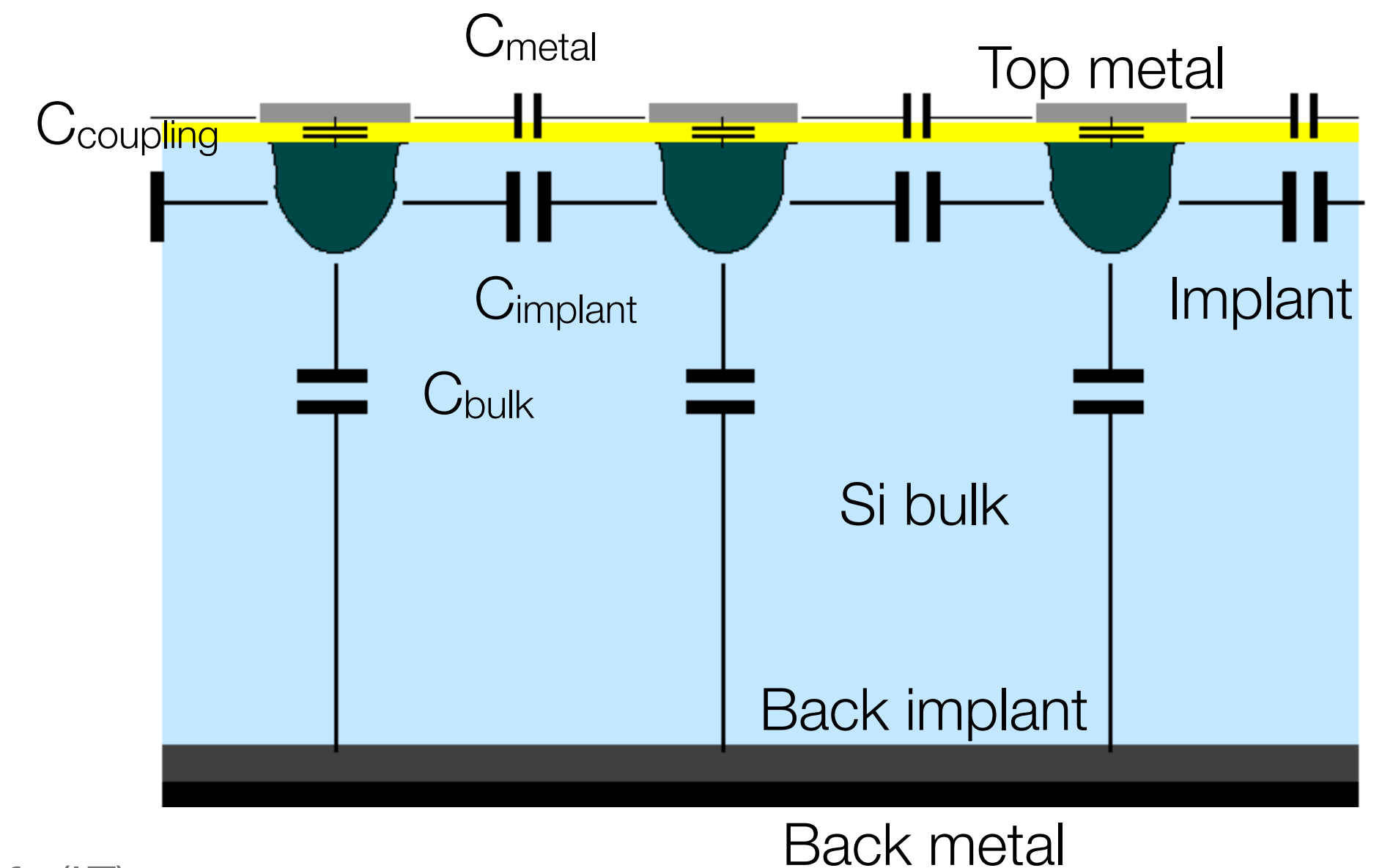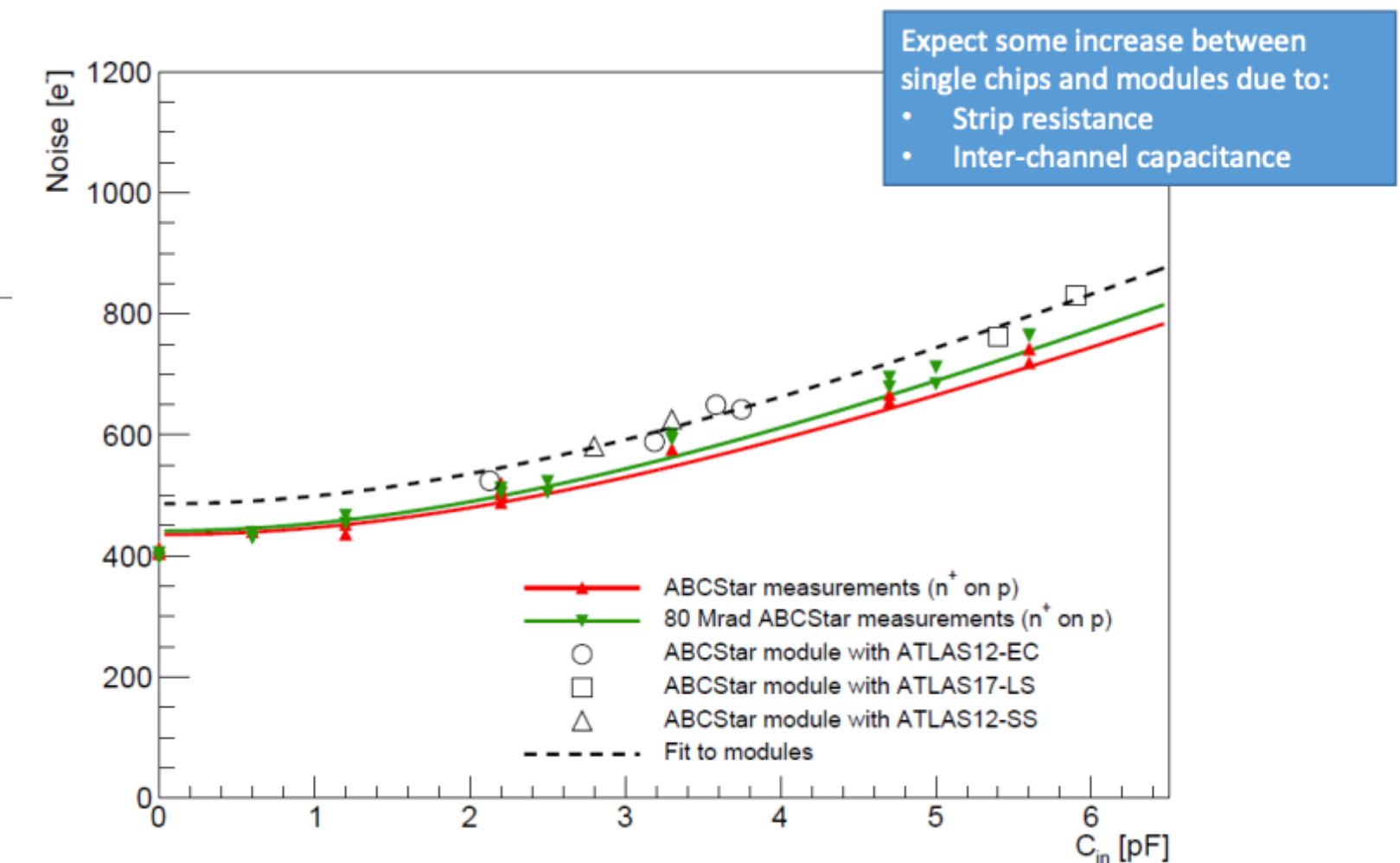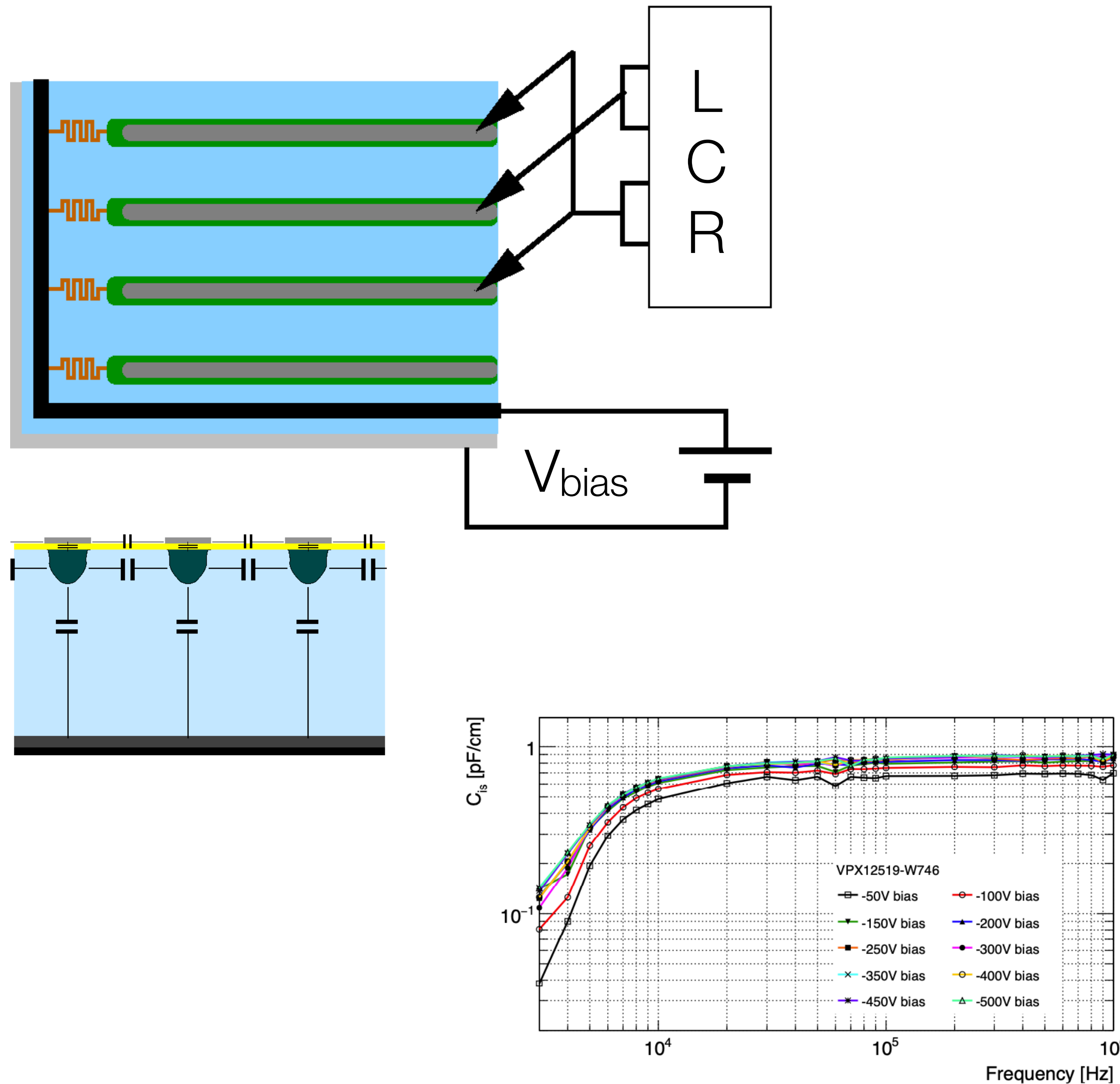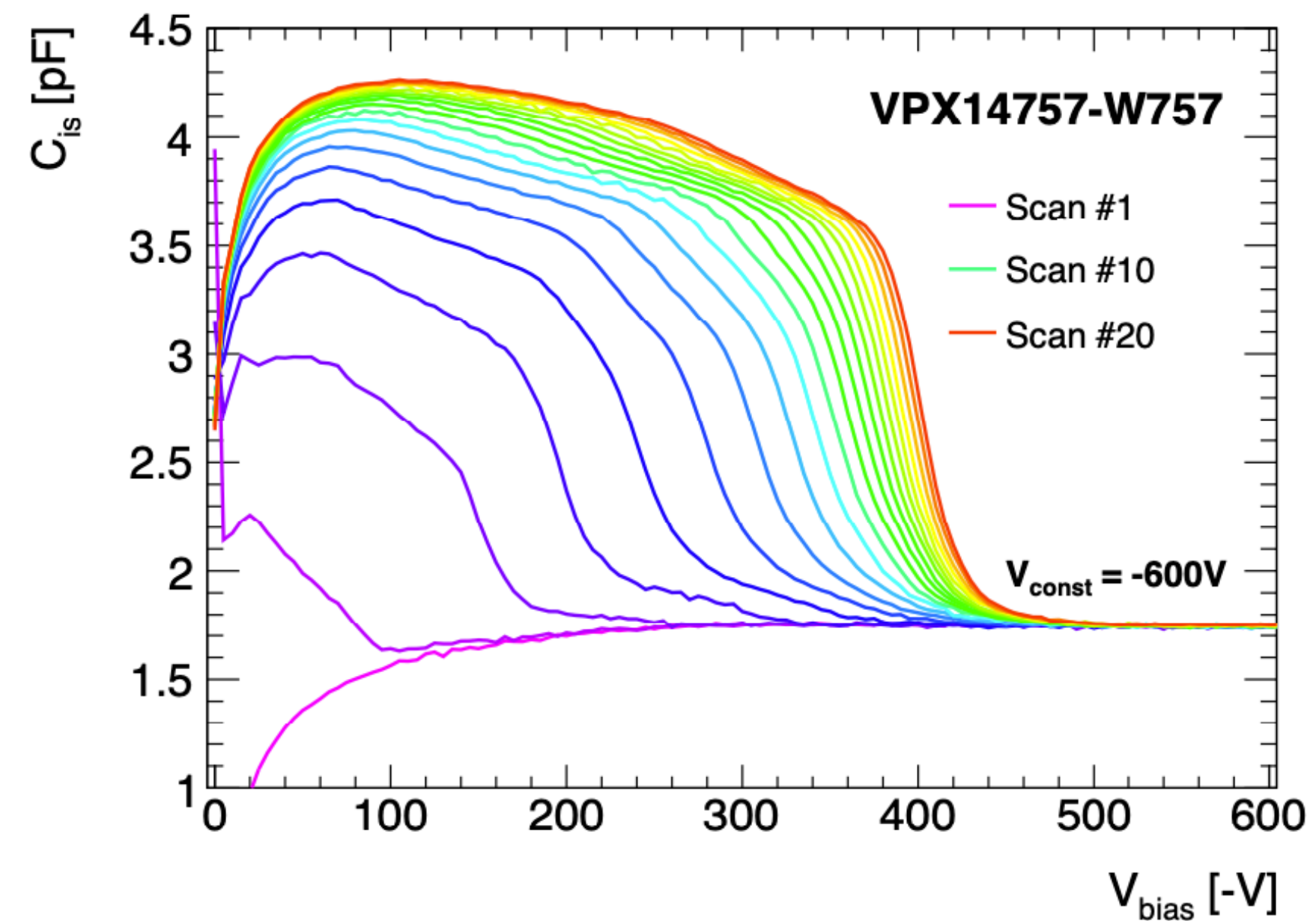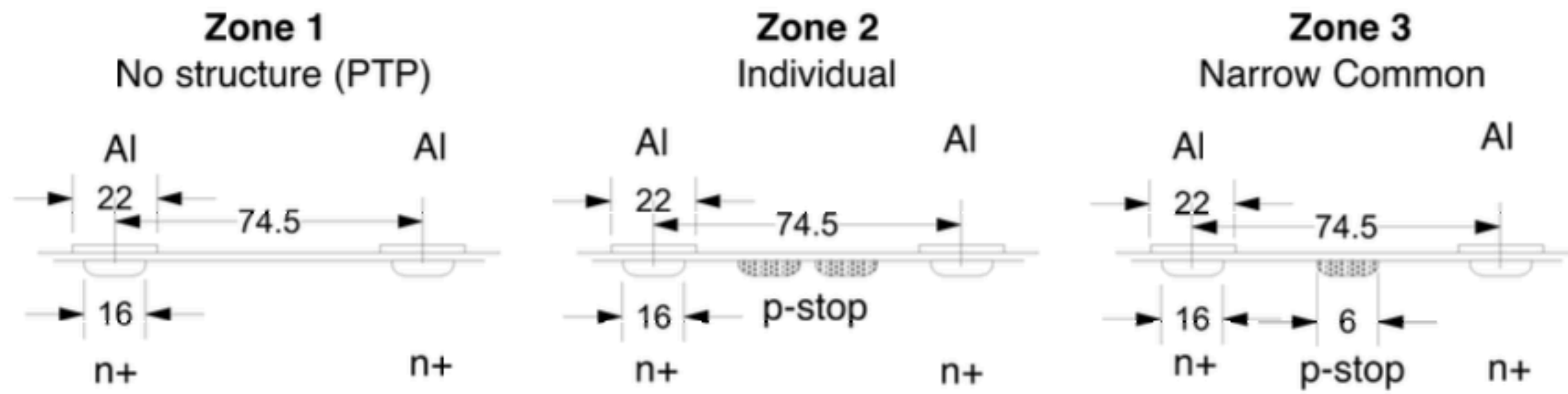
Cis/Cip measurement

