Electrical characterization of silicon micro-strip sensors

Nicoleta Dinu

National Institute of Nuclear Physics – Perugia, Italy
On leave from Institute of Space Sciences – Bucharest, Romania

Fermi National Accelerator Laboratory, 27 May 2003

Summary of the talk

- Introduction
  - About the lecturer
  - Historical perspective and motivation

- Examples of sensor design
  - CMS sensor (single-sided AC-coupled poly-silicon biased sensor)
  - AMS sensor (double-sided DC-coupled punch-through biased sensor)

- Electrical characterization
  - Hardware set-up
  - Electrical parameters
  - Characteristic defects detected during electrical characterization

- Conclusions

Introduction - about the lecturer

- A brief CV
  - Faculty of Physics, Nuclear Physics Section, Bucharest, Romania
  - Scholarship at National Institute of Nuclear Physics (INFN), Perugia Univ., Italy
    - Worked on electrical characterization of silicon micro-strip sensors for the AMS01 and the CMS experiments
  - PhD. at Institute of Physics and Nuclear Engineering – Horia Hulubei, Bucharest, Romania
    - Thesis: “Modifications of crystals properties using stable and radioactive ion beams”
    - Worked at Joint Institute of Nuclear Research (JINR), Laboratory of Nuclear Reactions/Center of Applied Physics, Dubna; studies of the effect of heavy ion irradiation on distribution and electrically activity of boron in silicon
  - Post-doc at INFN, Perugia Univ., Italy
    - Worked on studies of electrical properties of silicon micro-strip silicon sensors for the CMS and the AMS02 experiments
  - Senior researcher III, Institute of Space Sciences, Laboratory of Space Researches, Bucharest, Romania

Introduction - historical perspective (1)

- Physicists always wanted to understand the fundamental laws of nature

- Astrophysics and particle accelerators – go "hand in hand" to find answers to unsolved physics problems
  - Astrophysics
    - Cosmic rays (Hess, 1912) – natural source for very high energy particles
    - e^+, μ^+, μ^-, π^+, π^-, K, Λ, Σ, Ξ^- - first elementary particles discovered before the advent of particle accelerators
  - Particle accelerators
    - First particle accelerators (~ 1950) – allowed more systematic studies using artificial particles
    - The great advantage - the beams could be produced with known energies and directed precisely onto the target

- Determination of particle trajectories – basic requirement in astrophysics and particle accelerator fields

- <u>Silicon tracking systems</u> – high precision tracking devices for measuring of particle parameters

Introduction - silicon detectors (2)

- ➢ Challenging features of silicon tracking detectors:
  - ☺ High spatial resolution
  - ☺ Compactness in size
  - ☺ Very fast response time
  - ☺ Low power consumption
  - ☺ Good operation in vacuum and strong magnetic fields
  - ☺ High radiation hardness
- ➢ Large usage in high radiation environments in particle accelerator experiments:
  - ☞ Fixed target experiments:
    - HERA-B, HERMES, COMPAS and others.
  - ☞ Collider experiments:
    - CDF, D0, BTeV at Tevatron p-antiproton collider – FNAL;
    - CMS, LHCb, ATLAS and ALICE at LHC p-p collider – CERN;
    - STAR, PHENIX, PHOBOS, BRAHMS at RHIC heavy ion collider;
    - BABAR, BELLE, CLEO at B-factory colliders;
    - H1 and ZEUS at HERA e-p collider.
- ➢ Large usage in space experiments:
    - AMS, GLAST, PAMELA, AGILE, NINA and others.

Introduction - motivation (3)

- Particle detection efficiency and spatial resolution of the silicon tracking detectors
  - ☞ depend strongly on the electrical properties of their basic element: <u>the silicon sensor</u>

- Electrical properties of the silicon sensors:
  - ☞ contribute to the noise at the input of the read-out electronics
  - ☞ influence the performances of the detector

- Very accurate electrical characterization have to be performed prior final assembly of the silicon sensors
  - ☞ to obtain the best possible signal-to-noise ratio
  - ☞ to guarantee the quality of the measurements during all the data taking period

Examples of sensor design (1)

