Moisture sensitivity of AC coupled silicon sensors

5th RD50 - Workshop on Radiation hard semiconductor devices for vey
high luminosity colliders
Florence, October 14 – 16, 2004

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on behalf of the ATLAS SCT collaboration

Introduction

- AC coupled silicon strip sensors used for the ATLAS SCT
  - 86% made by Hamamatsu, including all the barrel region
    - These perform very well, without problem
  - 14% made by CiS
    - These show some moisture sensitivity
      - Implying more difficulty in commissioning parts of the endcap SCT, but OK for operation in ATLAS

- According to common specification given by SCT community (p-on-n technology), with design details optimised by each manufacturer

- Hamamatsu
  - SiO_2 passivation
  - metal strips are <u>broader</u> than implants (**Field plate geometry)**
- CiS
  - SiON passivation
  - metal strips are <u>narrower</u> than implants (**Non-field plate geometry)**
  - Bulk oxidized (SCT inner endcap modules only) to improve radiation tolerance

Radiation tolerance

- Radiation load in the CERN LHC for the scheduled 10 y of operation
  - Neutrons: $\leq 2 \times 10^{14}/cm^2$
  - Protons: $\leq 3 \times 10^{14}/cm^2$
- After moderate irradiation n$\rightarrow$p type inversion
  - p/n junction moves from strip side to backside
- Required bias voltage to get full depletion including safety margin
  - Initially only 150 V
  - Decreasing to a low value at type inversion
  - From type inversion on increasing until 450 V
- Both fabricates (Hamamatsu and CiS) have shown in extensive irradiation studies to give satisfactory performance

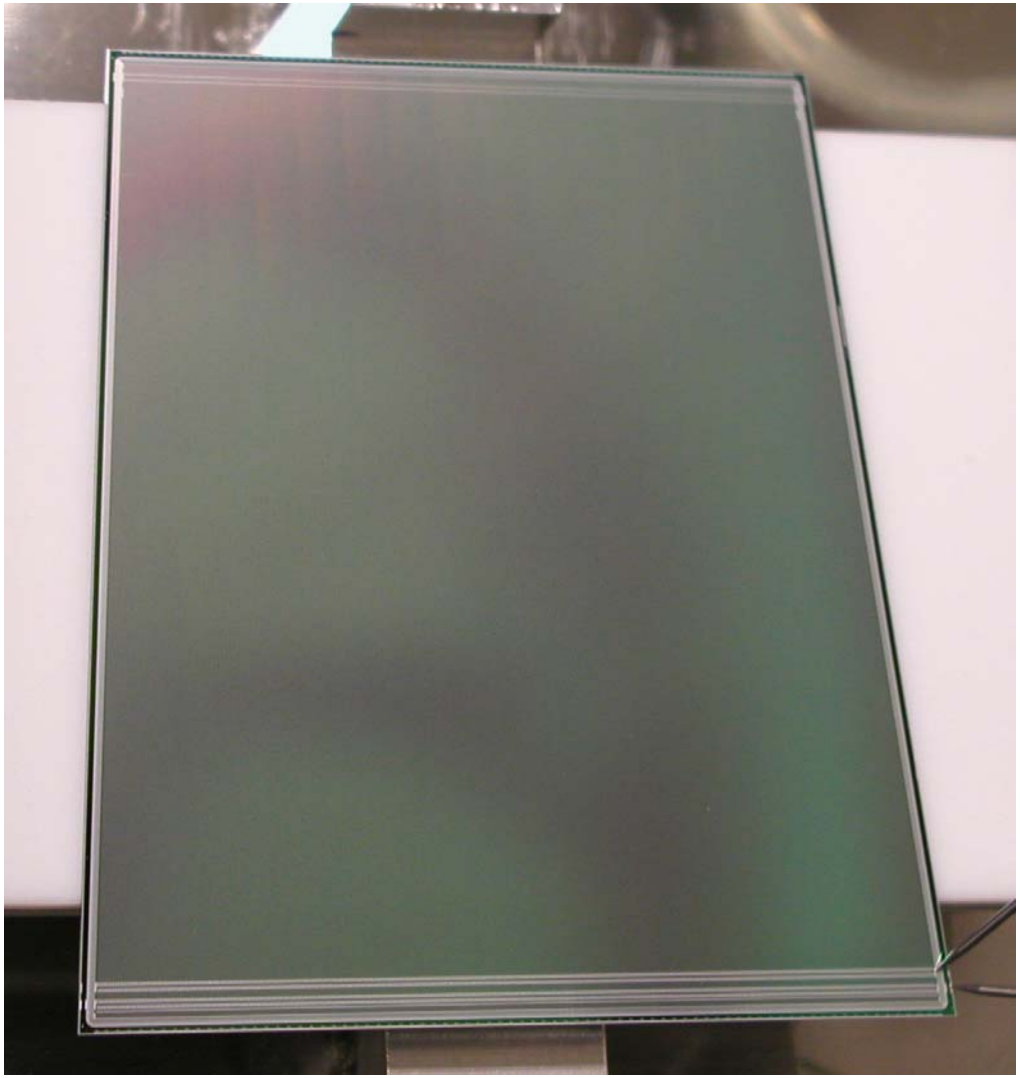
Breakdown problems for CiS non-field plate sensors

- For the majority of the unirradiated **non-field plate** CiS sensors a strange IV behaviour was observed during module production
  - Problems ranging from a bit unpractical in use until bad
  - Problems almost **not** observed for the **field plate** sensors from Hamamatsu (<1%)
- Nature of the problems with CiS sensors
  - Early IV breakdown
  - Awkward and irreproducible IV curves
  - IV results did not correspond to measurements by manufacturer
- Continued studies show clear moisture dependence of CiS IV behaviour
  - wet (45 – 50% RH) gives good IV curve
  - dry (< 10% RH) may give breakdown
  - transition region (30 – 40 % RH) => strange results
- Breakdown only occurs at strip side
  - => no breakdown problem **after** type inversion
  - Confirmed by irradiation tests by MPI (Ladislav Andricek, MPI Halbleiterlabor, Munich)
  - => breakdown is no problem for operation in ATLAS
- Simple qualitative explanation of the phenomenon will be given
  - Based on ideas from Rainer Richter (MPI-Munich)

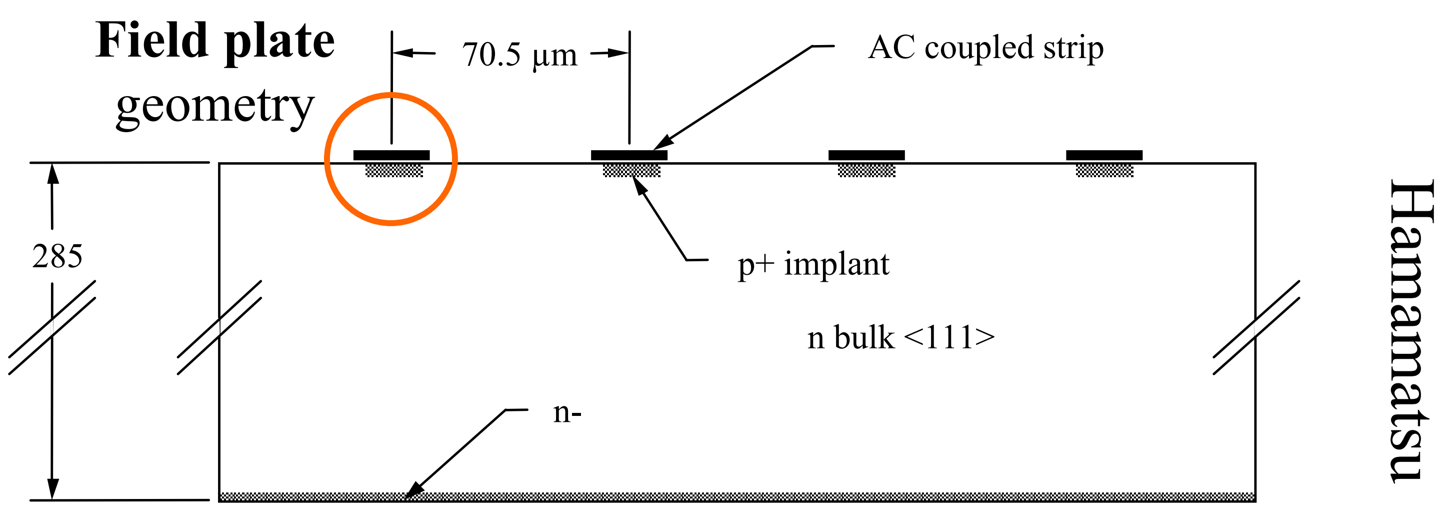
Properties investigated CiS silicon sensor