- 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…

Zone 1 — No structure (PTP)
Zone 2 — Individual
Zone 3 — Narrow Common

VPX14757-W757

Scan #1
Scan #10
Scan #20

$V_{const} = -600V$

# 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, -20oC):

  - Cluster size not as predicted
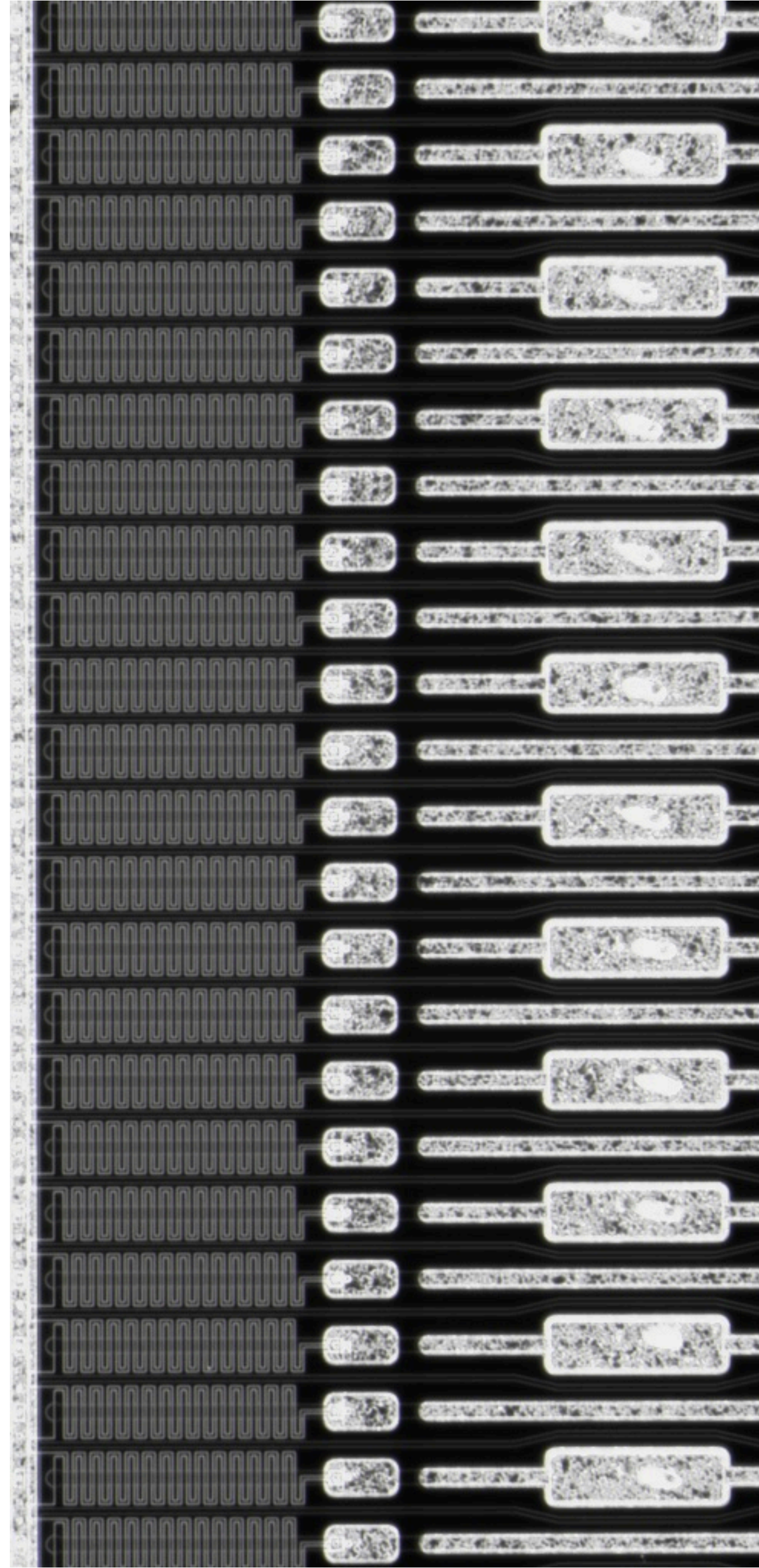
  - Higher noise

  - Could take hours/days to settle!
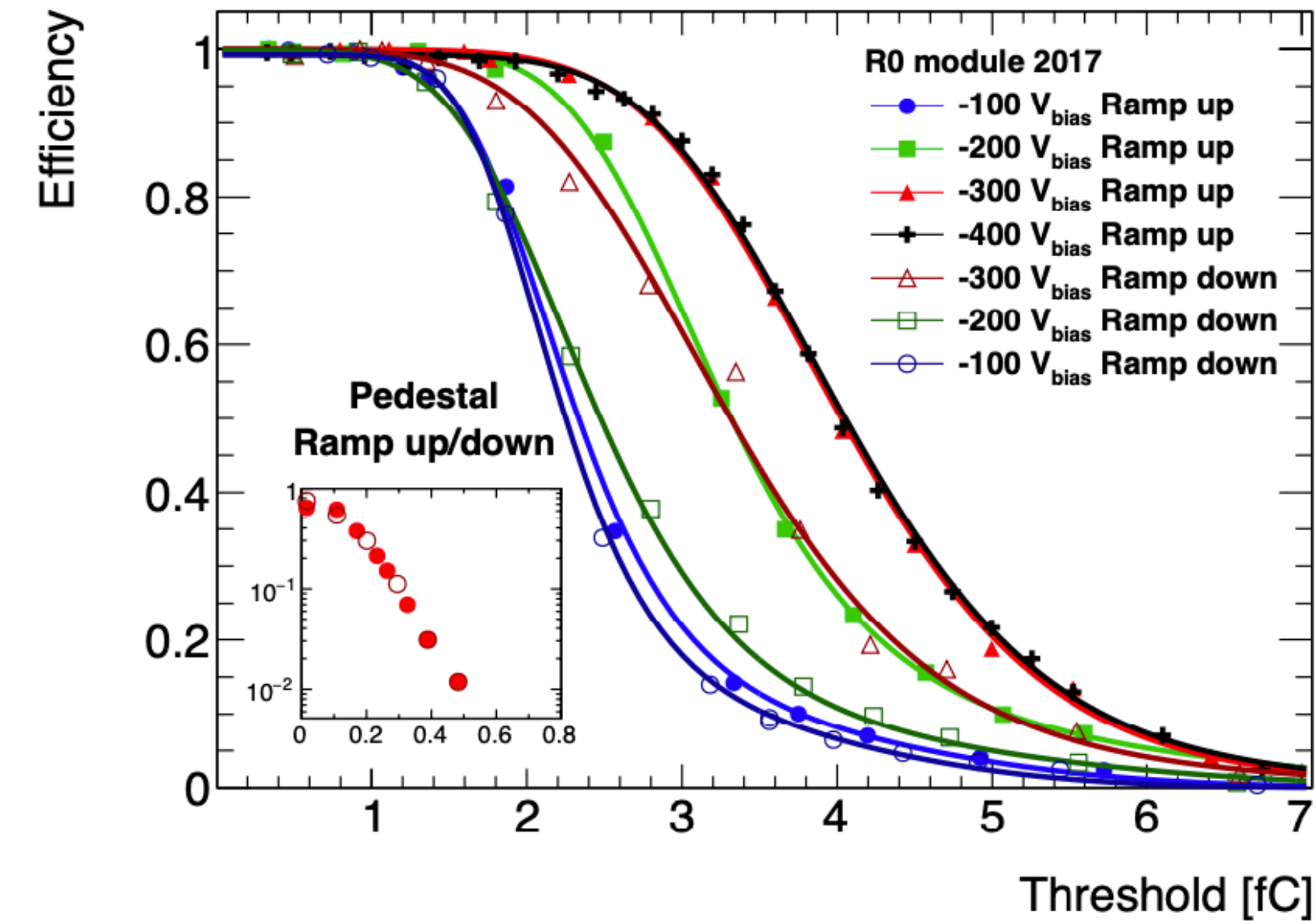
DESY testbeam data on ATLAS ITk strip modules
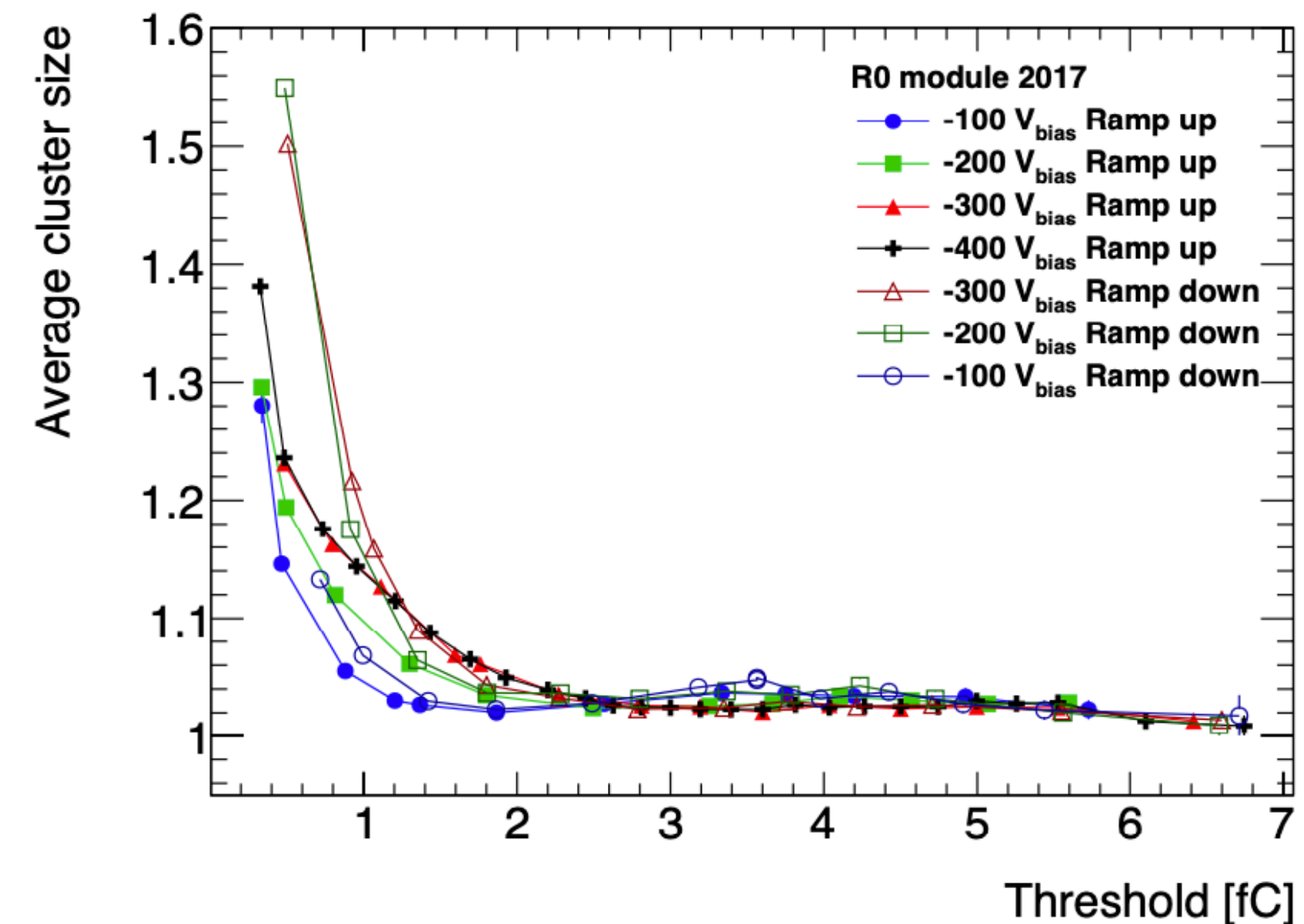
Test Structure Measurements
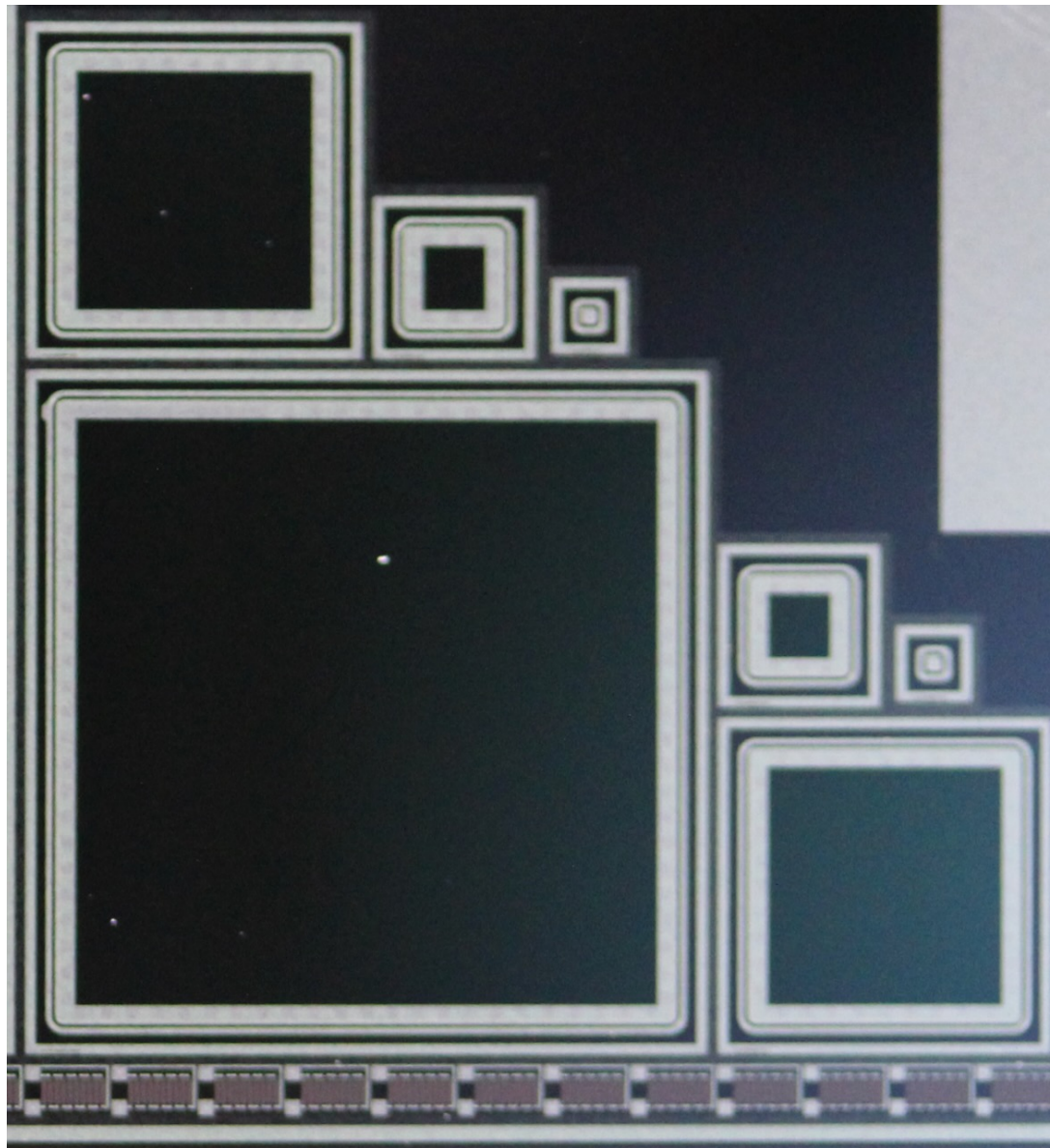
Flat-band Voltage
Punch-Through Protection

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
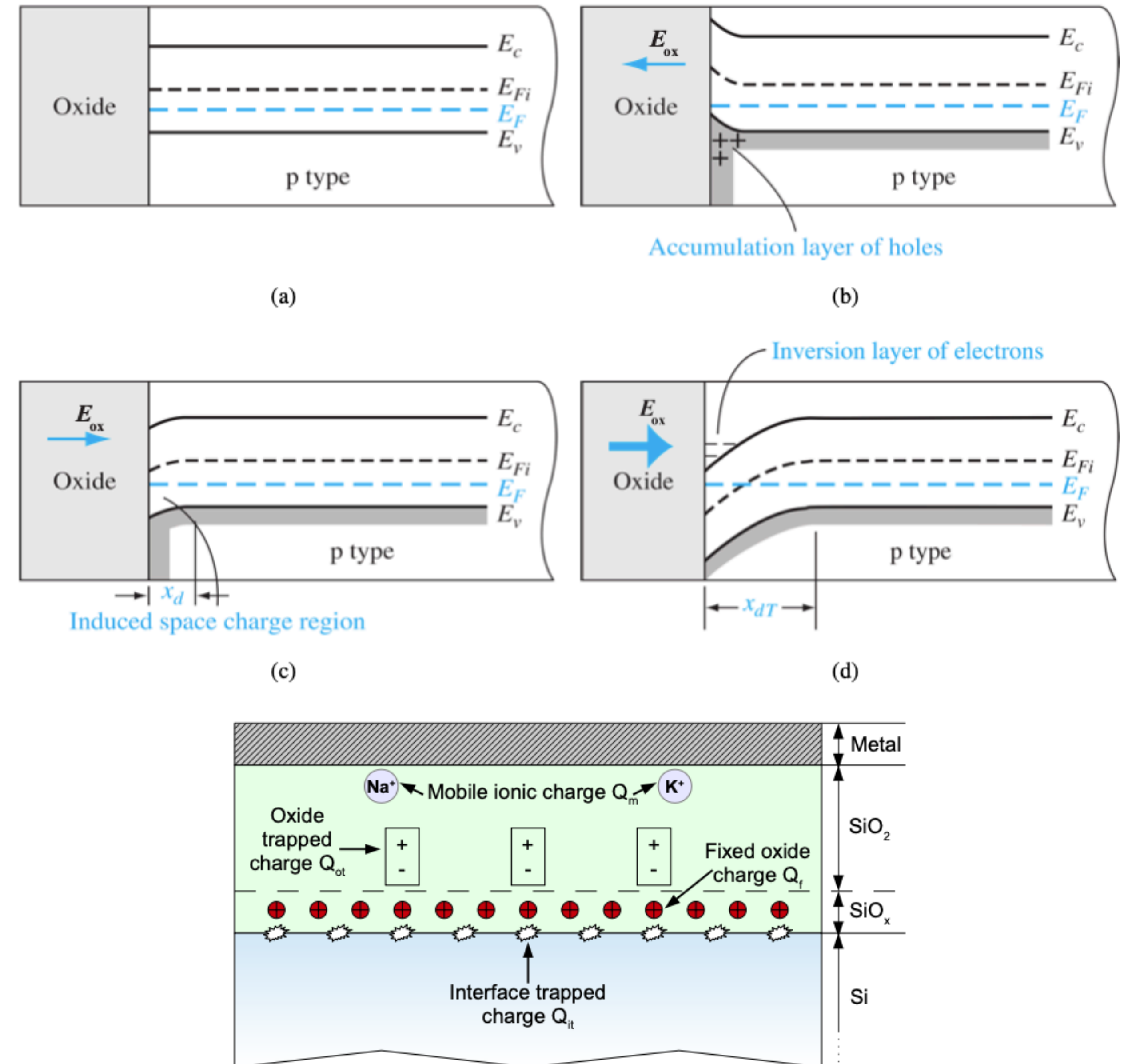
Measuring V_{FB}: MOS structures