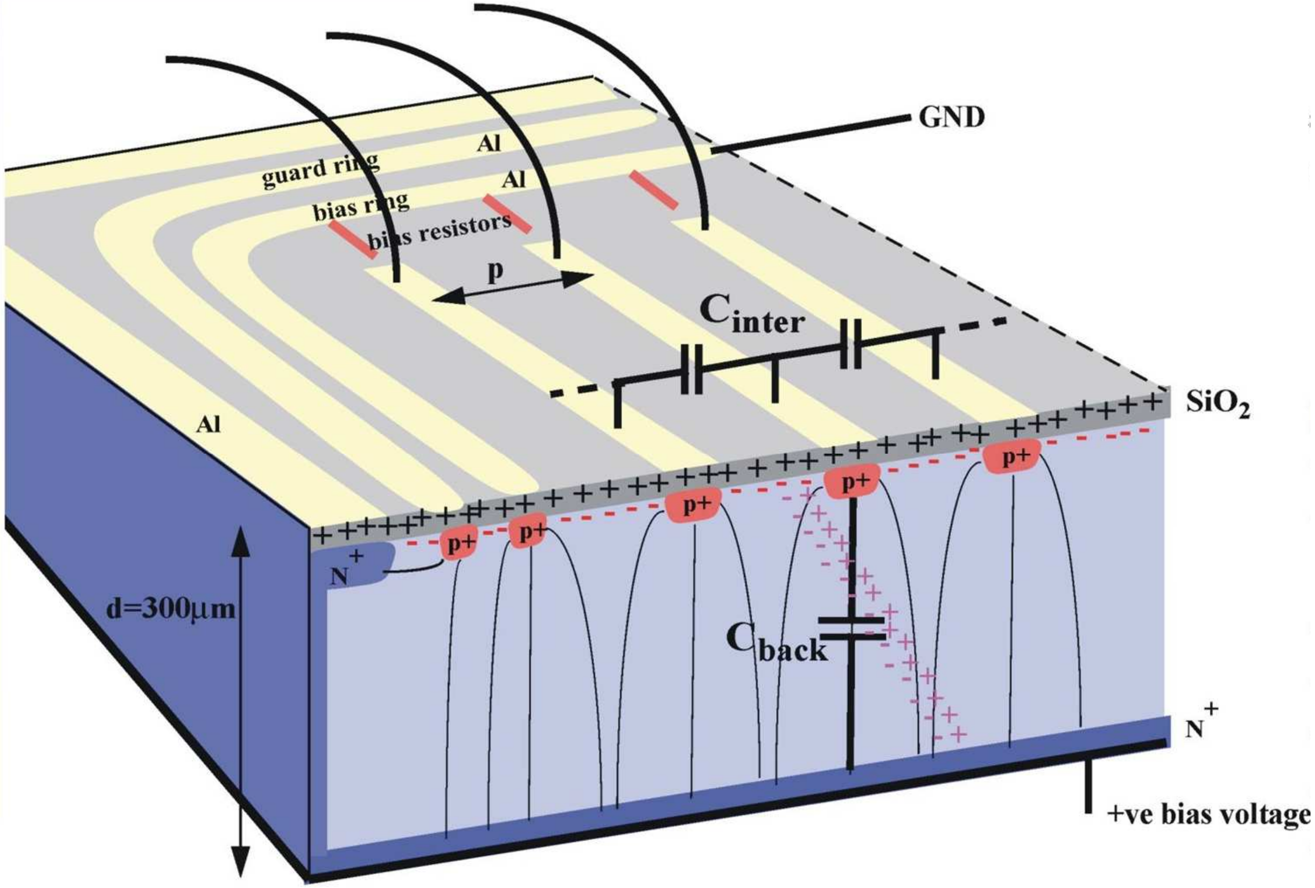
- Choosing of the sensor design must follow the physics requirements of desired experiment

- Important criteria for silicon micro-strip sensors design optimisation:
  - ☞ position-measurement precision
  - ☞ efficiency of charge collection and noise signals
  - ☞ the stability of the device and its radiation hardness

- Performance optimisation requires the simultaneous consideration of the geometrical parameters of the sensor and the associated electronics:
  - ☞ p or n bulk silicon
  - ☞ resistivity
  - ☞ thickness
  - ☞ strip pitch and read-out pitch
  - ☞ single or double side
  - ☞ type of biasing structure
  - ☞ AC or DC coupling

Examples of sensor design - CMS sensors (2)

- Compact Muon Solenoid (CMS)
  - Future exp. at LHC - CERN
  - World largest Silicon Strip Tracker
- Silicon Strip Tracker of CMS
  - ~ 25000 single-sided micro-strip silicon sensors (210 m^2)



Radiation environment

- $\Phi \approx 1.6x10^{14}$ n/cm^2
- This governs choice of many parameters of the silicon sensors