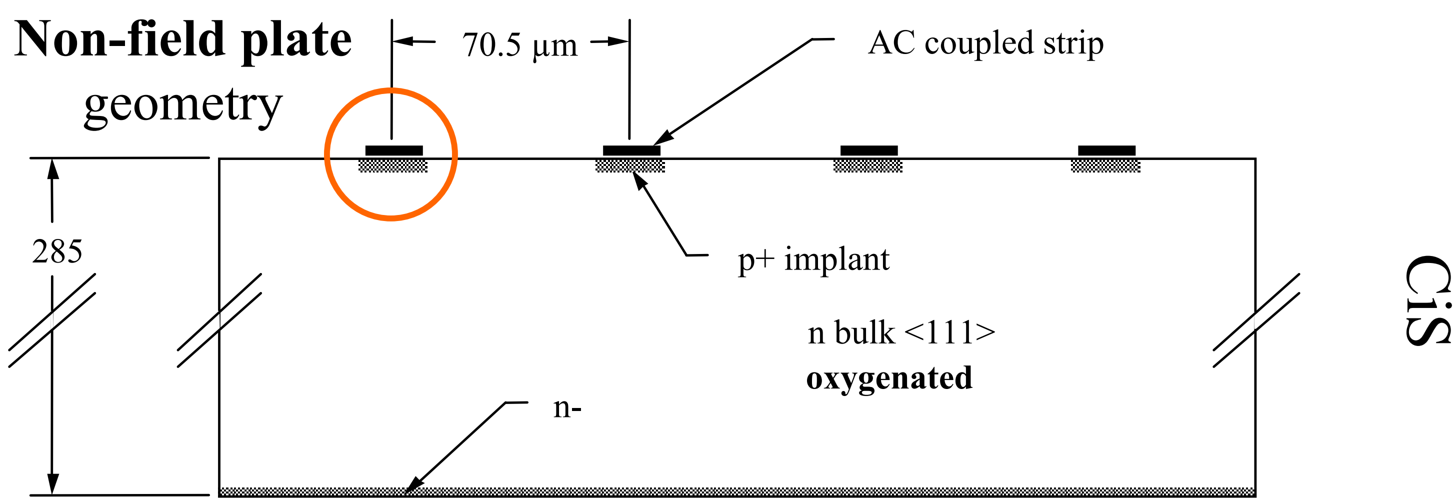
- Geometry: **non-field plate**
- Sensor type: W12 (inner endcap modules)
- Technology: p-on-n
- Additional oxygen dope: $10^{17}/cm^3$
- Orientation <111>
- Wedge shape 55.5 x 61 mm^2
- 768 AC coupled strips
- Average pitch 70.5 μm

- Tested until V_{bias} = 450 V



Two different sensor geometries in use at the SCT inner modules

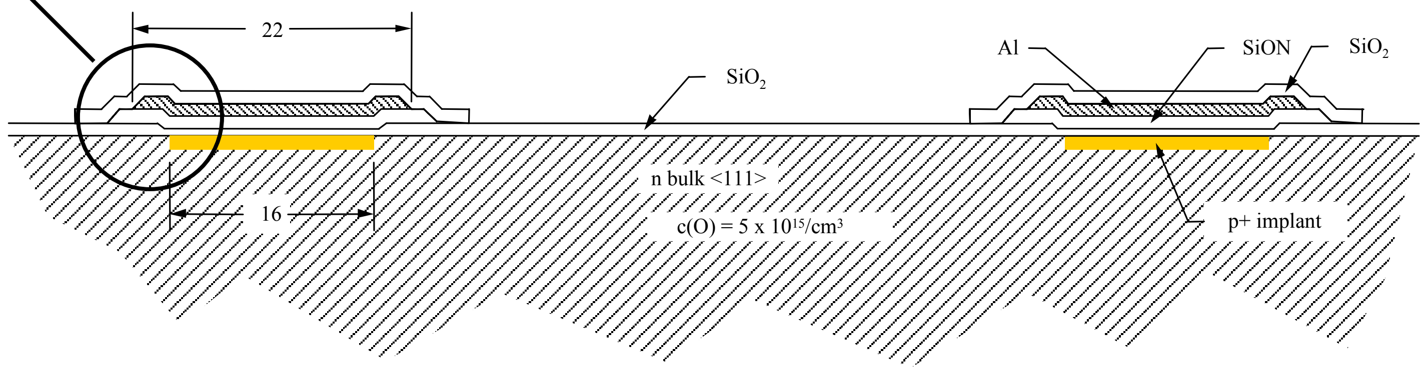




Two sensor geometries

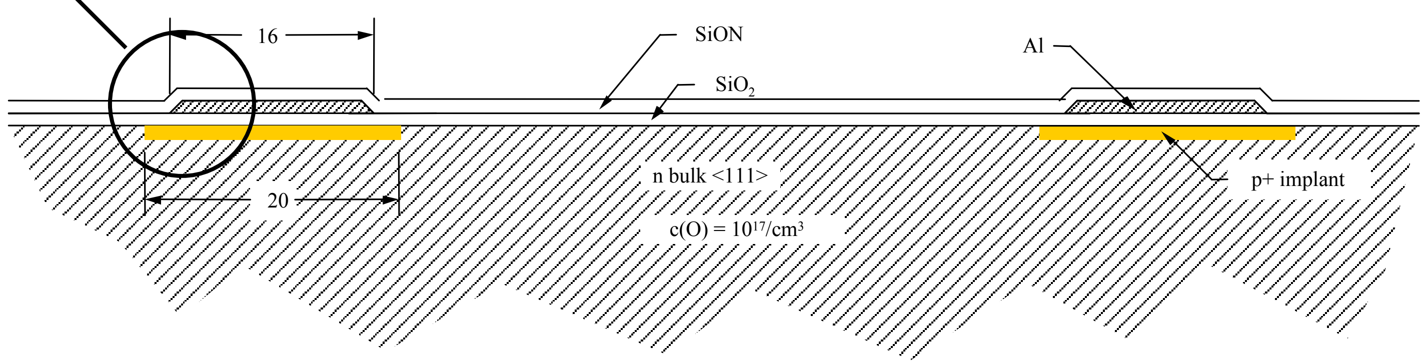
Metal shields implant

Field plate geometry (Hamamatsu)



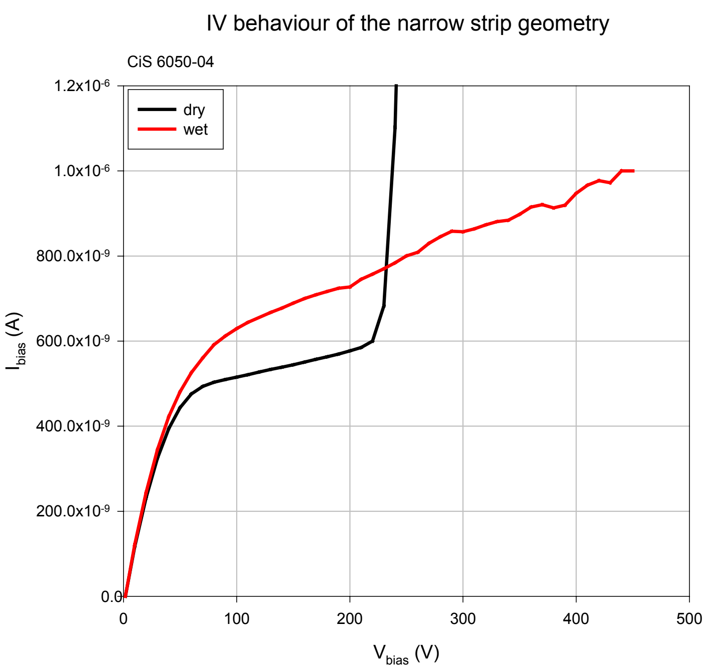
Implant edge not shielded

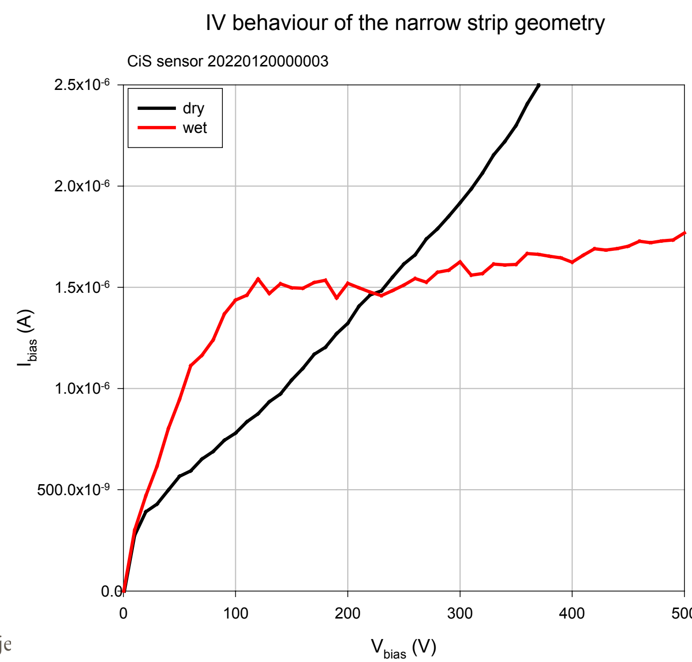
Non-field plate geometry (CiS)