- Gate capacitance:

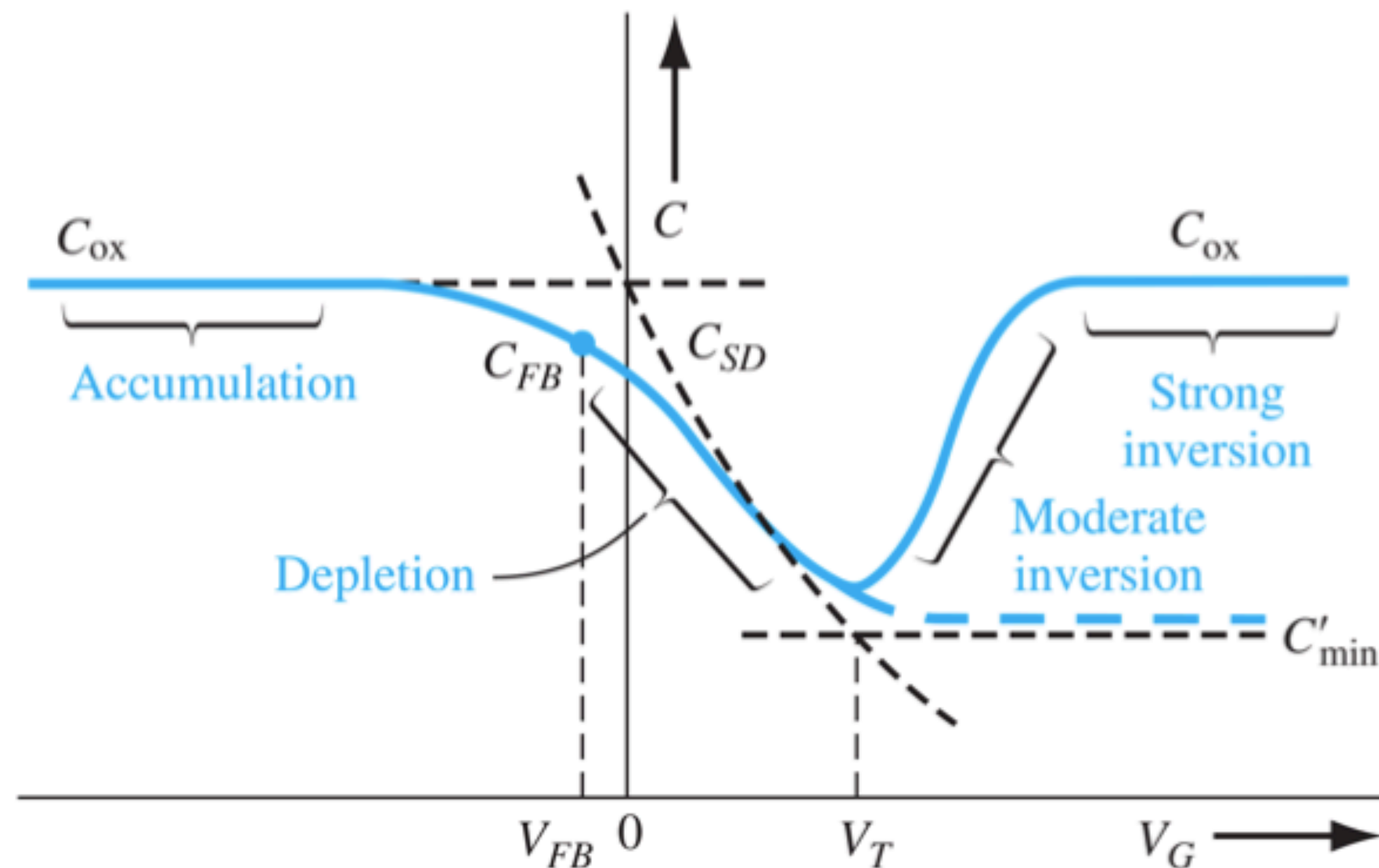$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}A$$

- 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

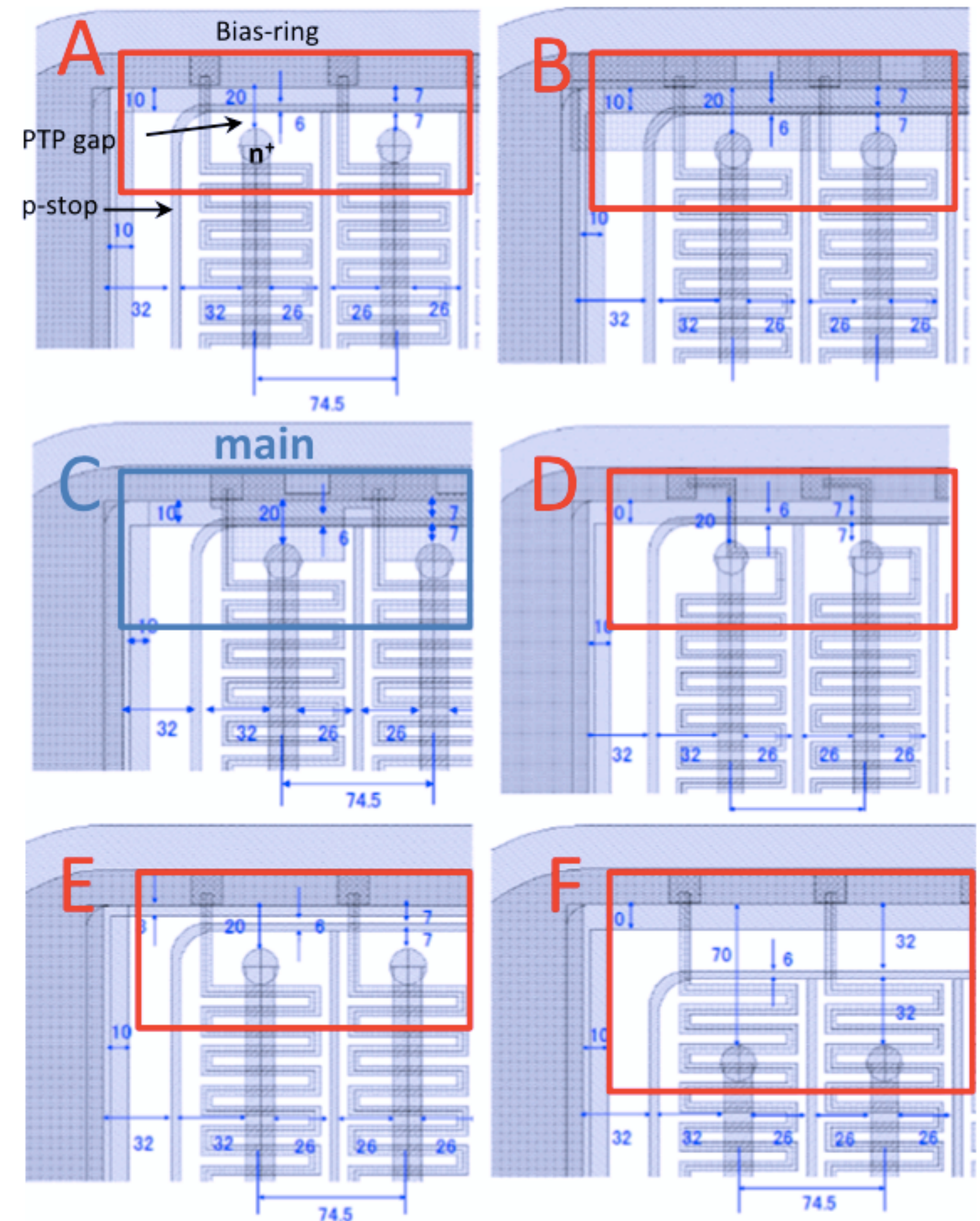 - Assess effectiveness of inter-channel isolation structures after irradiation
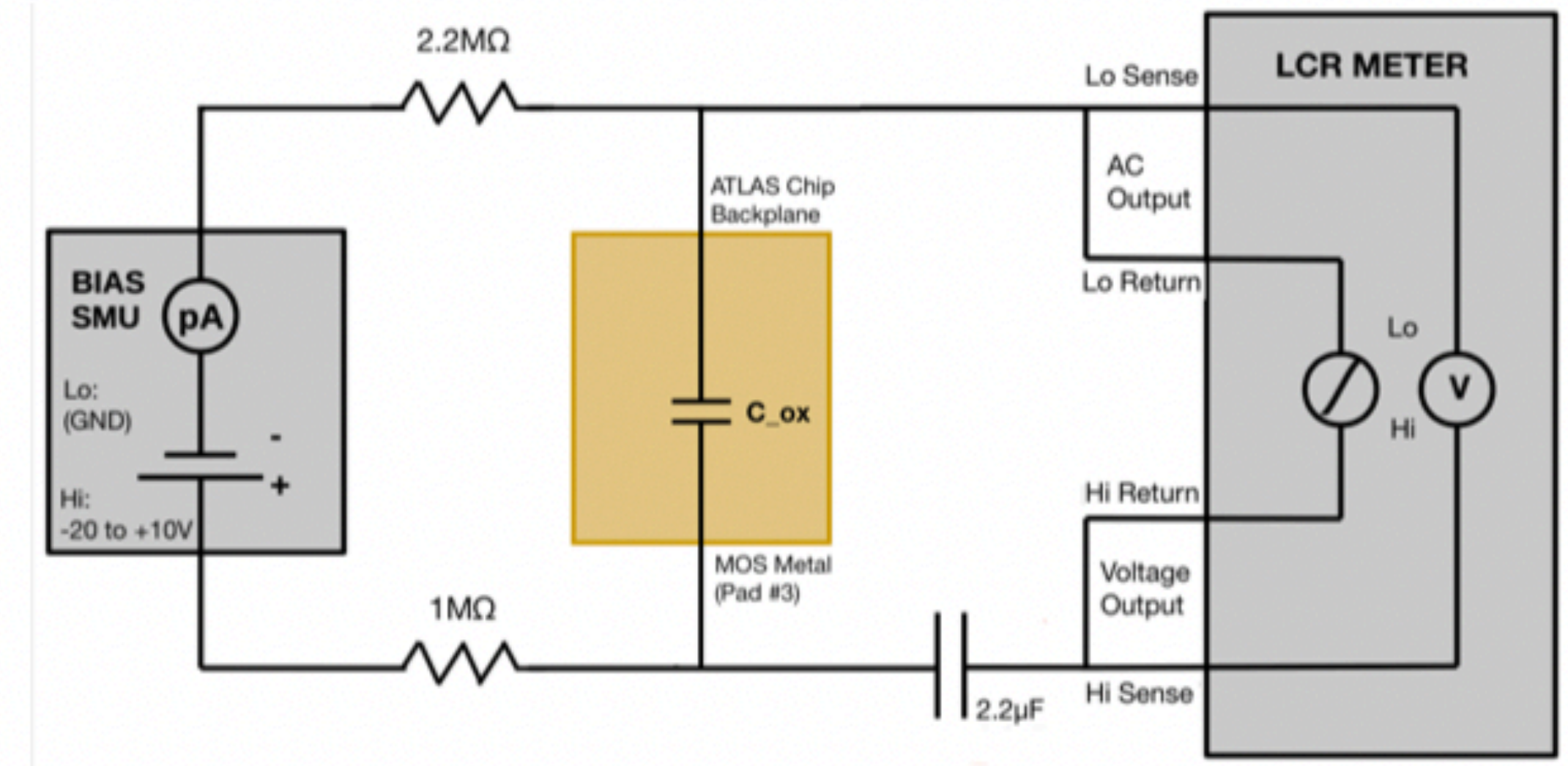
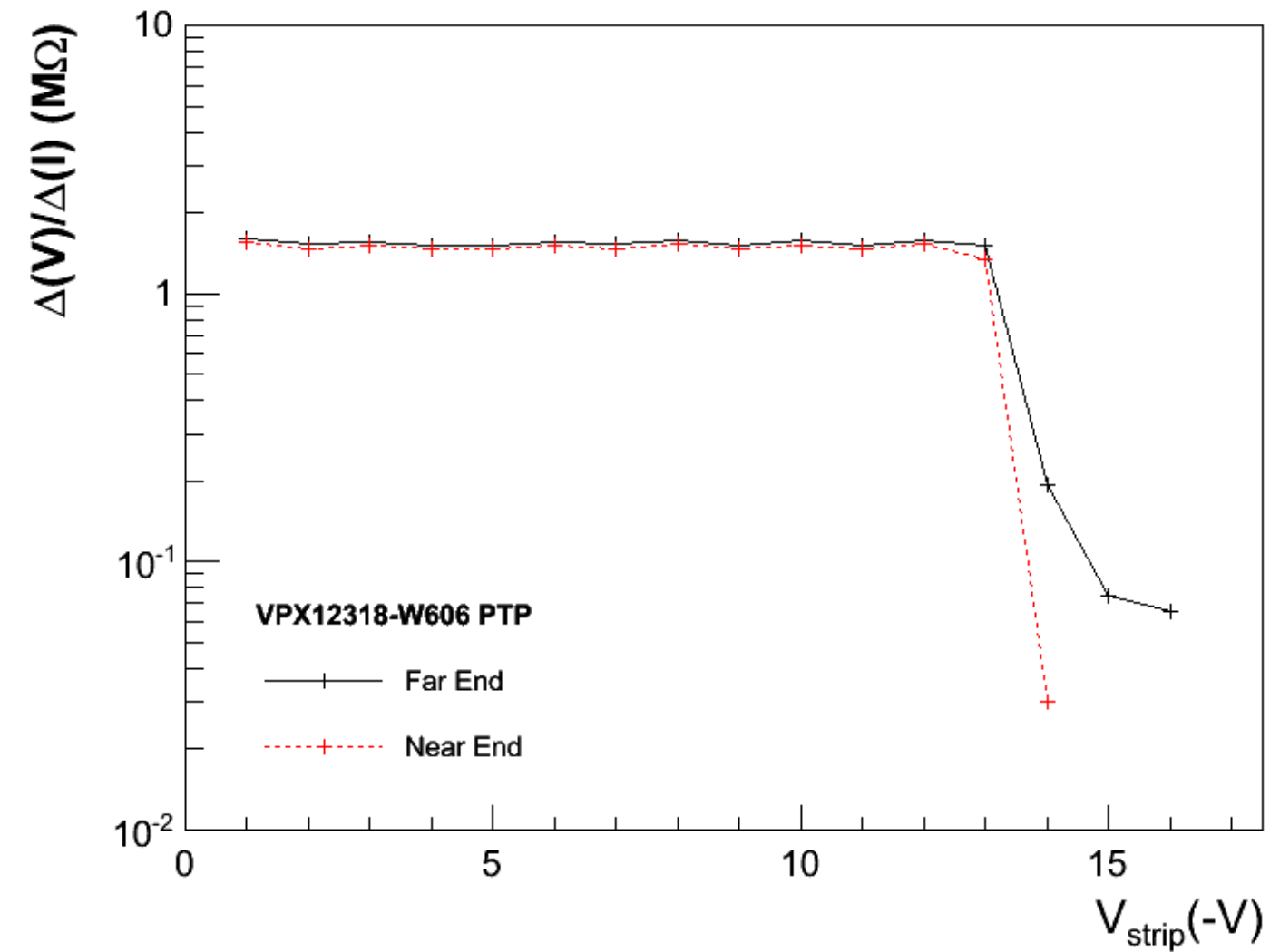ATLAS18R0 MOS Capacitors VPX32468 - CVs
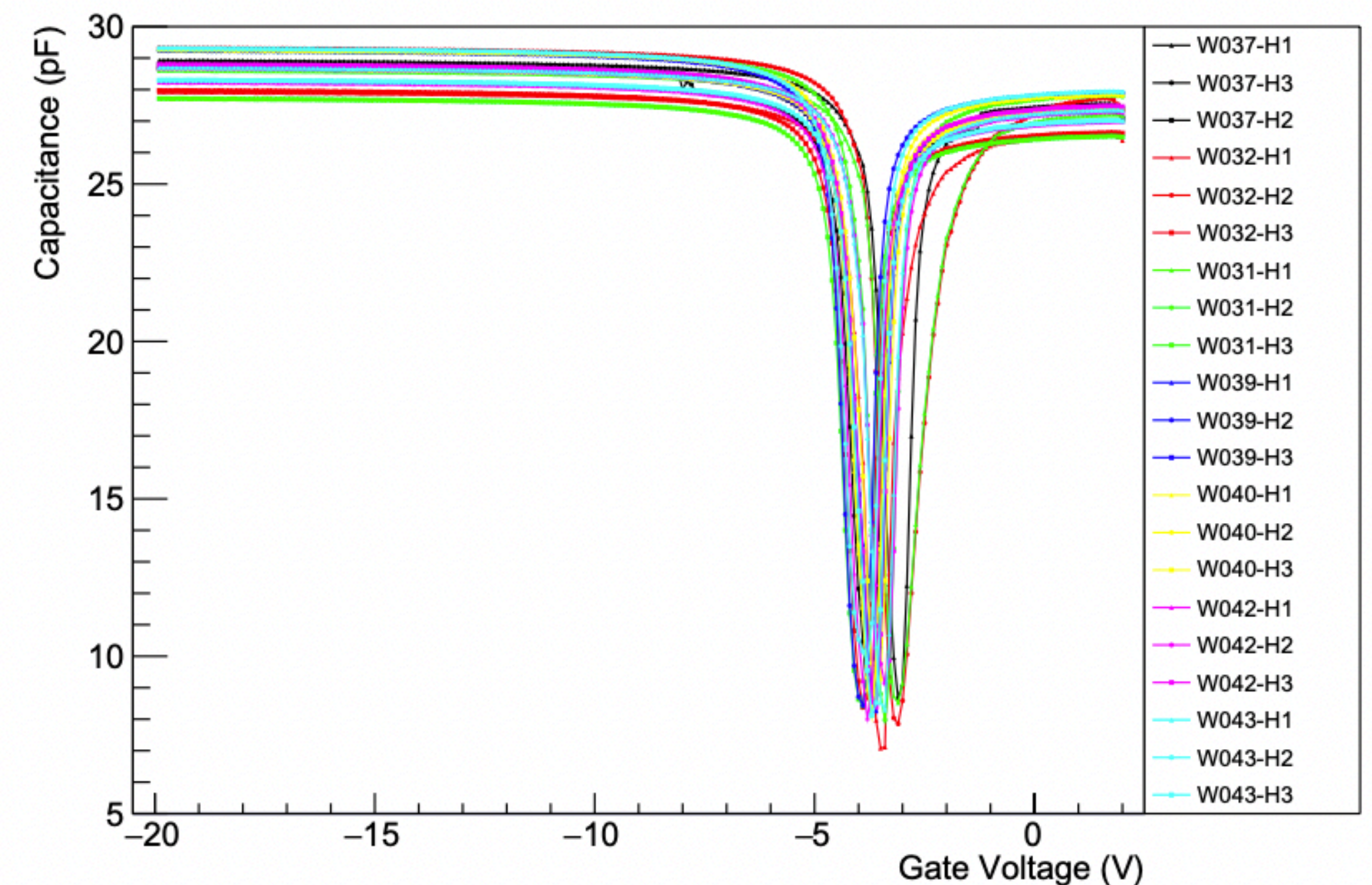
Punch-Through Protection