Crystal properties

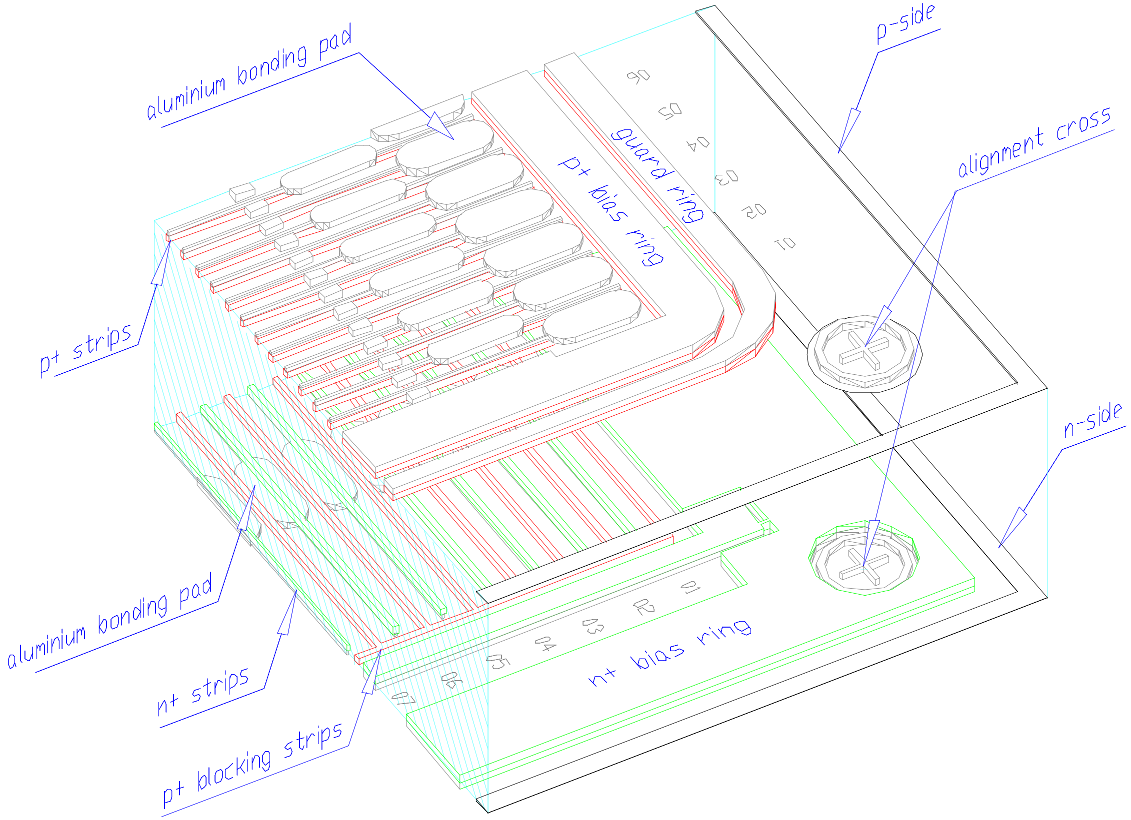
- **n-type silicon**
- **<100> orientation**
- **flatness < 100µm**
- **320±20µm;1.5÷3.0 kΩ cm**
- **500±20µm;3.5÷7.5 kΩ cm**

Sensor characteristics

- **single sided**
- **strips p$^+$ implanted**
  - **width/pitch ≈ 0.25**
- **AC coupled**
- **metal overhang 4÷8 µm**
- **poly-silicon biased**
- **bias-ring**
- **guard-ring**
- **n$^+$ along the edge**

Examples of sensor design - AMS sensors (3)

- Alpha Magnetic Spectrometer (AMS)
  - ☞ Exp. programmed to operate on the International Space Station from 2005 for at least three years
  - ☞ The biggest silicon tracker even flown in space
- Silicon Strip Tracker of AMS
  - ☞ ~ 3000 double-sided micro-strip silicon sensors
  - ☞ 8 planes (8 m^2)



Sensor crystal properties

- n-type silicon (4” wafers)
- high resistivity (> 6 kΩ cm)
- <111> crystal orientation
- 300±10 μm thickness

Sensor characteristics

- active area 7x4 cm^2
- both sides processed by planar technology
- cut with very high precision (<5 μm)
- **p-side**
- 1284 p^+ metallized strips (55 μm pitch)
- two p^+ guard-rings GR (70 μm wide)
- punch-through biasing (inner GR at 5 μm from the strips end)
- **n-side**
- 384 n^+ strips perpendicular to the p^+ strips on the opposite side (110 μm pitch)
- p^+ blocking strips surround each n^+ strip
- single guard-ring GR (500 μm wide)
- surface-through biasing

Electrical characterization (1)

- Efficient charge collection in a tracking detector
  - ☞ The signal given by a minimum ionizing particle must be much higher than the noise at the input of the read-out electronics
  - ⇒ All noise sources must be minimized
- Noise sources in a tracking detector derive from all components of electronic chain:
  - ☞ Silicon sensor
  - ☞ Read-out electronics
  - ☞ Electrical network
- The most important sources of noise occur near the beginning of the signal, where the signal is at a minimum
  - ☞ noise generated at this point undergoes the same amplification as the signal
  - ☞ noise generated further along the chain is usually much smaller than the signal

⇒*The noise sources derived from the silicon micro-strip sensor (connected to its electrical properties) represent an important contribution to the electronic noise and must be carefully analyzed*

Electrical characterization (2)

- Accurate electrical characterization of all electrical parameters of silicon sensors with contributions to the electronic noise must be performed prior final assembly of the sensors:
  - ☞ Leakage currents for every strip I_{ss} for the current shot-noise
    - ENC $\propto \sqrt{I_{ss}}$
  - ☞ Poly-silicon resistance (polysilicon resistor biasing)
  - ☞ Resistance to the bias-ring (punch-through biasing)