Two examples of moisture dependence for CiS non-field plate geometry

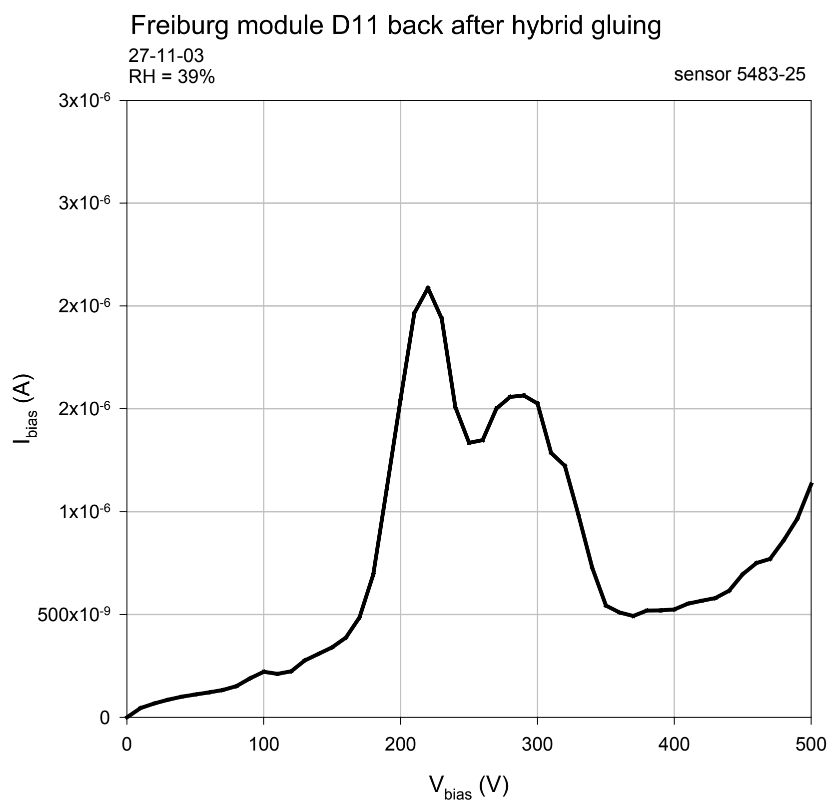
- In dry atmosphere (< 6% RH) breakdown
- In wet condition (RH = 45 – 50%) no problem
- I_{bias} lower in dry atmosphere before breakdown
- Effect of lower I_{bias} in dry atmosphere also observed for Hamamatsu sensors with the field plate geometry but here < 1% breakdown
  - A.Chilingarov, Lancaster University, talk on Vertex 2004, Menaggio, on 17 September 2004





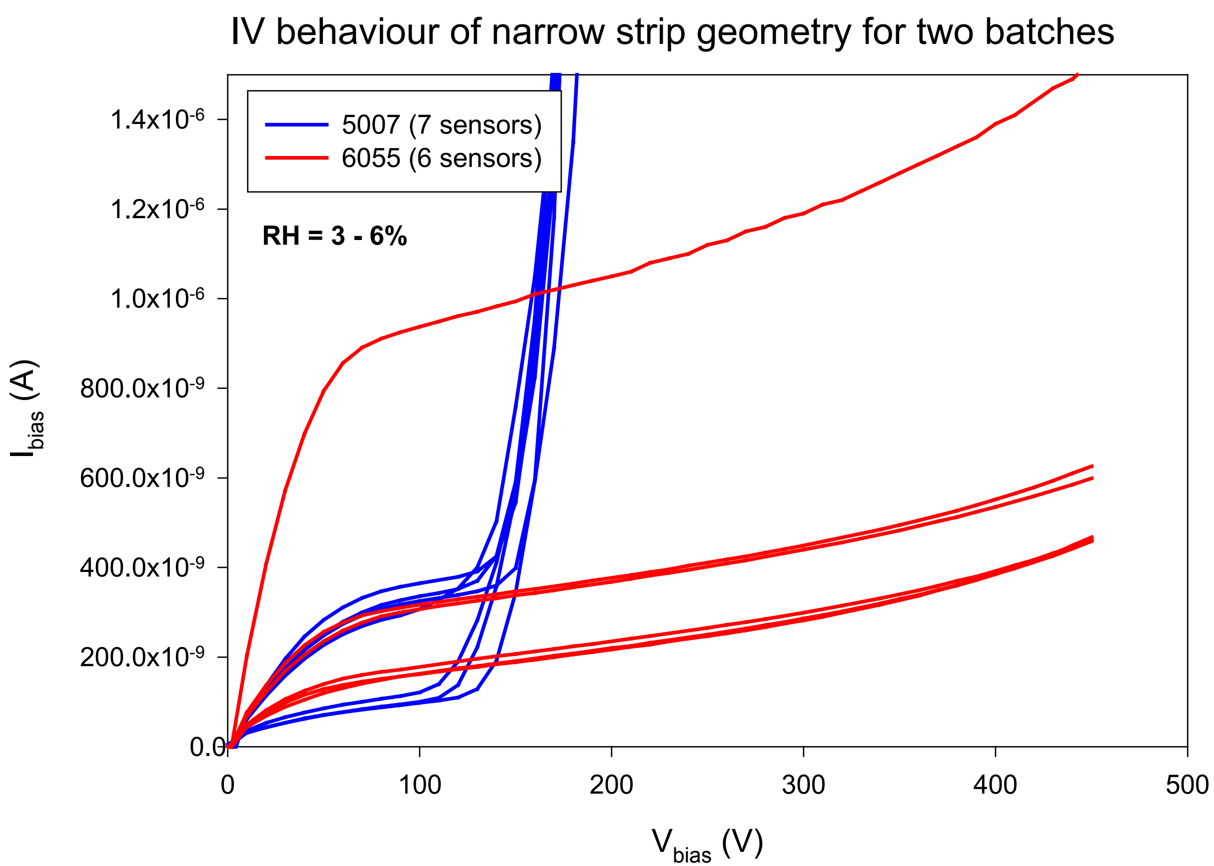
Measurement in the transition region for CiS W12 sensors

- Measured at 39% RH => transition region dry/wet behaviour
- Breakdown sets in but disappears during measurement



Other examples of IV behaviour of CiS non-field plate geometry in dry atmosphere

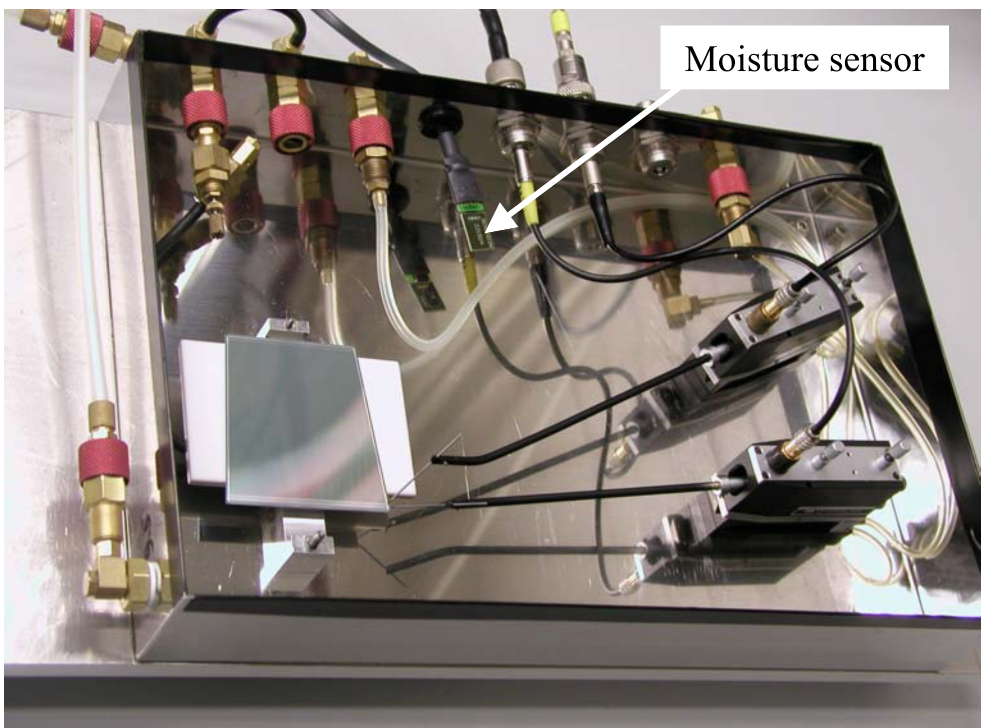
- Altogether there is a wide spectrum of breakdown voltages ranging from ~ 50 V to 400 V
- But often strong correlation within the same batch



Test box used for IV studies

- Small volume probe box
- Rapid moisture sensor
  - type SHT15 with τ = few s from Sensirion
- IV measurement with Keithley 2410
  - Steps of 10 V, ramping at 10V/s
  - 10 s waiting time prior to measurement

- Simple moisture control by water bubbler
- => rapid switching of moisture level possible (< 1 min)



Study on the moisture dependence of the CiS non-field plate silicon sensors

- What do we see if we change from dry to wet while V_{bias} is on?