- 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
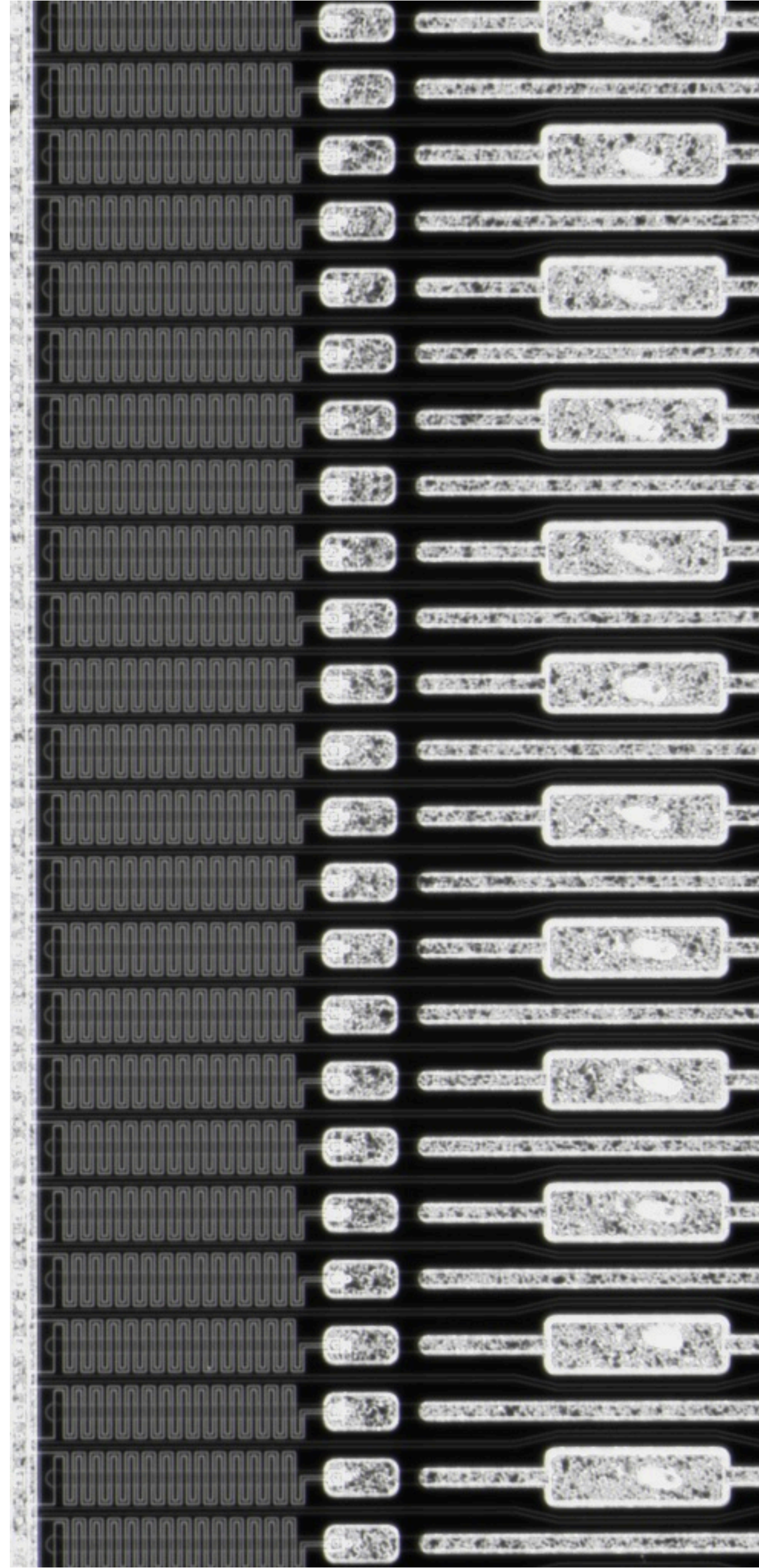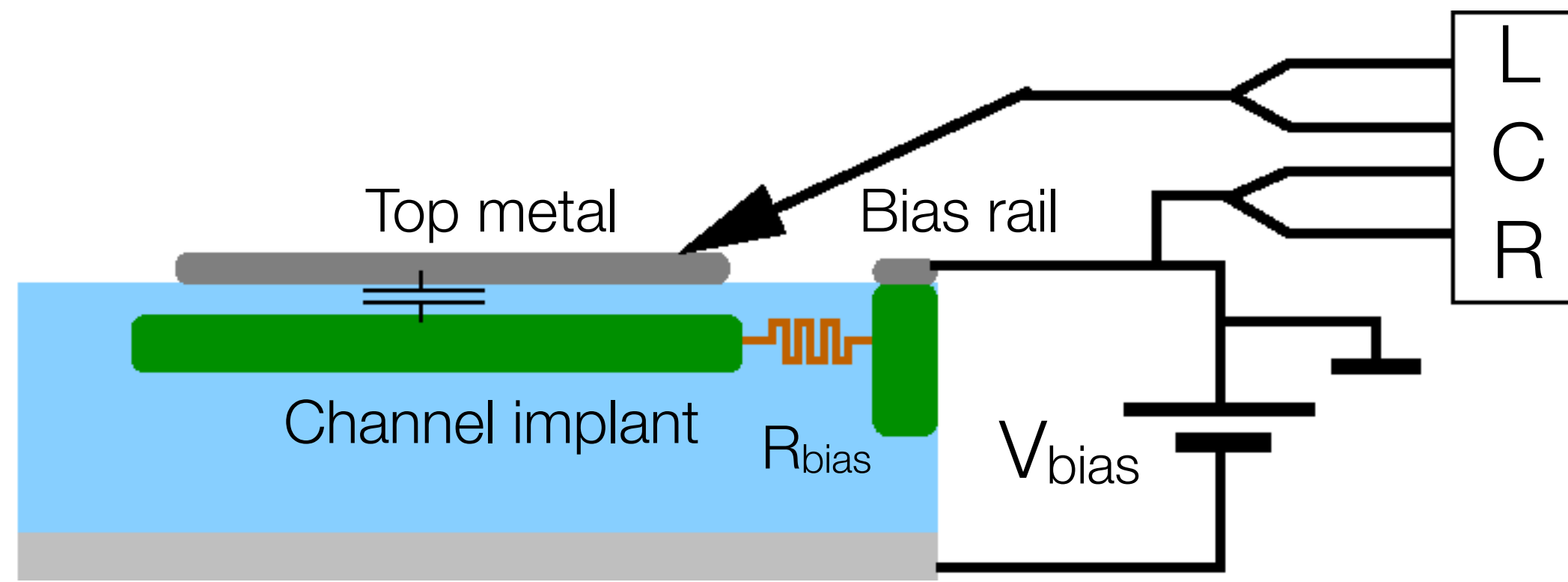
- Before PTP gap acts: measurement sees R_{bias}

  - PTP breakdown changes R to $O(10k\Omega)$

  - Implant resistance $O(1k\Omega)$

- Surface structure: altered by charged particle flux

  - Need to make sure PTP performs well towards end of detector lifetime
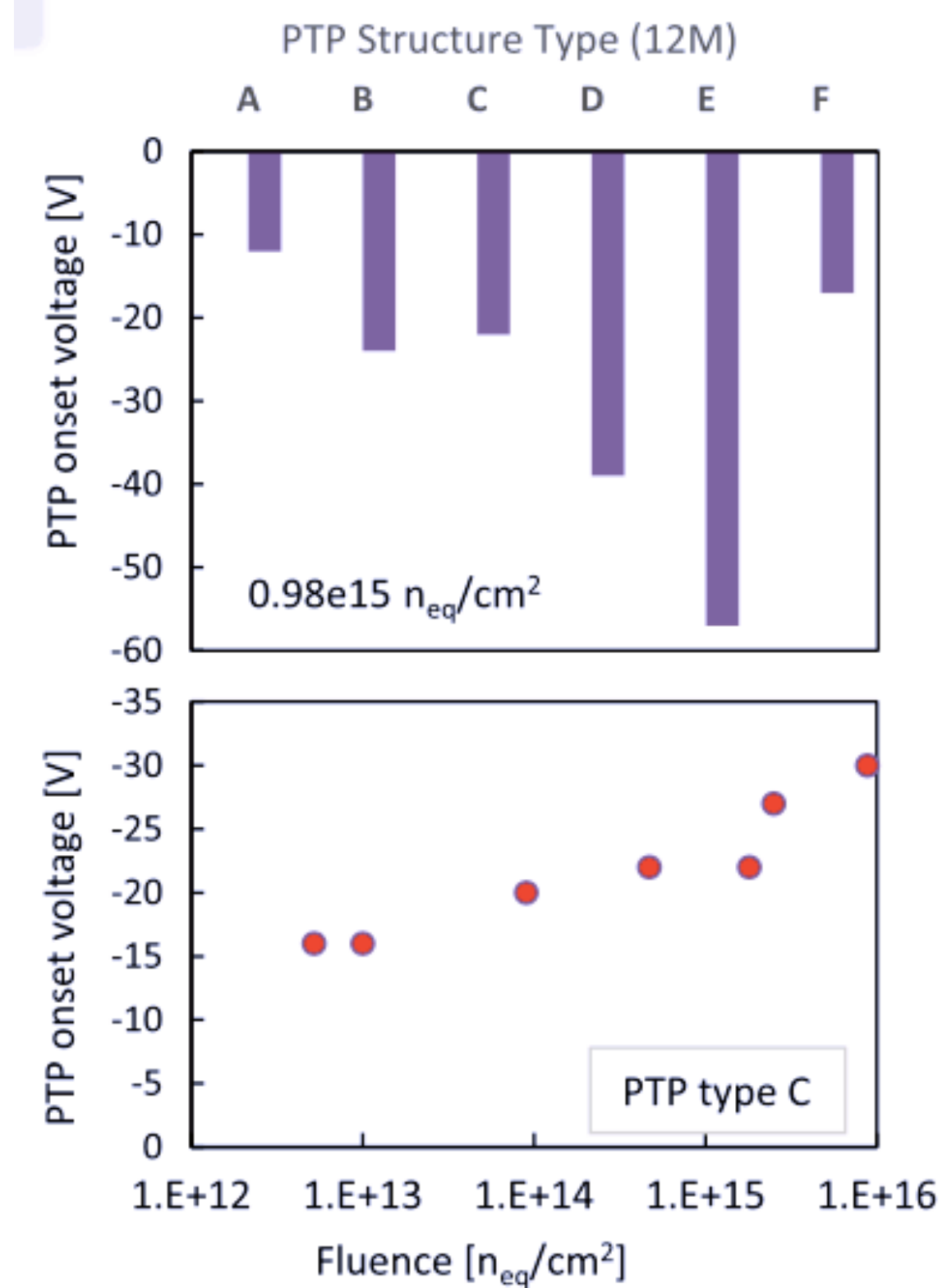
Multi-channel characterisation

Coupling Capacitance
Strip test protocols

AC coupled channels

- Coupling capacitance between implant and top metal

- $C_{coupling} \gg C_{is}$

- 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
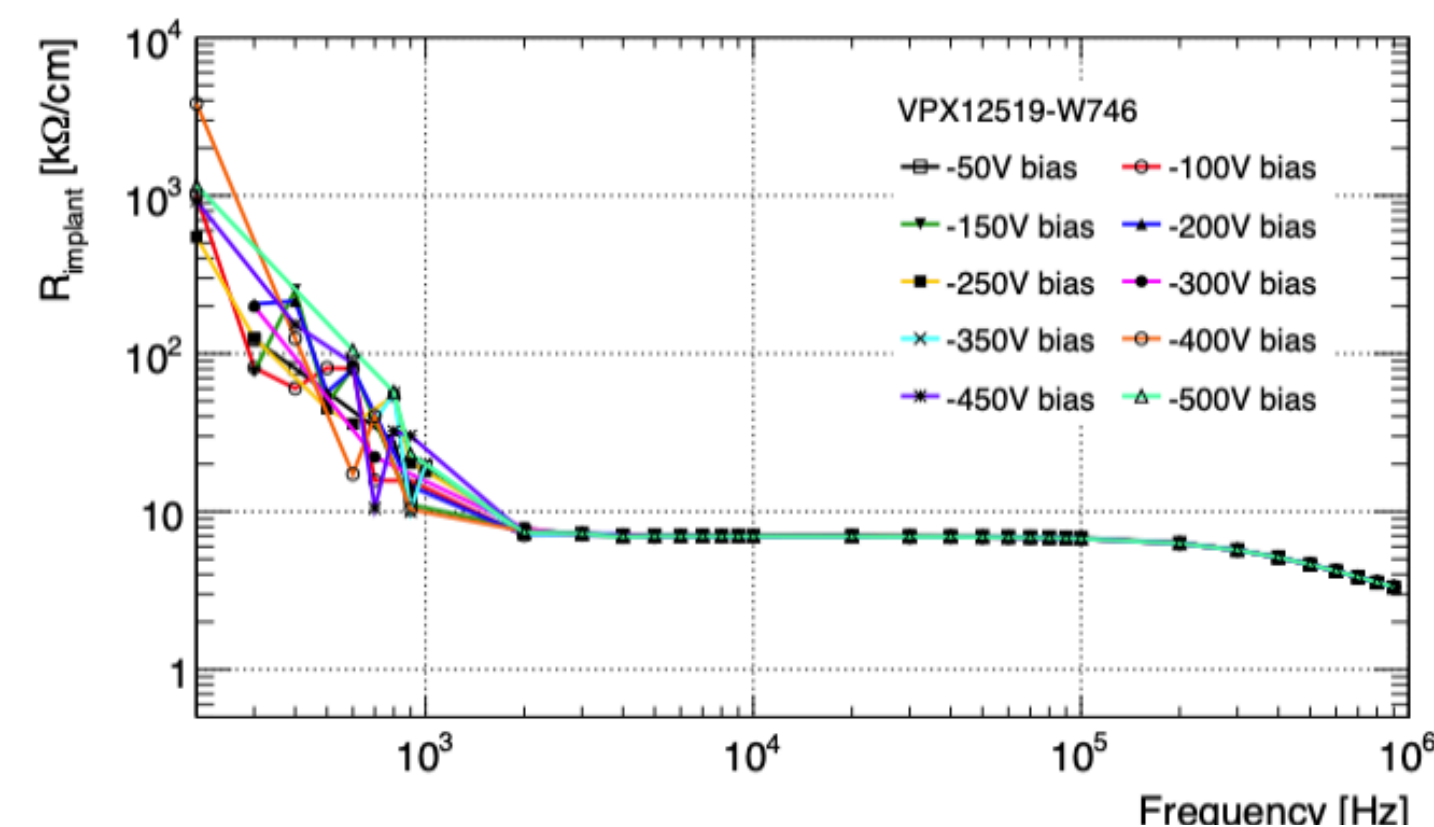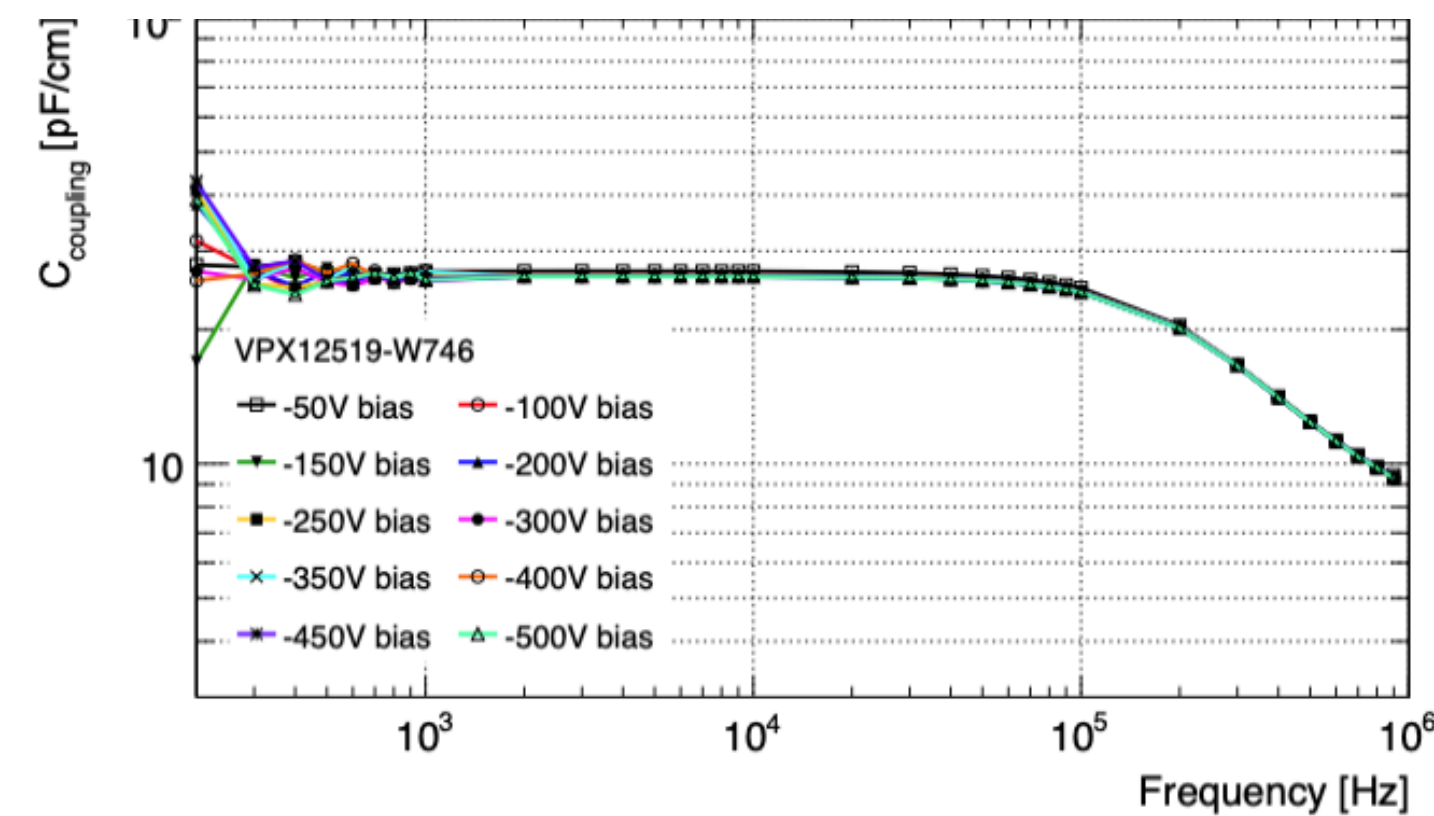
Coupling capacitance: V step function