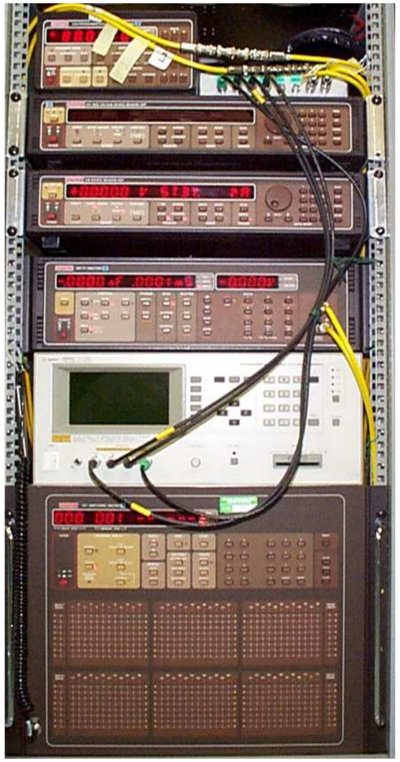
    } for the thermal noise
    - ENC $\propto \sqrt{(kT/R)}$
  - ☞ Coupling capacitance (for AC coupled sensors)
  - ☞ Interstrip capacitance

    } for the capacitive load C_d
    - ENC $\propto C_d$
  - ☞ Interstrip resistance for the DC electrical isolation

Electrical characterization - hardware set-up (3)

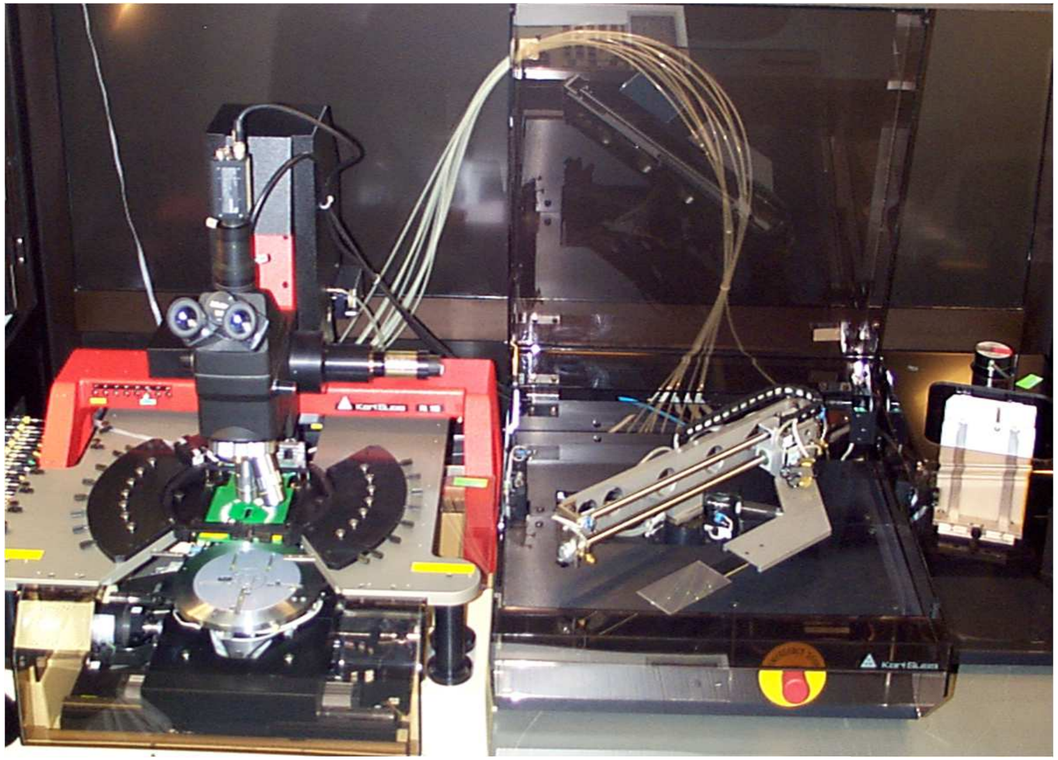
- Main characteristics of the hardware system for electrical characterization of silicon micro-strip sensors:
  - ☞ At least 10% accuracy for:
    - Current levels ranging from O(100pA) to O(10mA)
    - Resistances of O(GΩ) to O(TΩ)
    - Capacitances down to O(pF)
  - ☞ Reproducible results immediately interpretable
  - ☞ Automated for fast quality control of a large number of sensors in short time
  - ☞ Measurements performed in a clean-room:
    - purity class 10000 or less
    - controlled temperature (21±1°C) and humidity (35±5% RH)

Electrical characterization - example of hardware set-up (4)