- And when going back again?
  - Non breakdown situation
  - Breakdown situation

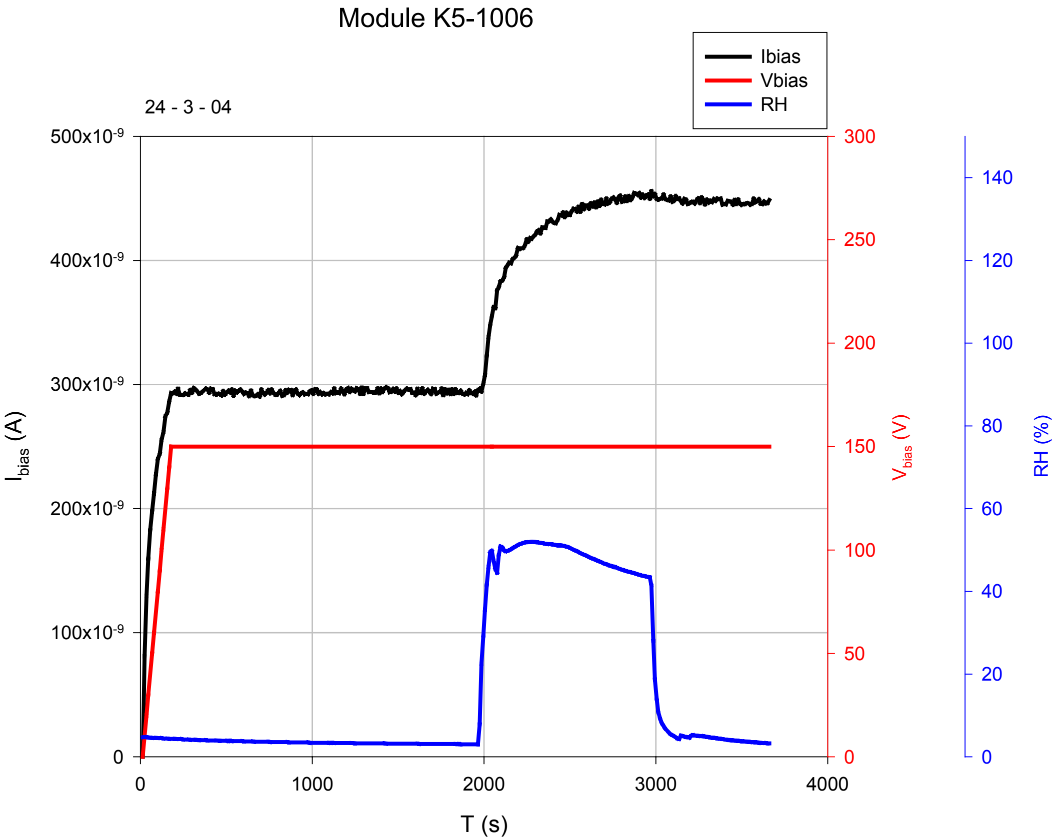
- Can we train a module by ramping V_{bias} up in wet and subsequently switch to dry?

- Has an IV discharge impact on the sensor signal?

Switching dry to wet level when V_{bias} is on

Non-breakdown situation

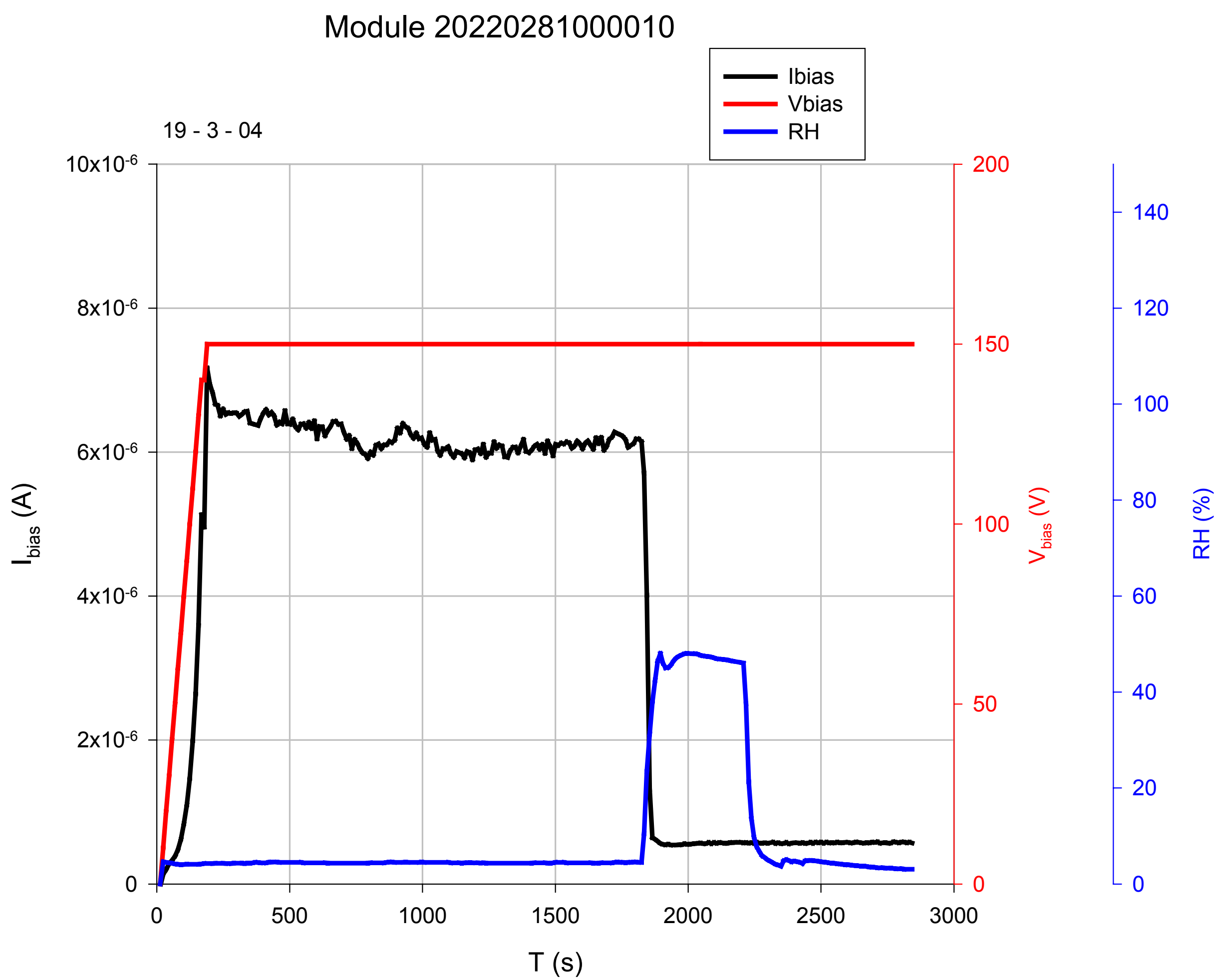
- V_{bias} ramped up to 150 V in dry atmosphere
  - No breakdown yet for this module
- I_{bias} increasing when switching to 50% RH
- But I_{bias} does **not** return to original level when switching back to dry