- 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
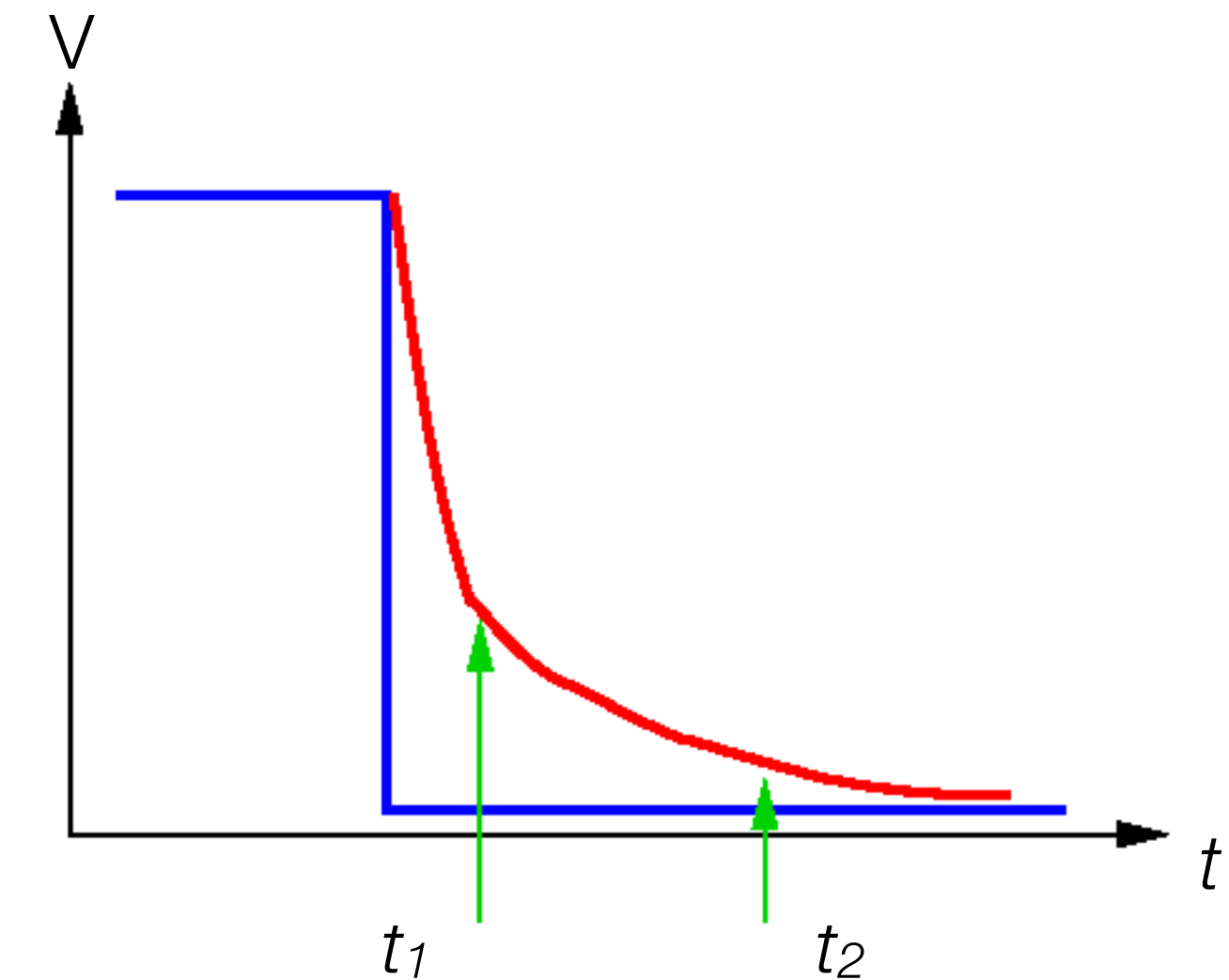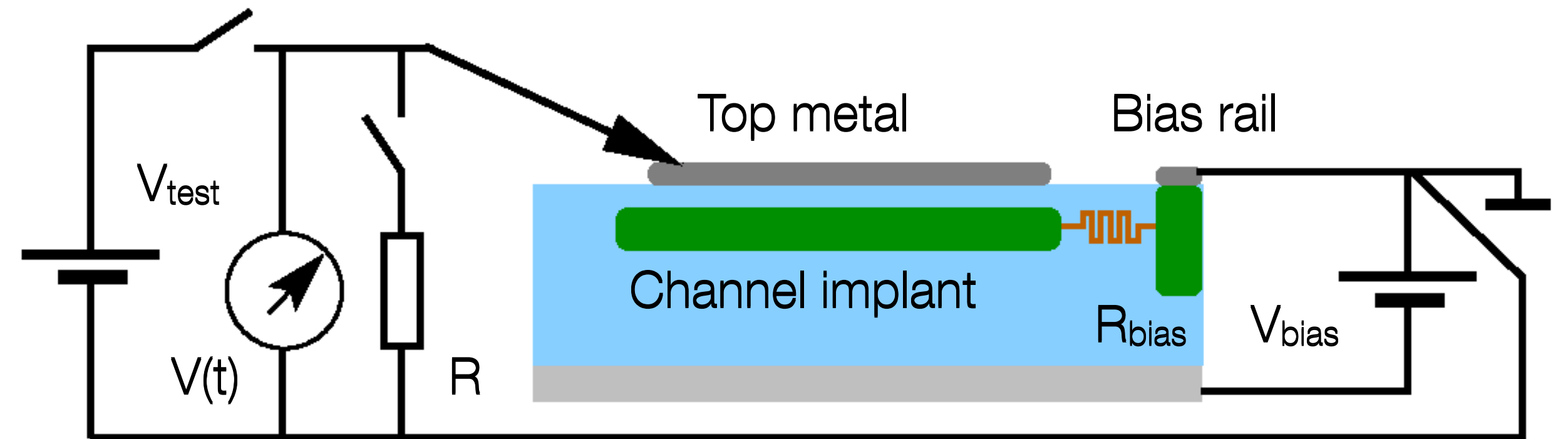
Biased AC coupled structures

- Access to more failure modes
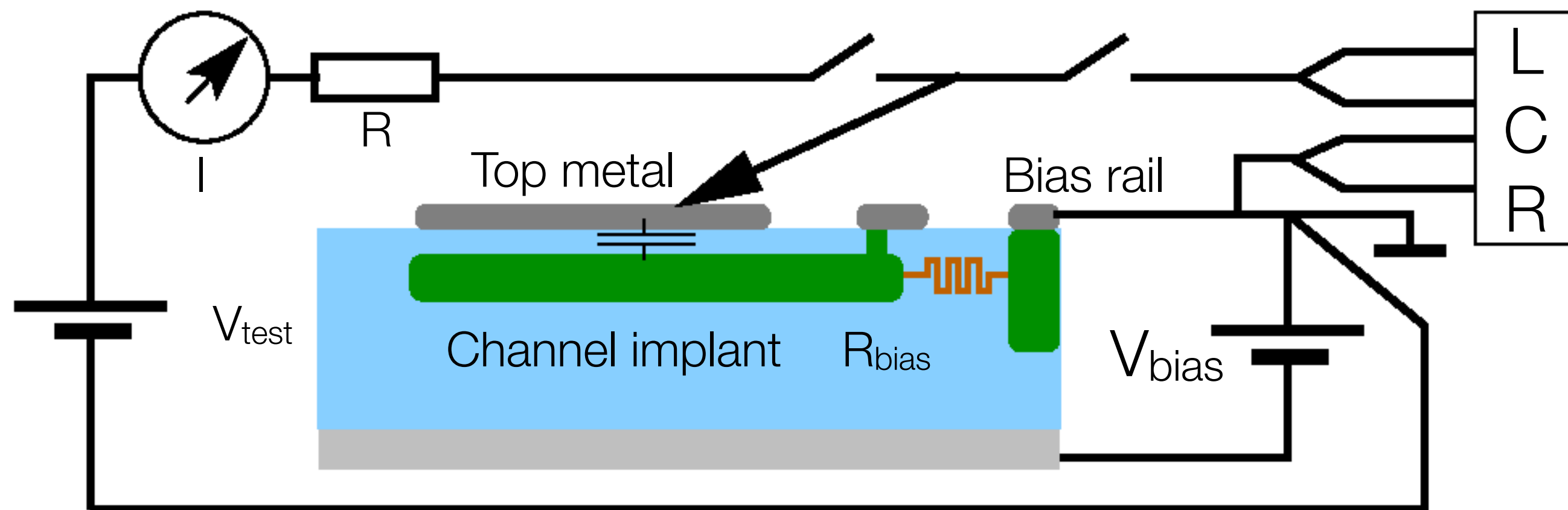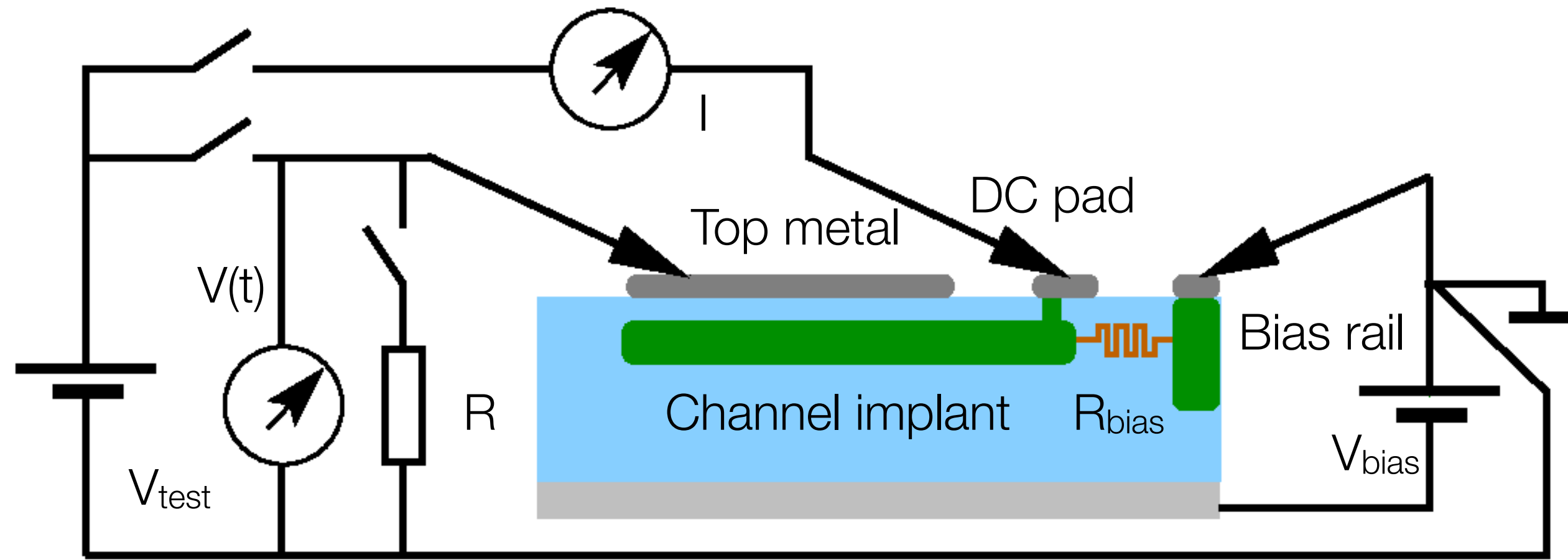
Strip test protocols

- 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
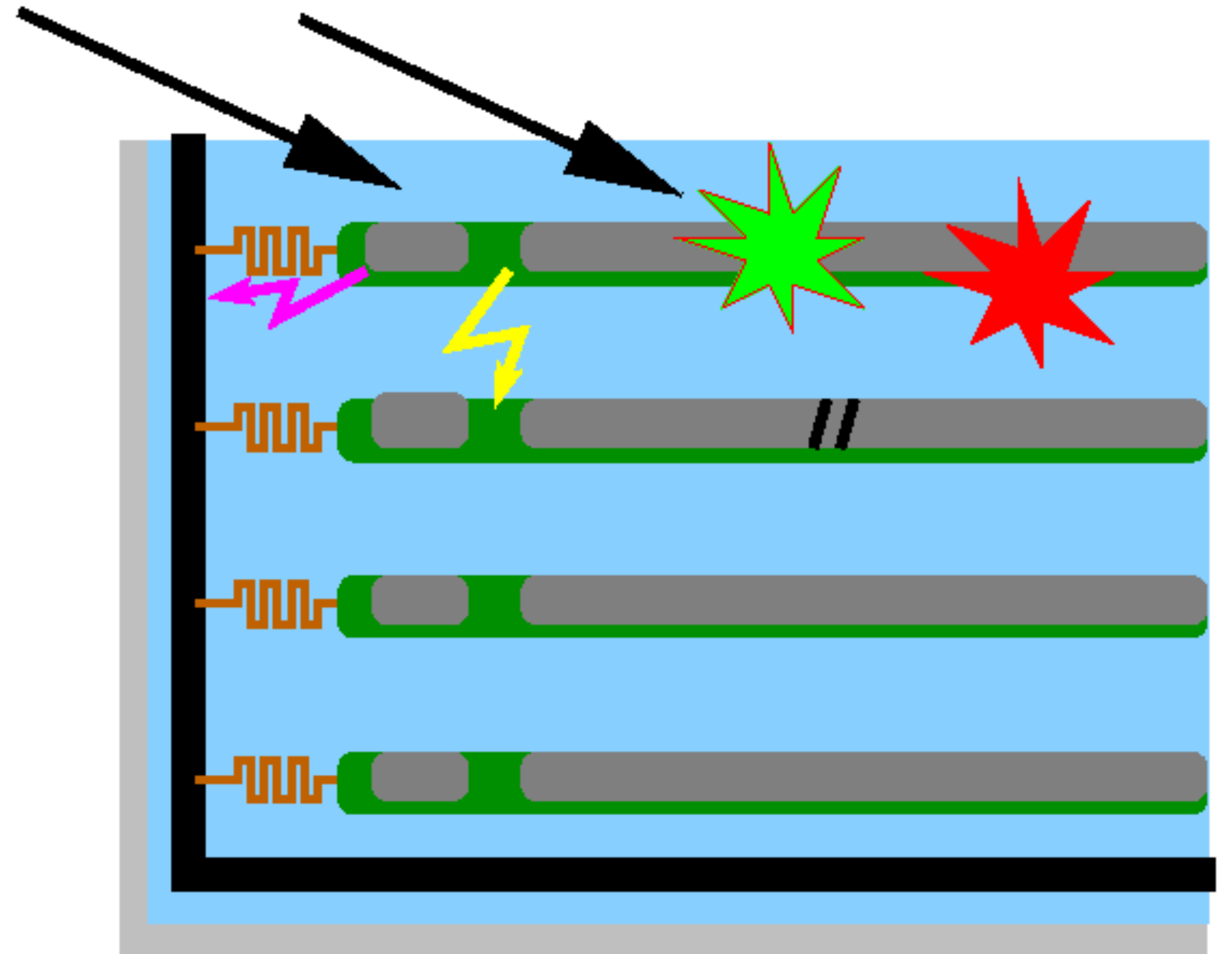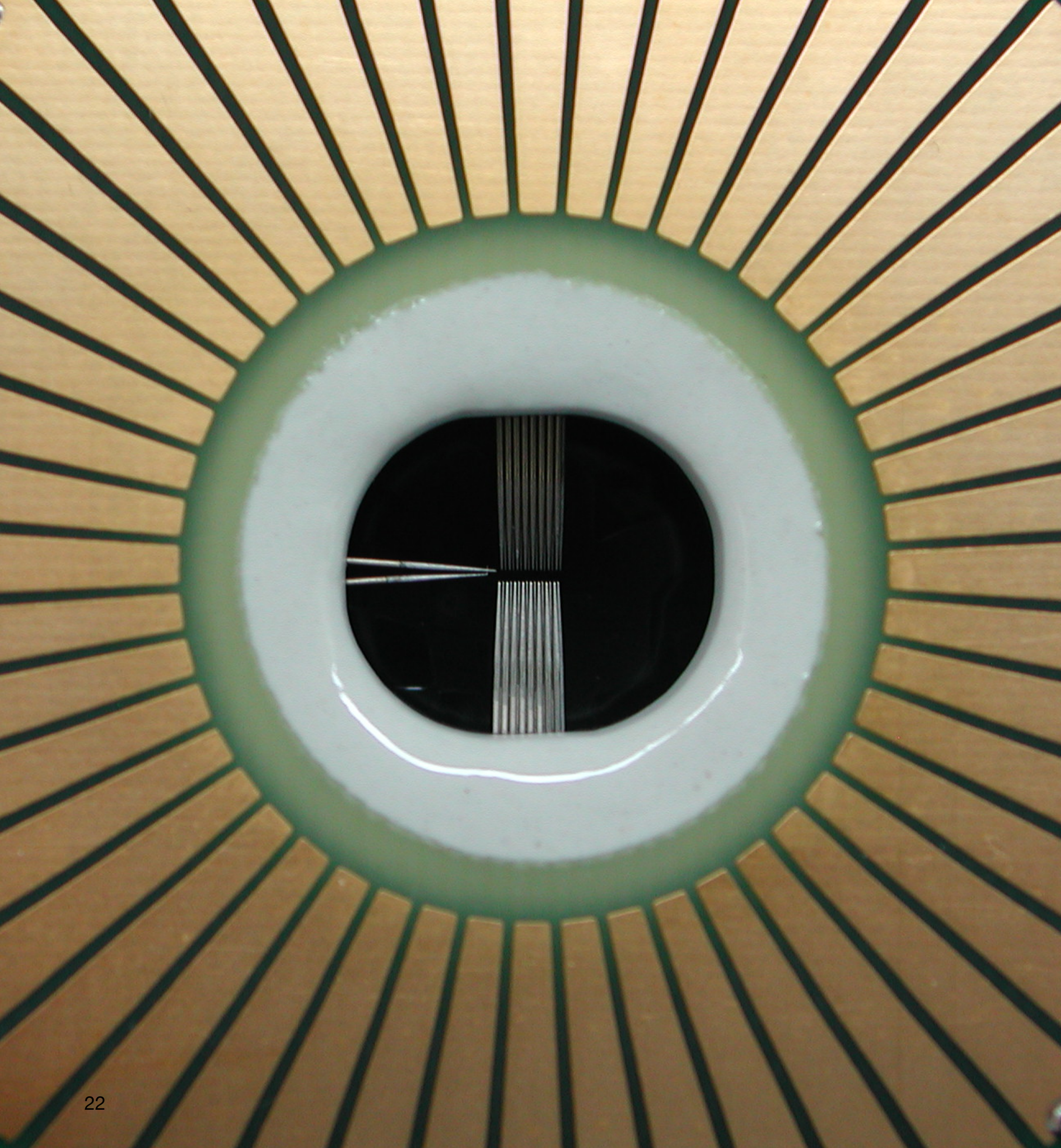
Probecard