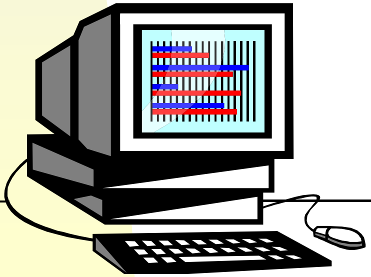


Electrical instruments

cables



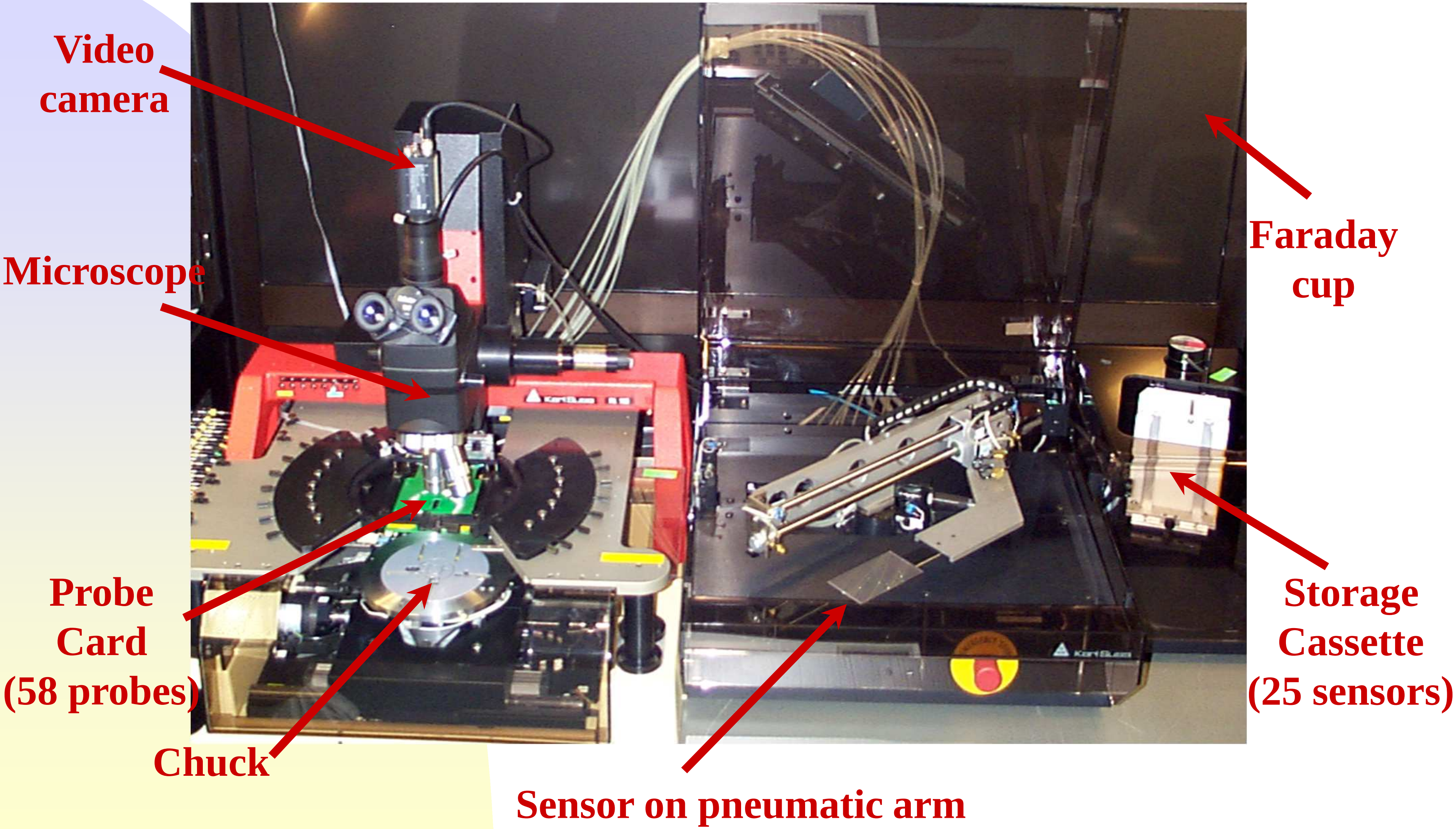