Switching dry to wet level when V_{bias} is on

Breakdown situation

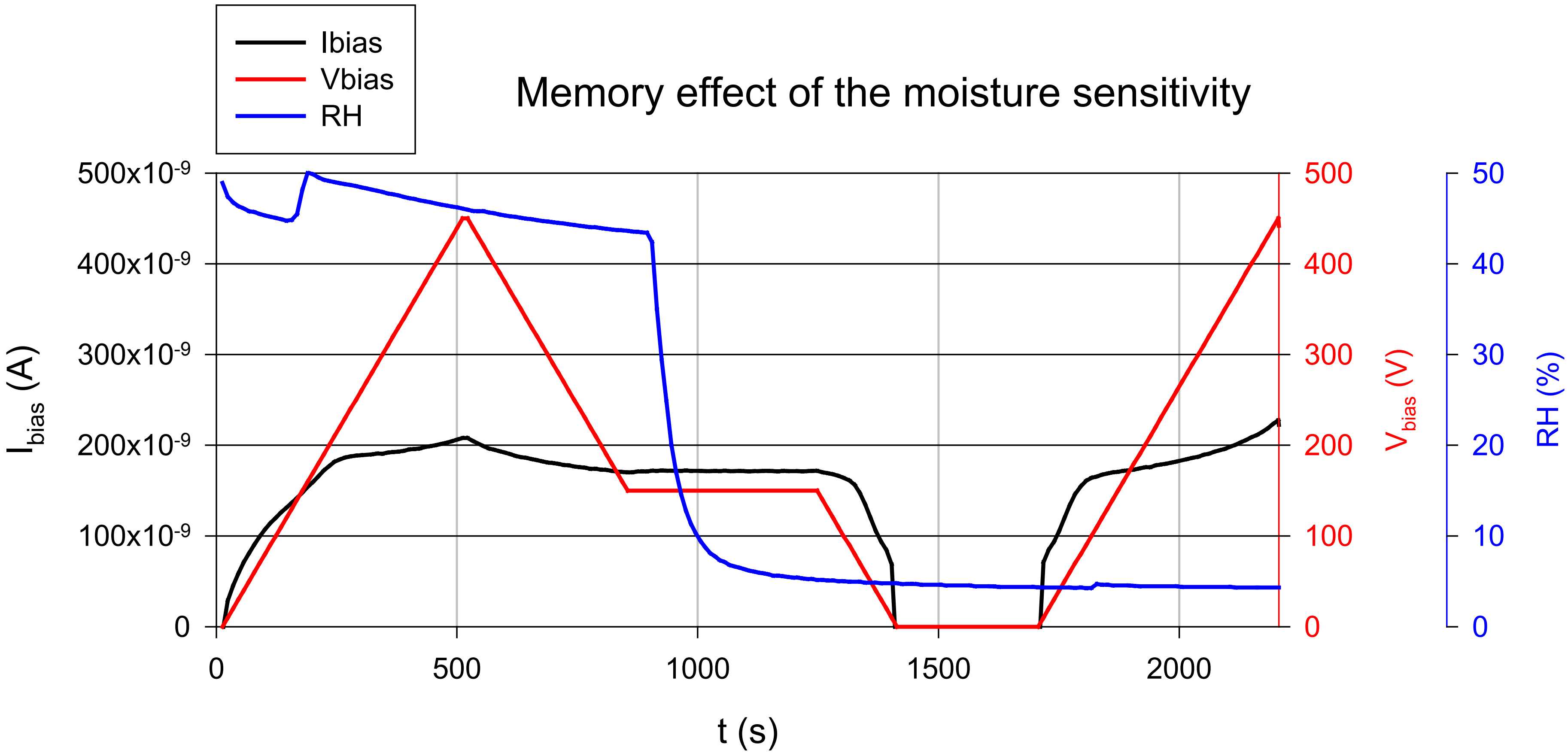
- I_{bias} initially in a discharge mode
  - $I_{bias} > 6\ \mu A$
  - Normal: $< 1\ \mu A$
- Discharge mode disappears instantaneously in moist atmosphere
- And discharge mode does **not** return when dry atmosphere is restored
- => module is well capable of operating in dry atmosphere



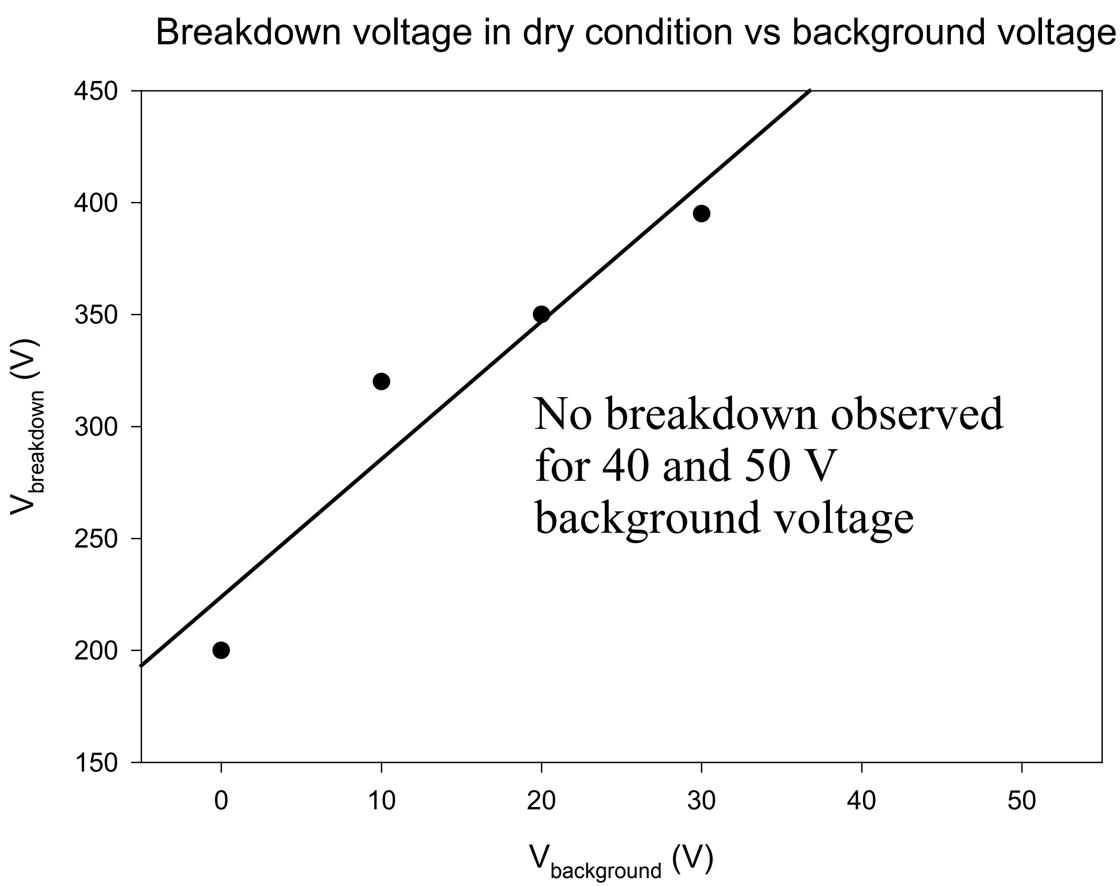
Training by switching from wet to dry while V_{bias} is on

- **No** breakdown if moisture level is switched at V_{bias} = 150 V instead of V_{bias} = 0

- => sensor is well capable of operating in a dry atmosphere if properly trained



What happens if we train at a lower voltage than 150 V?

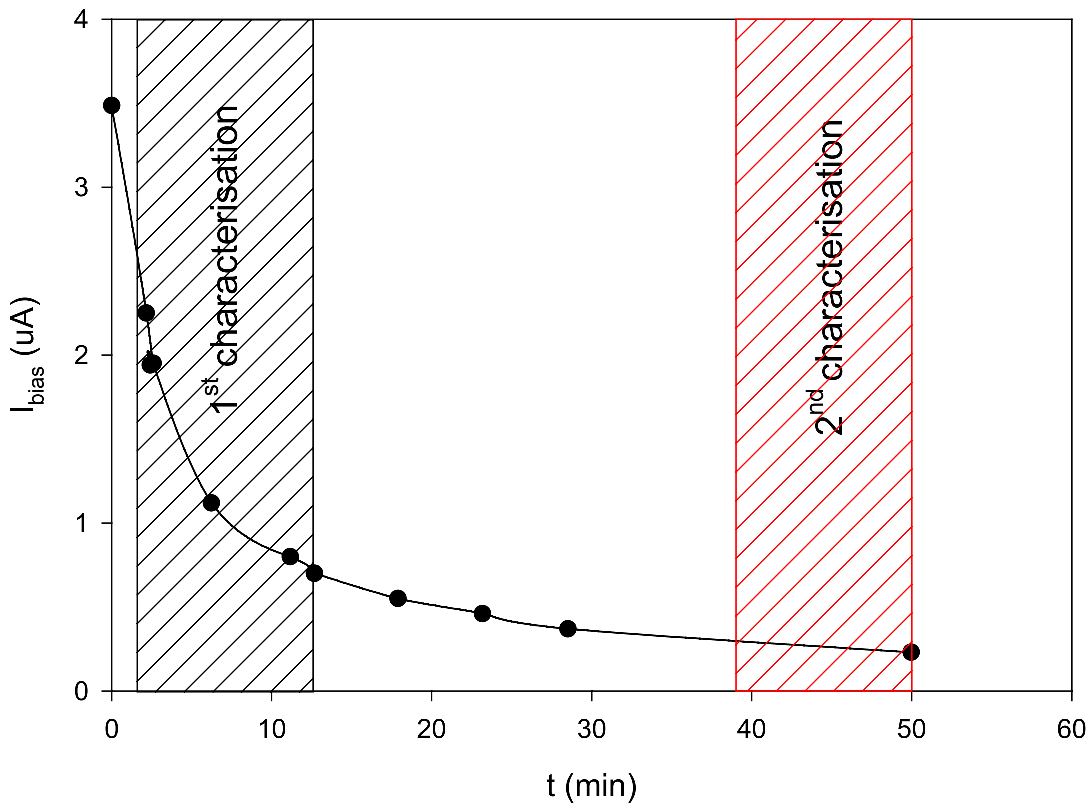


- => For this sensor breakdown can be avoided if we keep it at 40 V background voltage