- 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
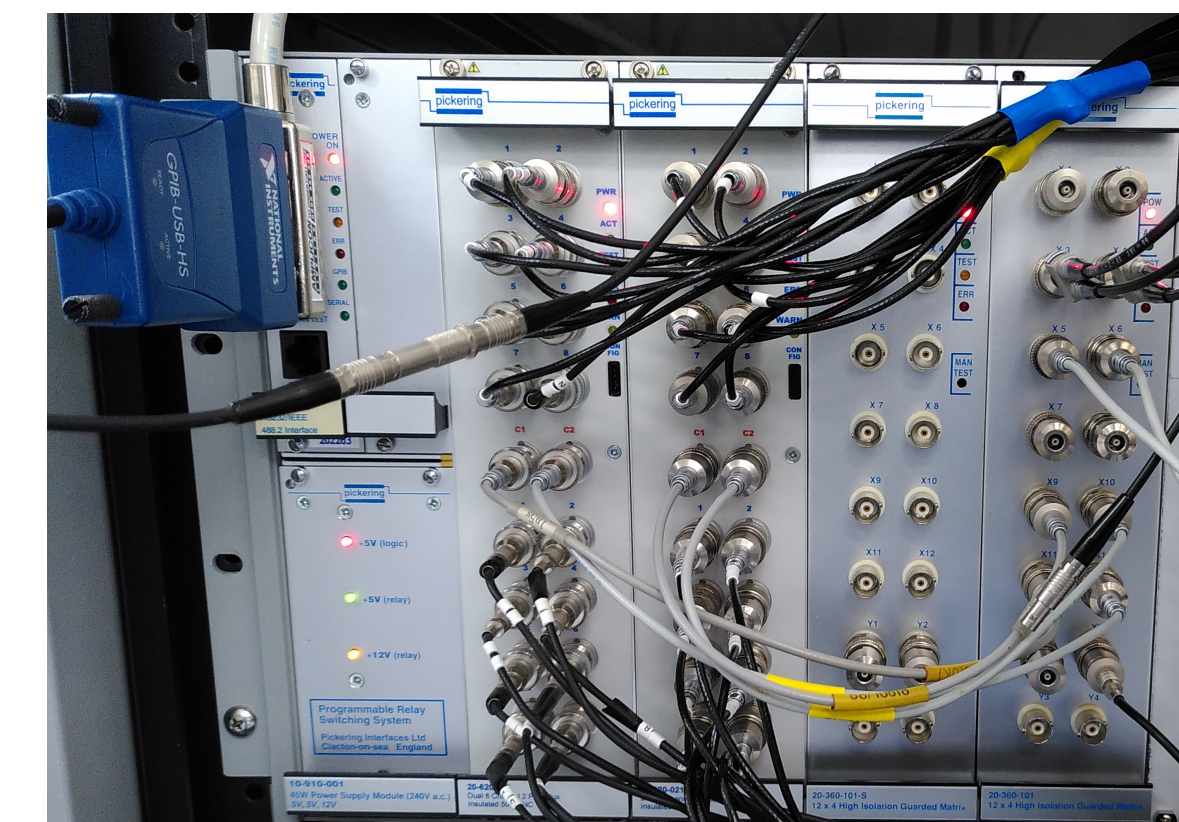
Advanced Imaging

Pinpointing breakdown in Silicon sensors
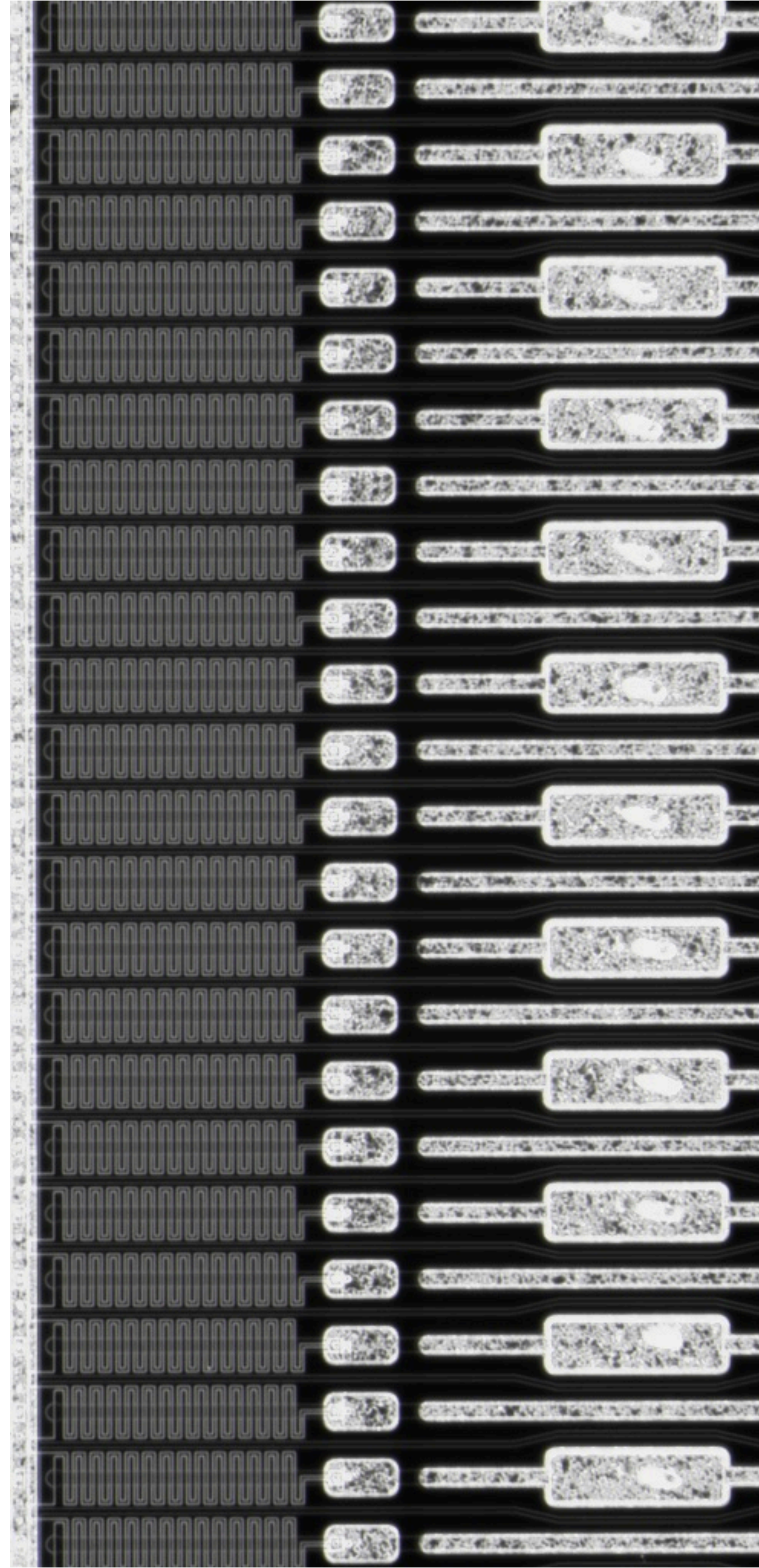
Advanced Imaging:
pinpointing sensor breakdown

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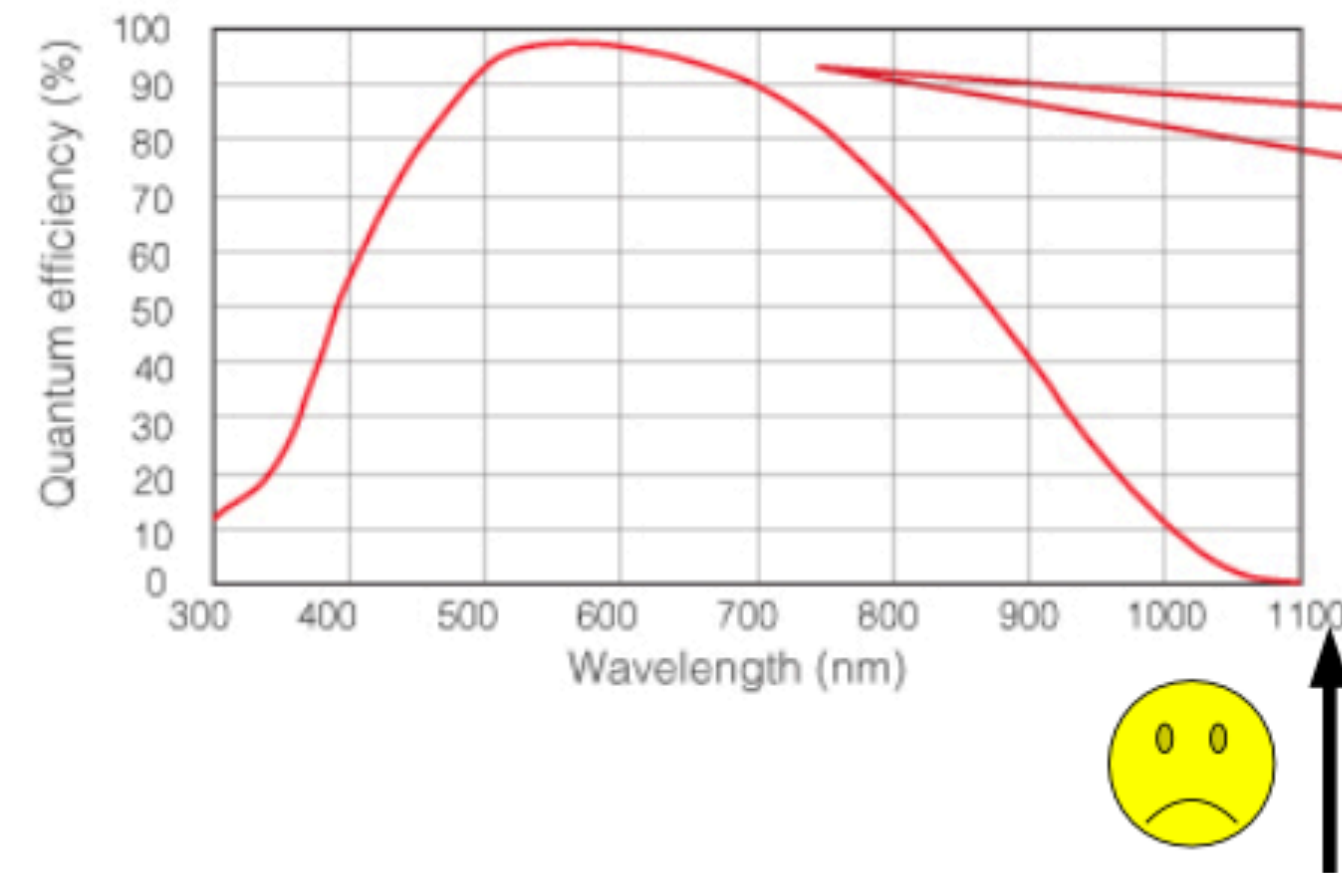
The beloved EM-CCD sensor provides over 90 % peak QE.