PA 200 Karl Suss test station



GPIB

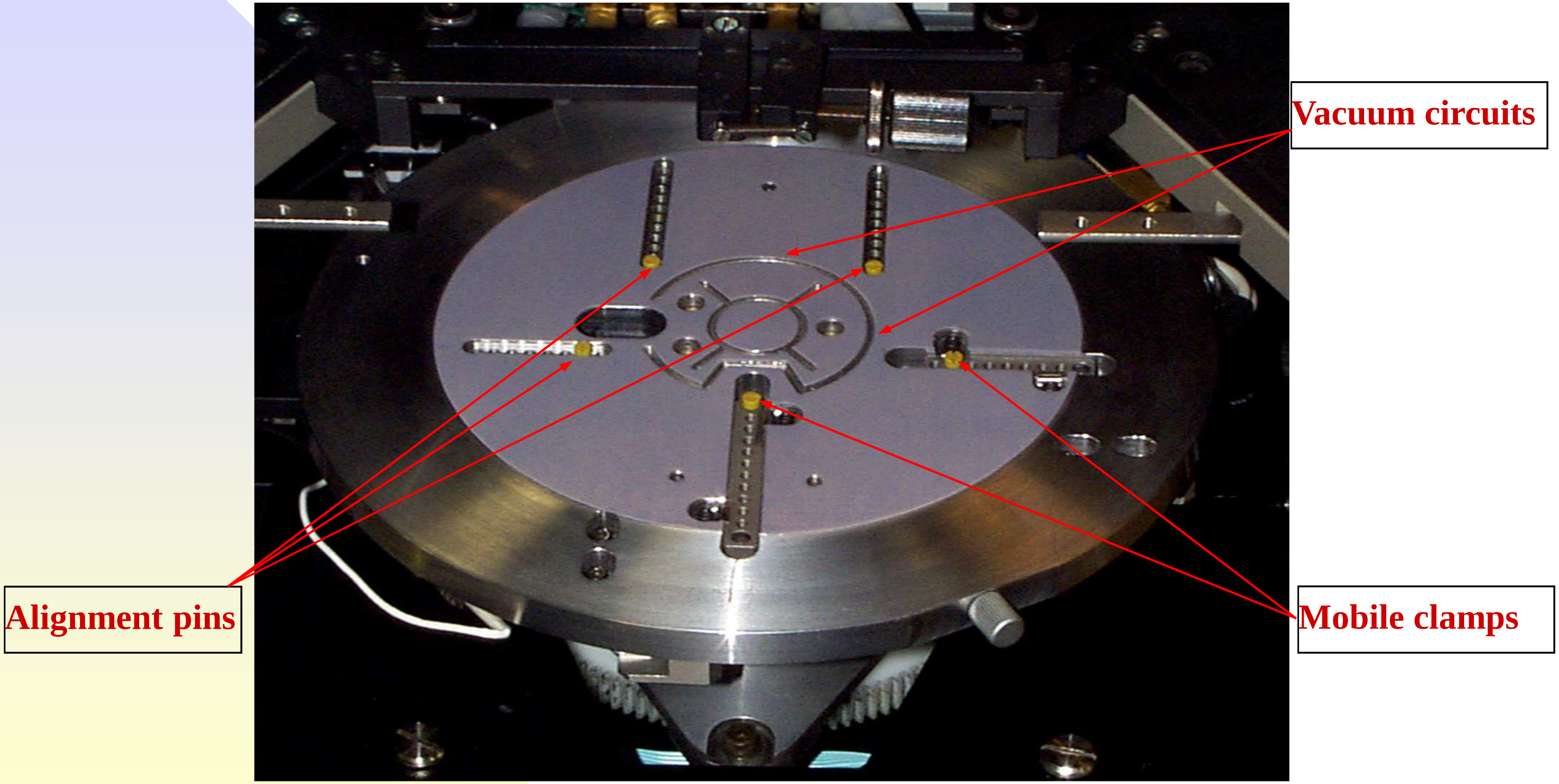
Serial port

Electrical characterization - hardware set-up (5)