Impact of breakdown current on signal properties

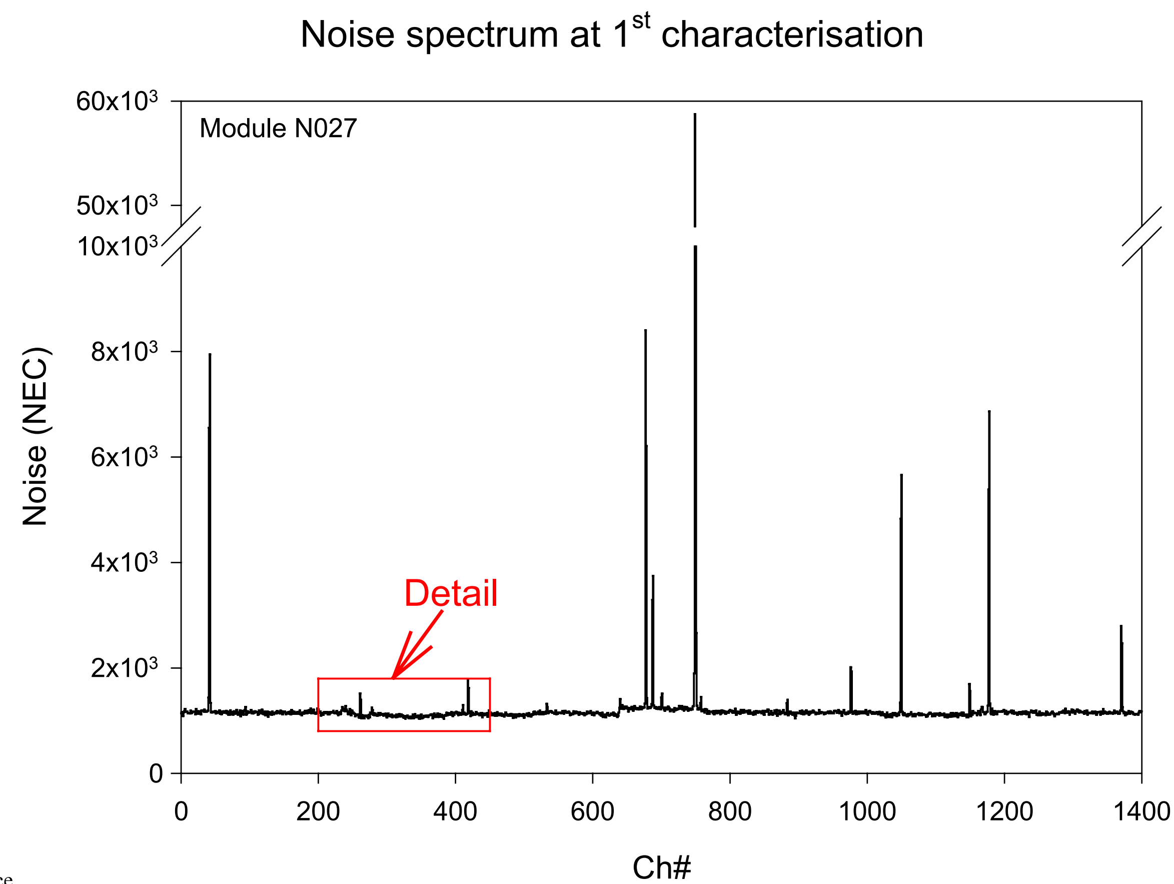
- Module at low temperature (~ 0 ºC)
  - => bulk current low (« 1 µA)
  - V_{bias} = 150 V
- Decaying breakdown current
- Two noise characterisations done
  - immediately after biasing
    - => I_{bias} ~ 2 µA
  - 40 min later
    - => I_{bias} « 0.5 µA

I_{bias} during characterisation of module N027



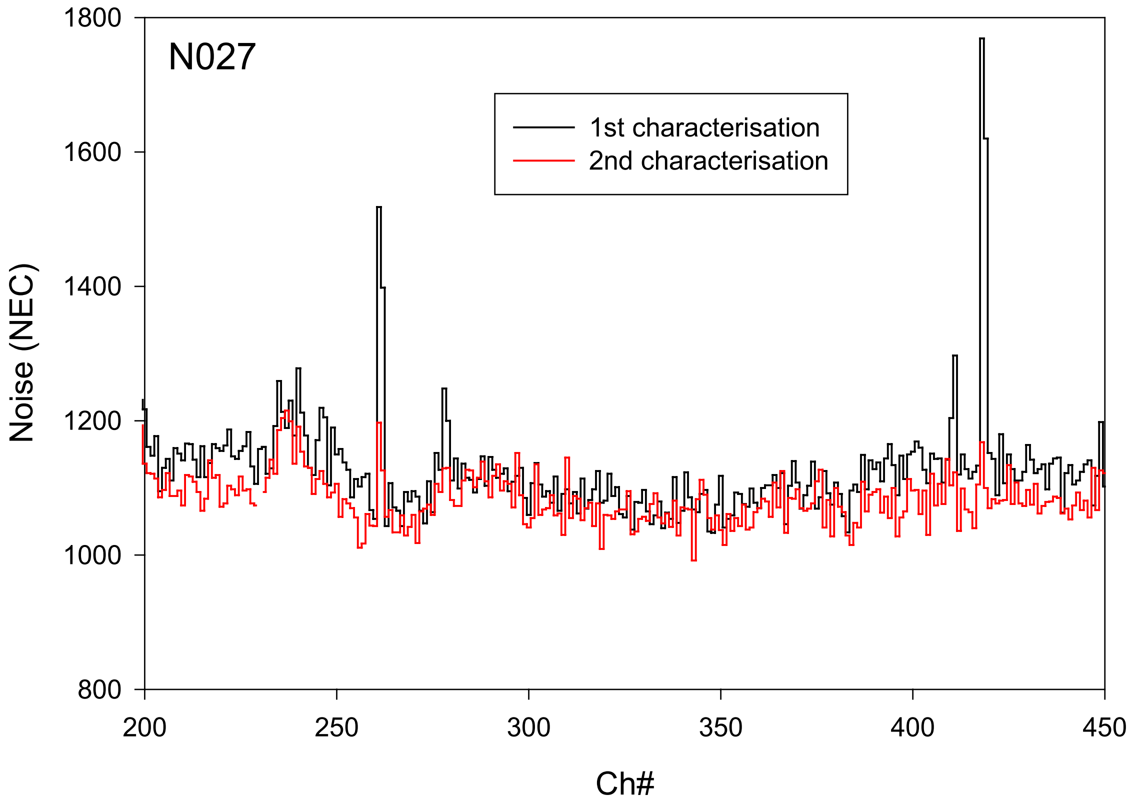
Noise spectrum at 1st characterisation with a module using CiS sensors

- Discharge currents are not stable (stochastic process)
  - =>Number of huge noise spikes are visible indicating the breakdown spots
- Discharge currents are not evenly distributed across the surface but occur at a small number of critical points