We want to be measuring here: 1.12eV Si bandgap

CC126MU
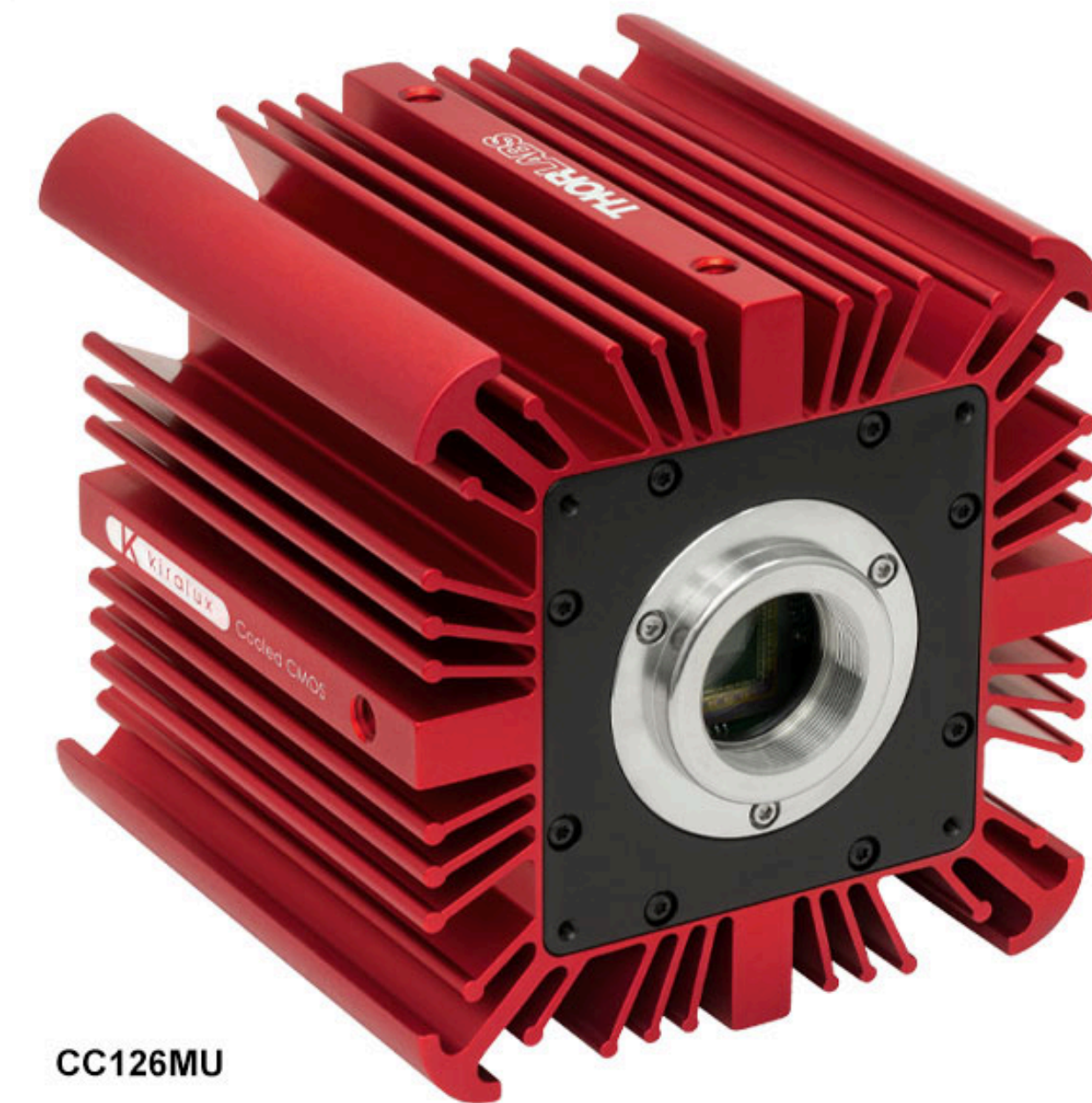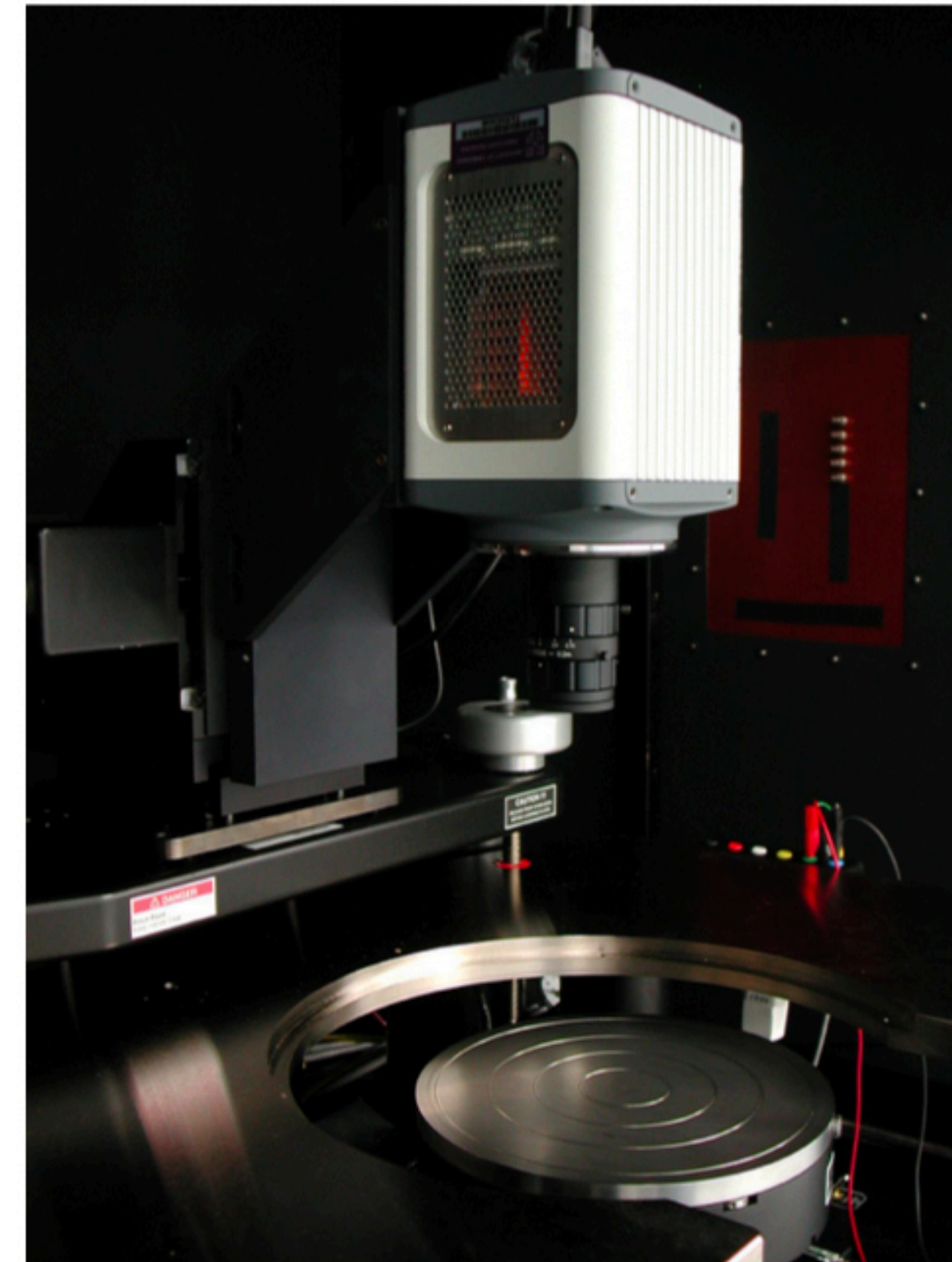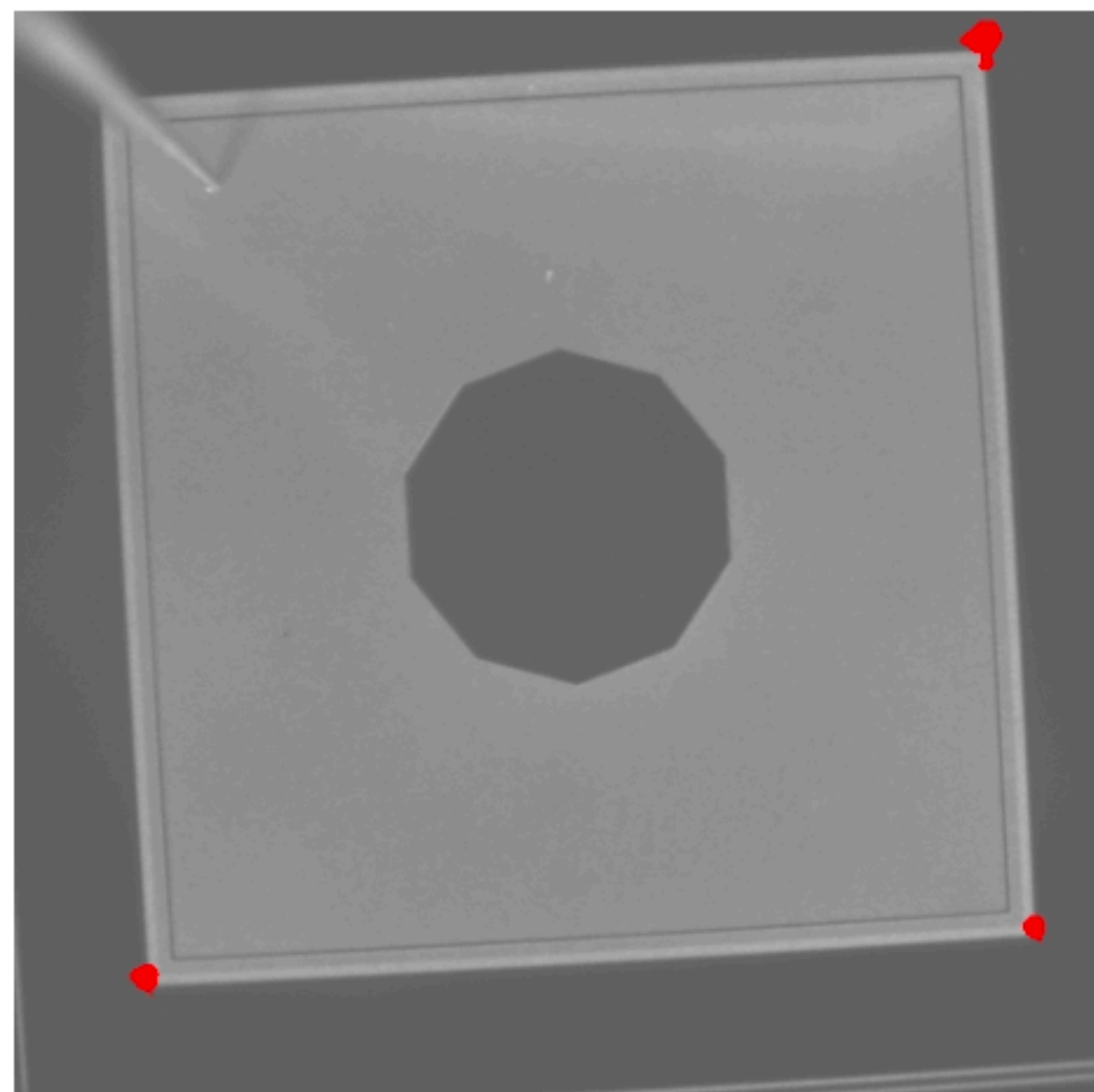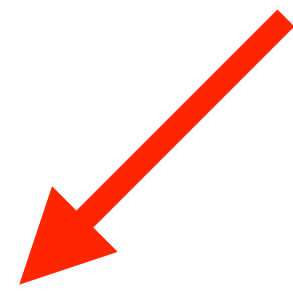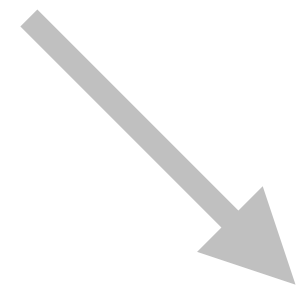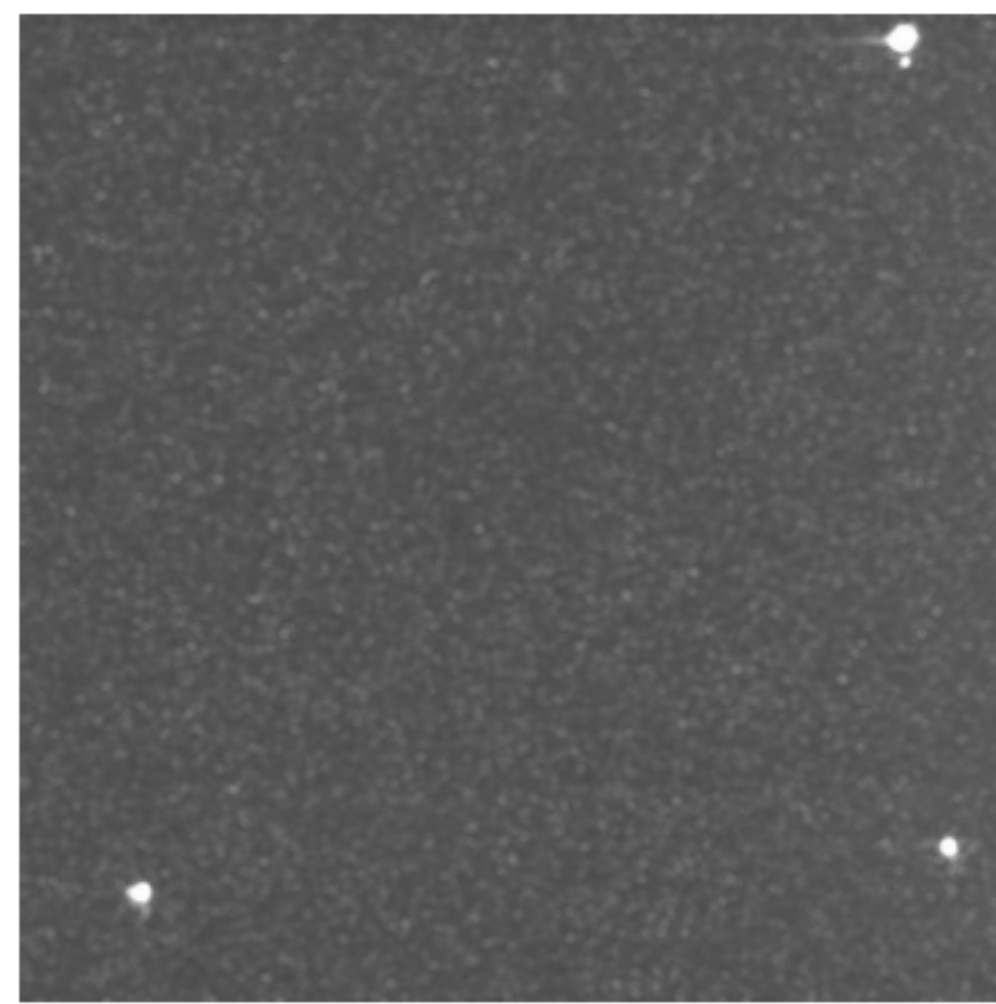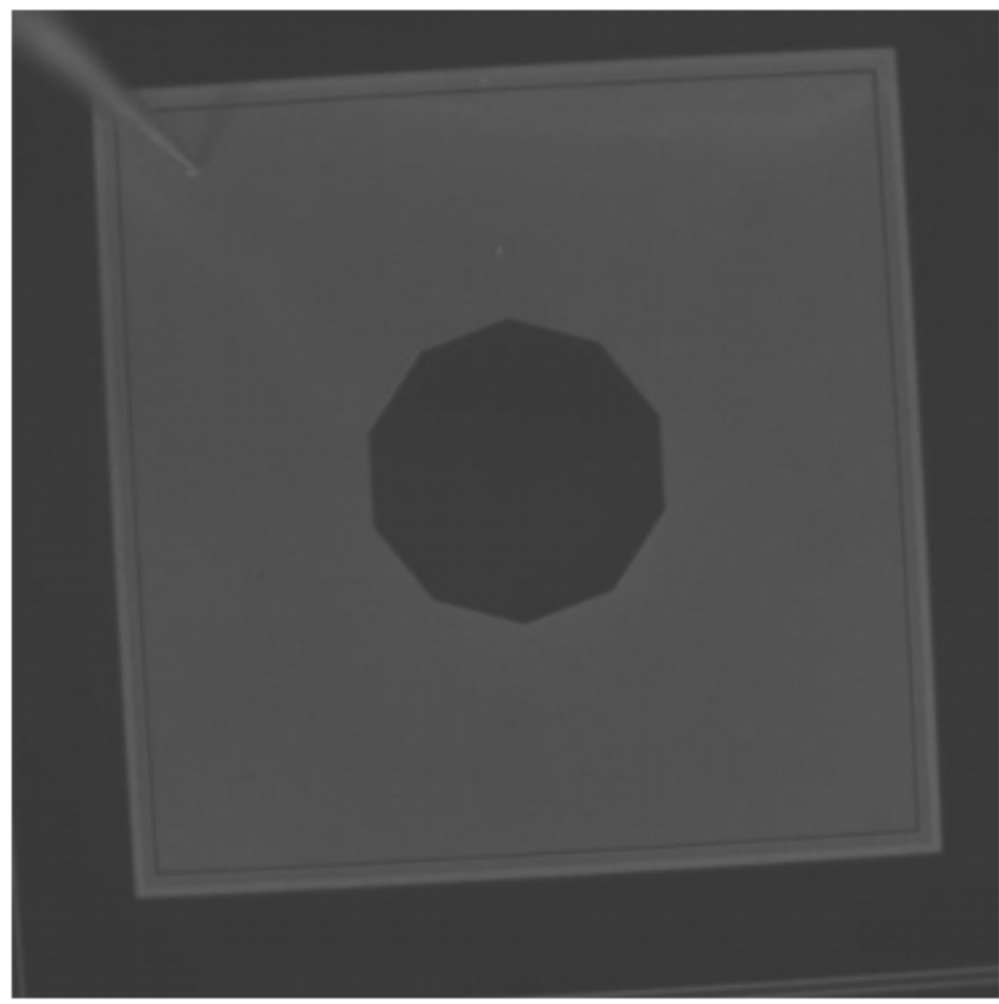
Breakdown imaging