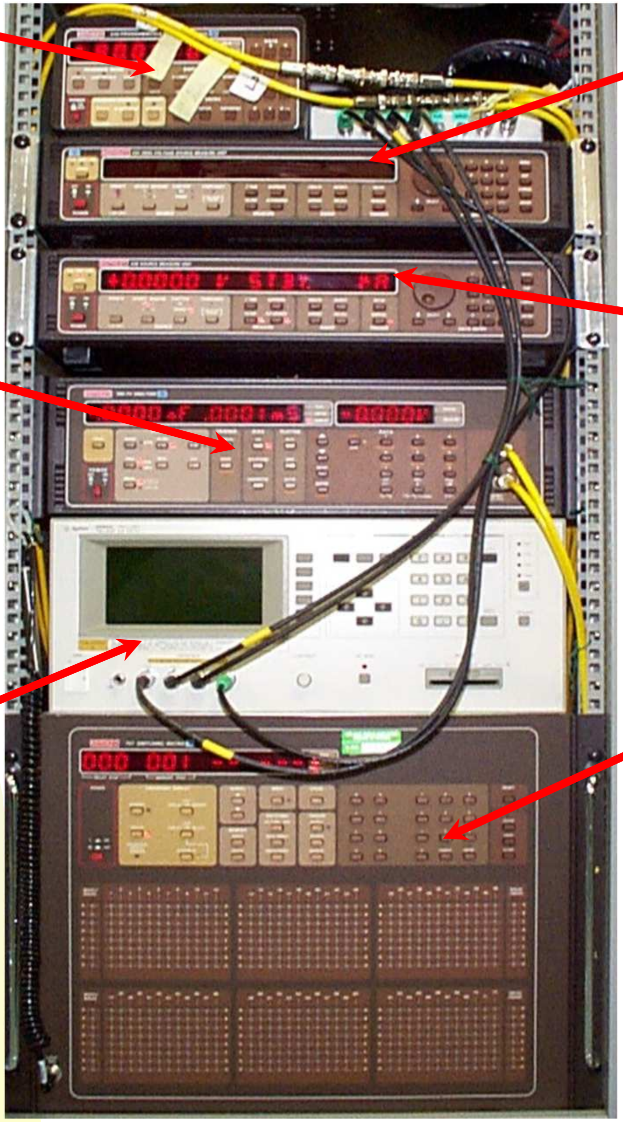


Electrical characterization - hardware set-up (6)

Detailed view of chuck



Electrical characterization - hardware set-up (7)



Keithley 230 Voltage Source

Voltage source: ± 100mV to ± 100 V

Keithley 590 CV Meter

Frequency range: 100 kHz, 1 MHz
Capacimeter sensibility: 1 fF
Internal bias source: ± 20 V
Applied external bias source: ± 200 V

Agilent 4284 LCR Meter

Frequency range: 20 Hz, 1 MHz
Capacimeter sensibility: 1 fF
Bias source: ± 40 V

Keithley IV 236

Source V: ± 100 μV to ± 110 V
Measure I: ± 10 fA to ± 100 mA
Source I: ± 100 fA to ± 100 mA
Measure V: ± 10 μV to ± 110V

Keithley IV 237

Additional capabilities
Source or measure up to ± 1100 V
at ± 10 mA maximum

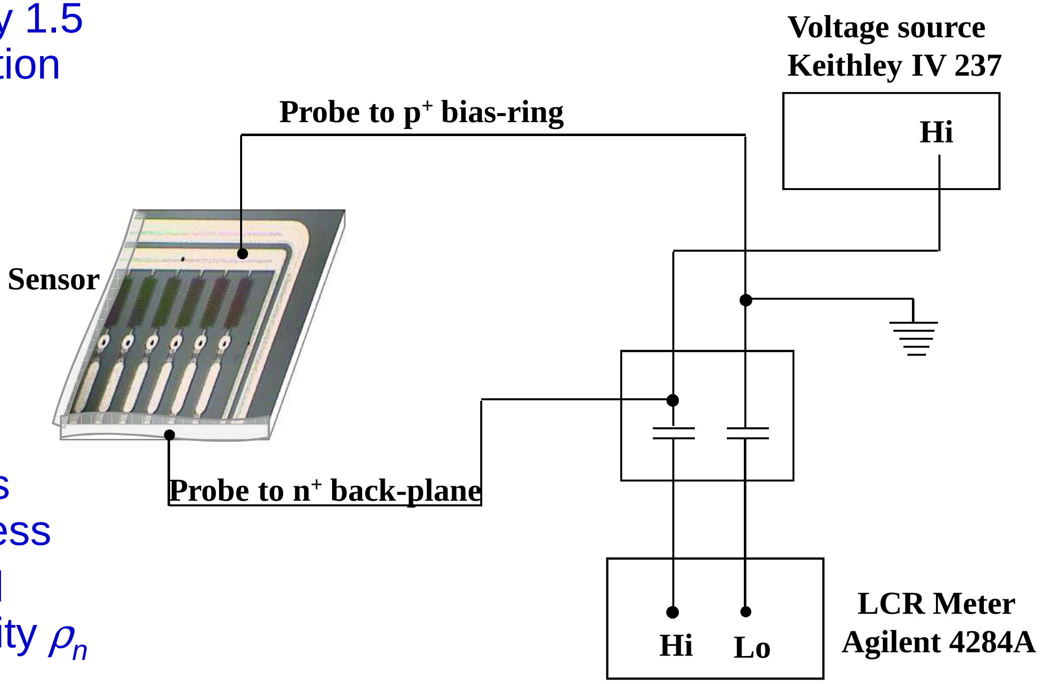
Keithley 707 Switching Matrix

Matrix 8 (lines) x 72 (columns)
lines (A÷H) - instruments
columns (1÷72) – needless of the probe-card

- **Triaxial cables with guarded shielding**

Electrical characterization - electrical parameters (8)