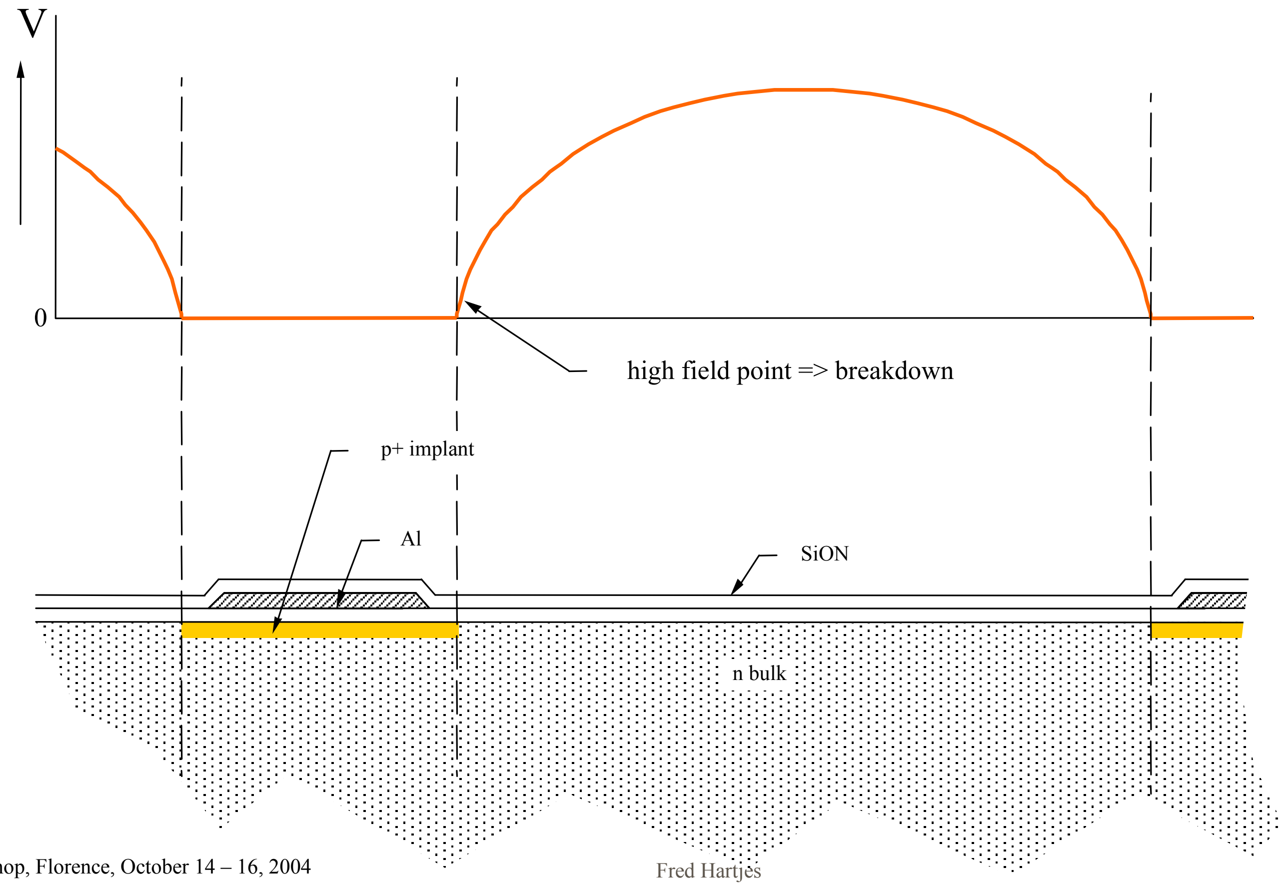
Detail noise plot N027

- Most spikes gone at 2nd characterisation



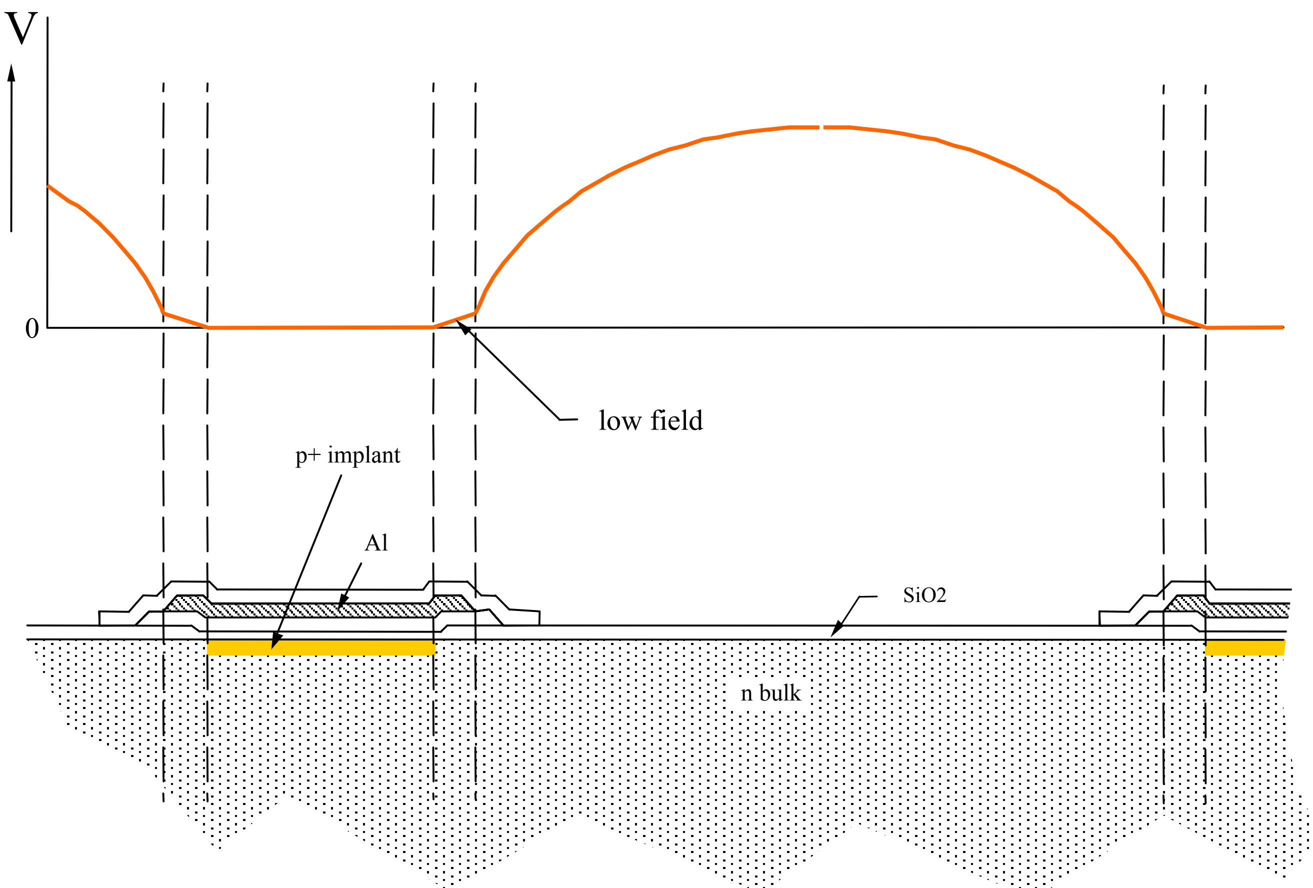
Schematic potential distribution at CiS non-field plate surface

- Dry => non conductive surface assumed
- Positive potential is induced by backplane across the interstrip surface
- High field occurs near edge of implant => **breakdown**