- 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....
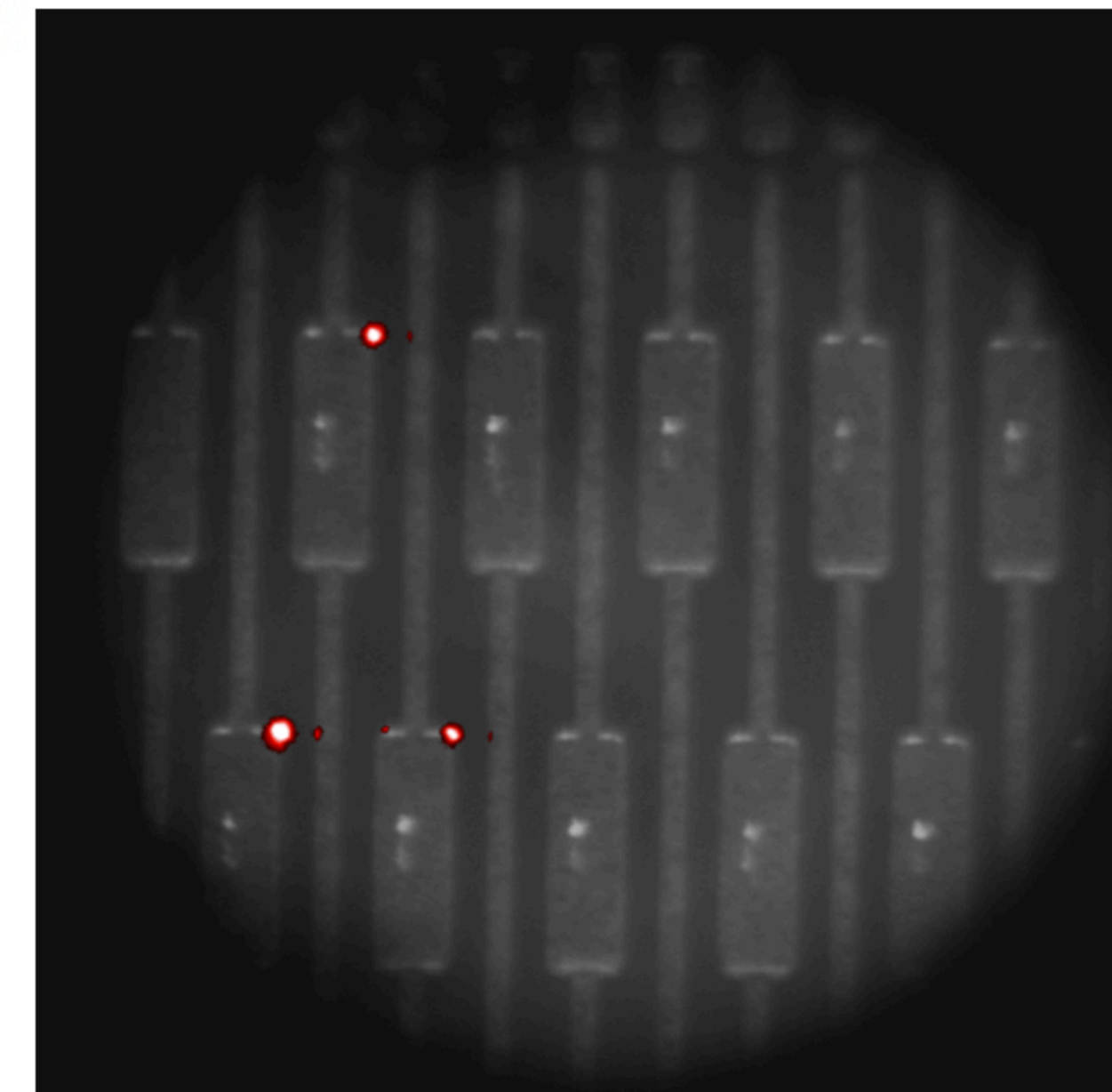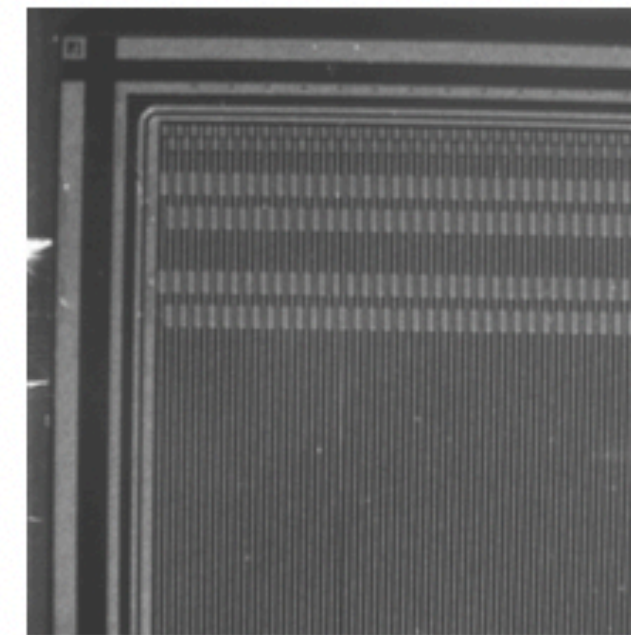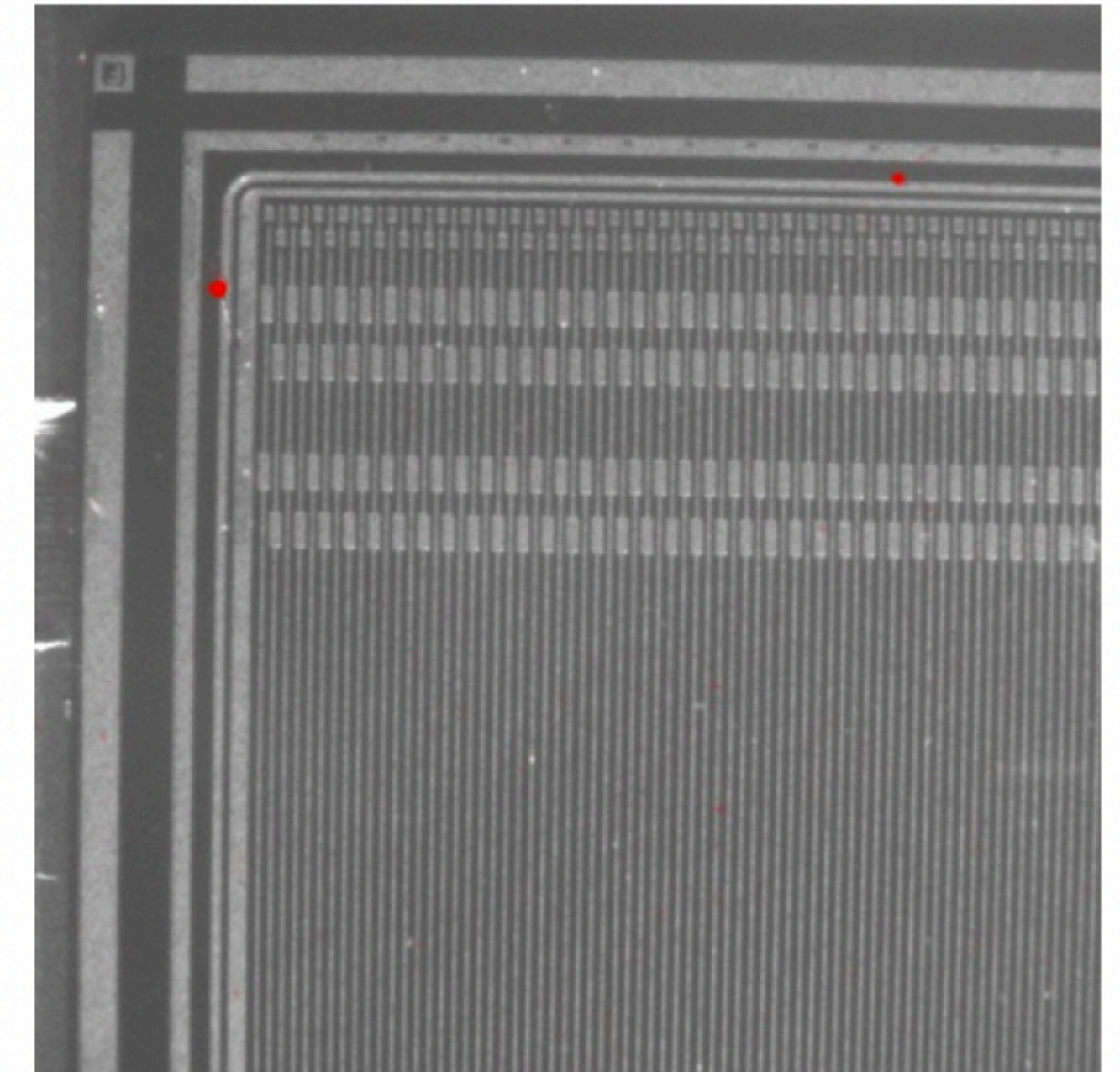
Source measurements

- Different emitters to establish detector performance:

  - 55Fe: 5.6 keV X-rays

  - 137Cs: 0.51 MeV $\mathscr{B}$-

  - 90Sr: 0.9336 MeV $\mathscr{B}$- (avg)

  - 241Am: 5.486 MeV α

  - 22Na: 0.543 MeV $\mathscr{B}$+

X-ray tubes

- X-rays: spot ionisations

- Rate capability / detector current

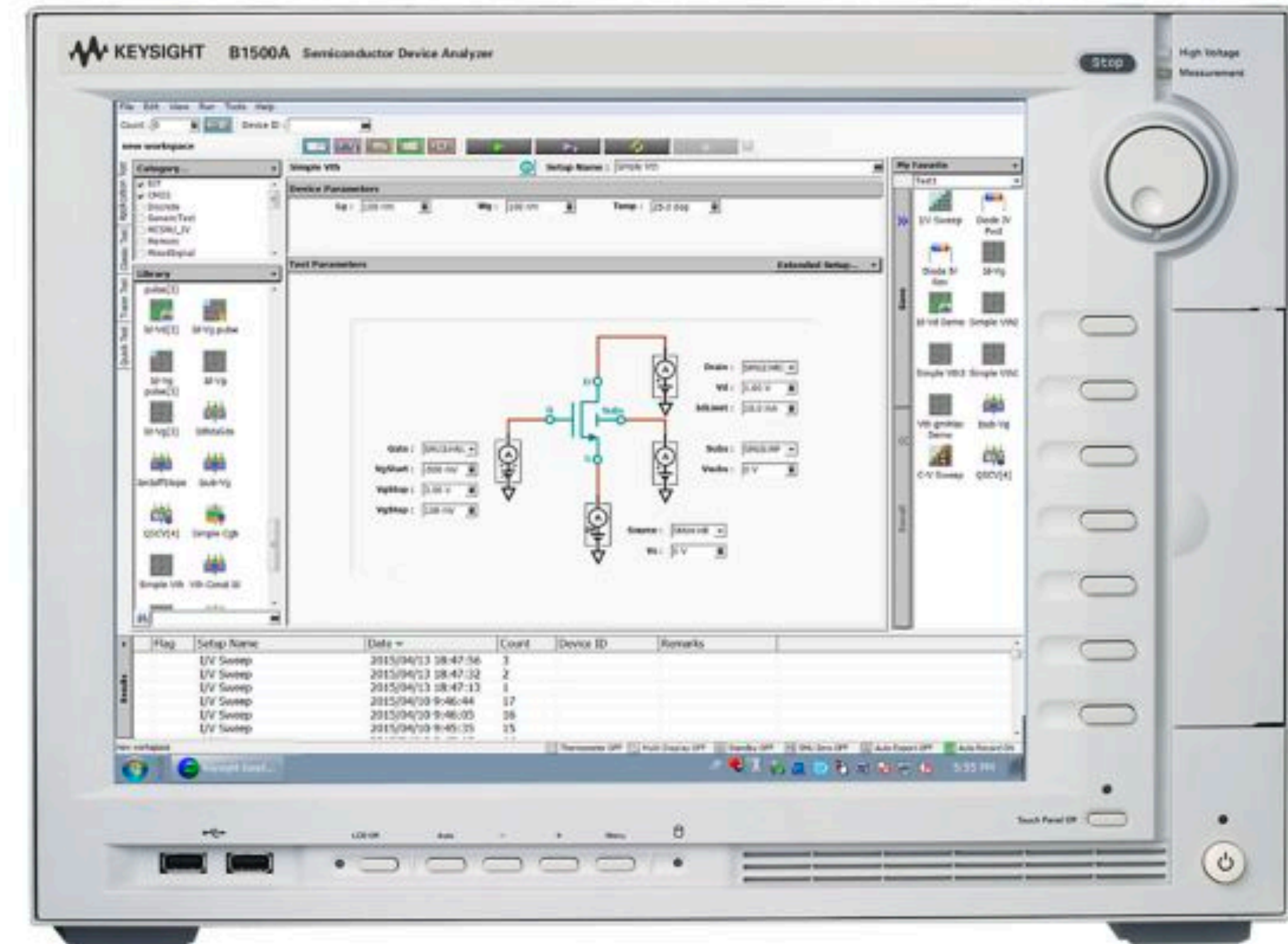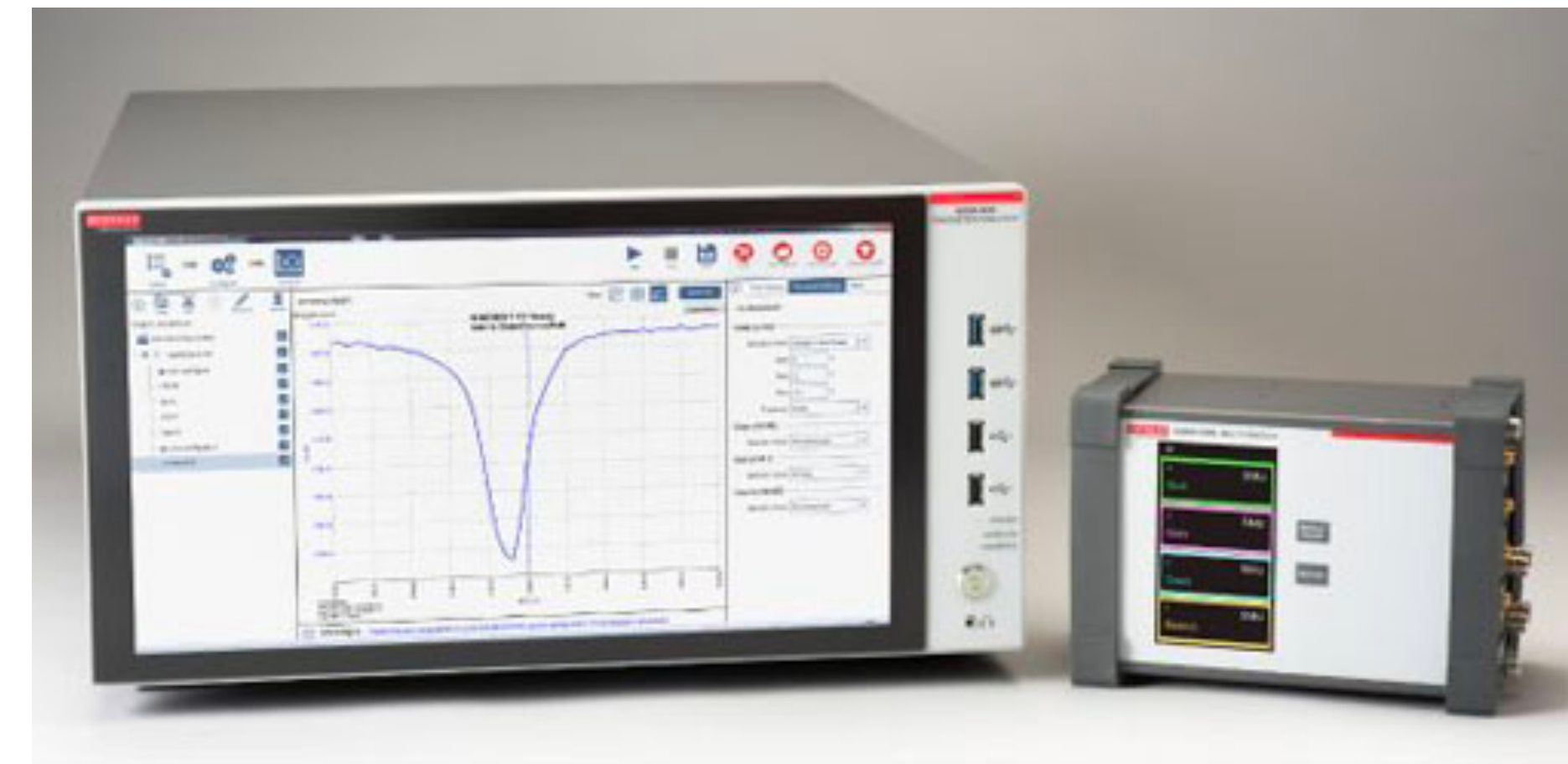- Resolve muons (comics) whilst being irradiated with X-rays

-

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 capability?

  - 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
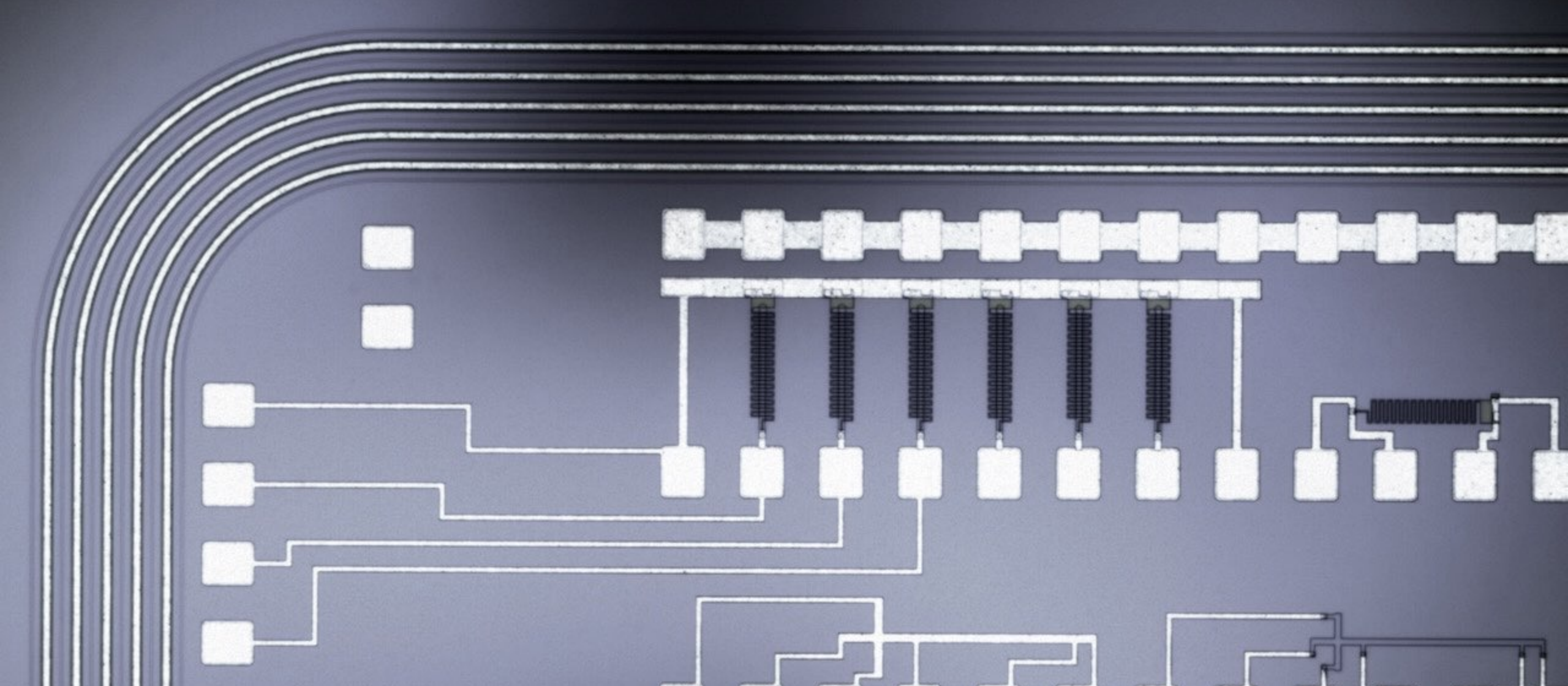
Thank you !

Bart Hommels: hommels@hep.phy.cam.ac.uk

References

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https://doi.org/10.17863/CAM.45814

- J. Ong: Stability analysis of ATLAS ITk Sensors

- C. Sawyer: The ATLAS ITk Strip Detector System for the Phase-II LHC Upgrade

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- E. Staats: Electrical Characterization of Silicon Strip Sensors for the ATLAS ITk at the HL-LHC with Extended Investigations of Sensor Properties

https://curve.carleton.ca/a5662611-f583-47eb-ace8-b98171e6c121