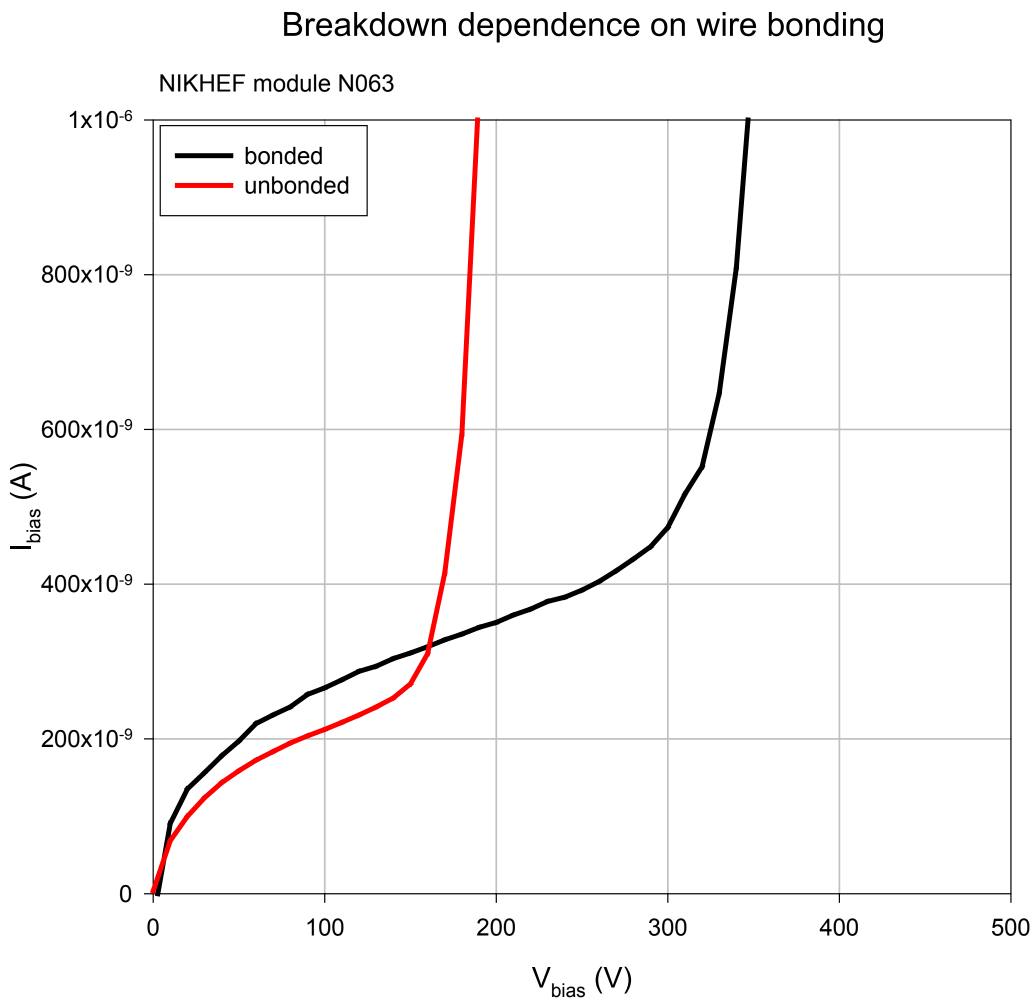
Avoiding breakdown with field plate geometry of Hamamatsu

- Non conductive surface (dry)
- Metal strip capacitively coupled to implant
  - Implant shielded by metal => field near edge of implant reduced
  - **No breakdown**



Effect of wire bonding for non-field plate sensors

- Measured in dry condition
- Wire bonding generally improves breakdown behaviour but often not sufficiently
- Improvement is minor for low breakdown voltages (< 100 V) but substantial for higher (>150 V) breakdown voltages
- Explanation: metal strips are no longer floating when bonded



Moisture film on insulator surface

- Moisture films of atomic thickness are formed on all insulators starting
  - Well known behaviour for insulators
  - Continuous decrease of surface conductivity for decreasing relative humidity †

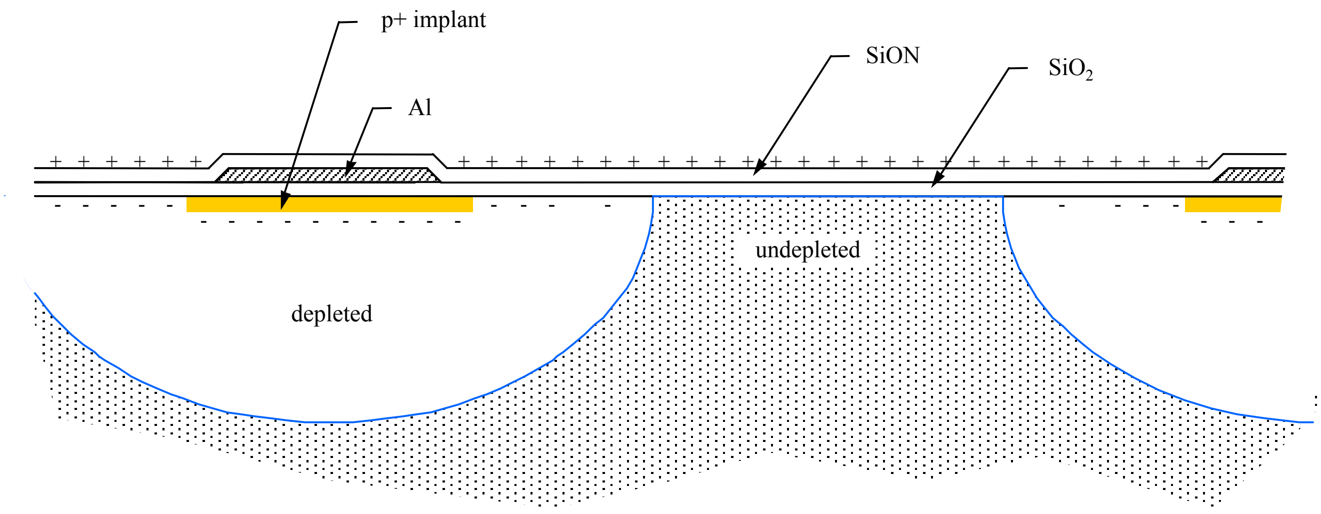
- Moisture effect on surface conductivity material dependent (hygroscopic materials)
  - => There may be a difference between the SiO_2 passivation (used for field plate sensors) and the SiON passivation (used for non-field plate sensors)

- My own observation: dry air removes moisture film within seconds

† A.Chilingarov, talk on Vertex 2004, Menaggio, on 17 September 2004.

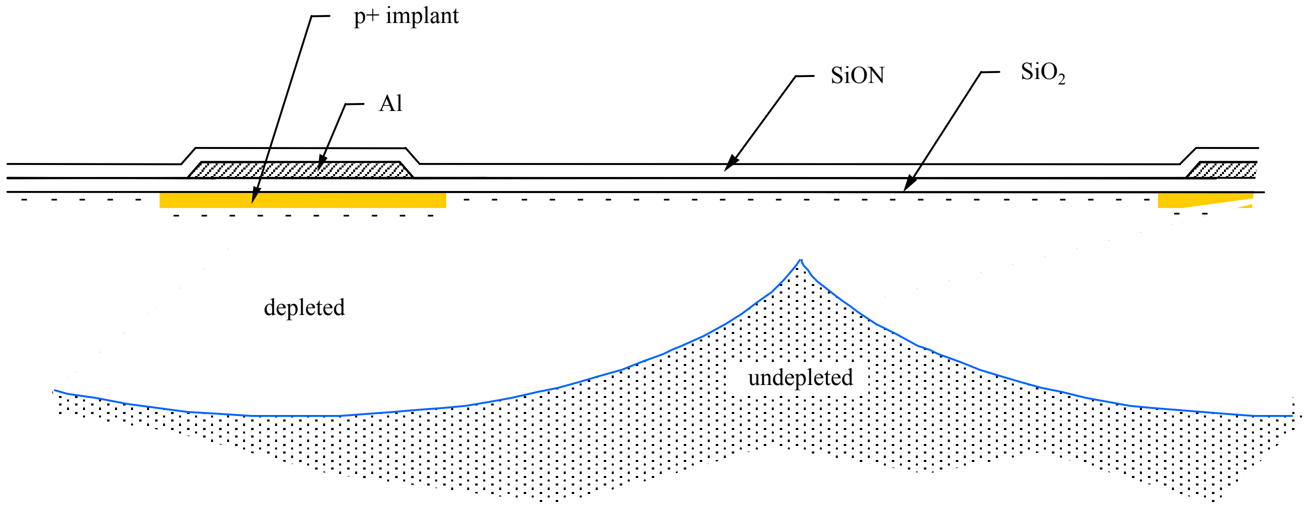
Partially depleted situation in dry atmosphere

- Assumed depleted area for **non-field plate** geometry
- Surface not conductive => positively charged by induction
  - Positive space charge in SiO_2 layer neglected
  - Undepleted zone between strips
  - High interstrip capacitance (A.Chilingarov, talk on Vertex 2004, Menaggio, on 17 September 2004)
  - Lower bias current
  - For non-field plate geometry high field at edge of implant => **Breakdown**



Partially depleted in <u>moist</u> atmosphere

- Assumed depleted area for non-field geometry
- Surface conductive => no external charge
  - Fully depleted zone between strips => low interstrip capacitance
  - Higher bias field => higher bias current
  - Reduced field at edge of implant => **No breakdown**
- When switching from wet to dry then the negative charge on the insulated surface is preserved
  - => we do get the same charge distribution back if we test V_{bias} on a later moment as long as the sensor is <u>permanently</u> kept in a dry atmosphere



Summary and conclusions

- Sensors with early breakdown can be trained by applying bias voltage in a moist atmosphere followed by switching to dry *while* V_{bias} *is on*

- Breakdown currents show themselves as a small number of high spikes in the noise spectrum
  - => discharges probably confined to small spots

- The lower bias current in a dry atmosphere compared to moist for both detector geometries can be explained from reduced field strength in the dry atmosphere

- Observed breakdown phenomena in CiS sensors are unpractical in during commissioning of the ATLAS SCT endcaps but do **not** affect operation in the ATLAS SCT