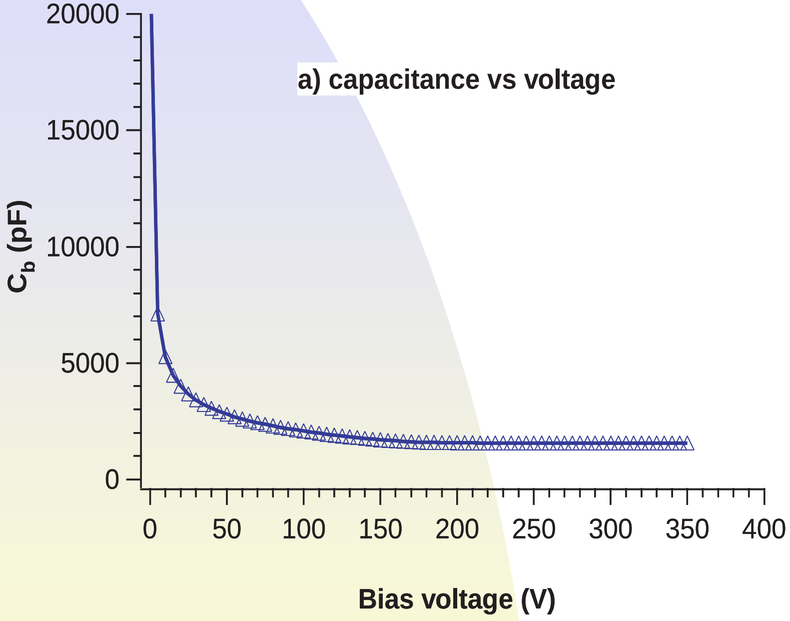
- Over-depleted mode operation
  - across the sensor is applied an reversed bias voltage usually 1.5 or 2 times higher then depletion voltage

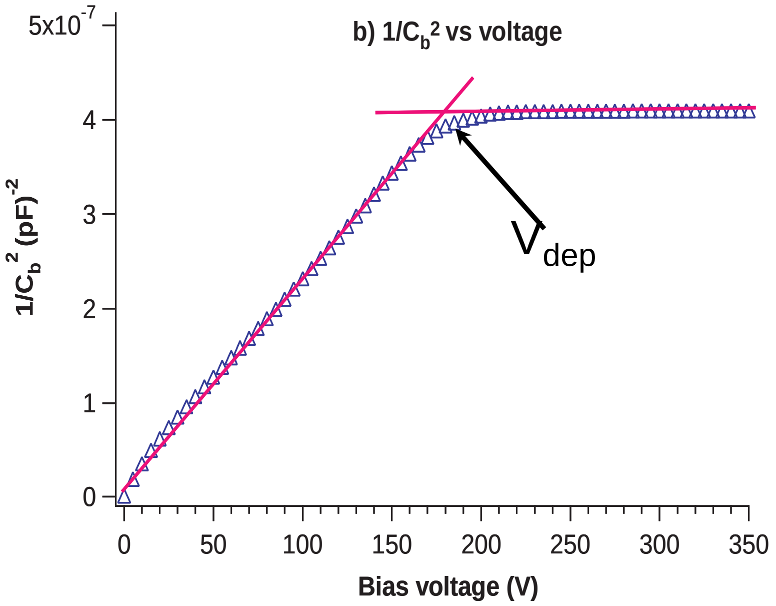


- Depletion voltage V_{dep}
  - space charge region extends through the full wafer thickness
  - property of the n-type crystal (depends of the bulk resistivity ρ_n of the crystal)
  - determined by measuring the bulk capacitance C_b versus reverse bias voltage V_{bias} between the p^+ bias-ring and the n^+ back-plane of the sensors

Electrical characterization - electrical parameters (9)

- Depletion voltage V_{dep}
  - ☞ extracted from the fit of the knee in the plot $1/C_b^2$ versus V_{bias}

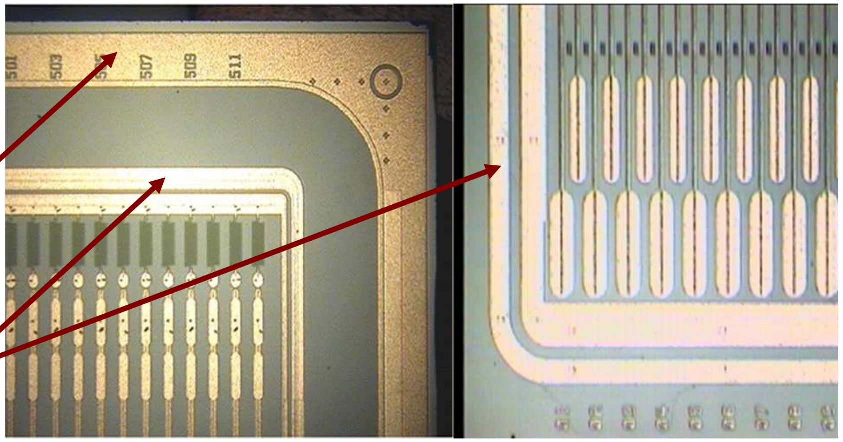

a) capacitance vs voltage


b) $1/C_b^2$ vs voltage

- Depletion voltage values:
  - ☞ CMS sensors: $V_{dep} = 100 \div 300$ V $\Rightarrow V_{operation} = 400$ V
  - ☞ AMS sensors: $V_{dep} = 20 \div 50$ V $\Rightarrow V_{operation} = 80$ V

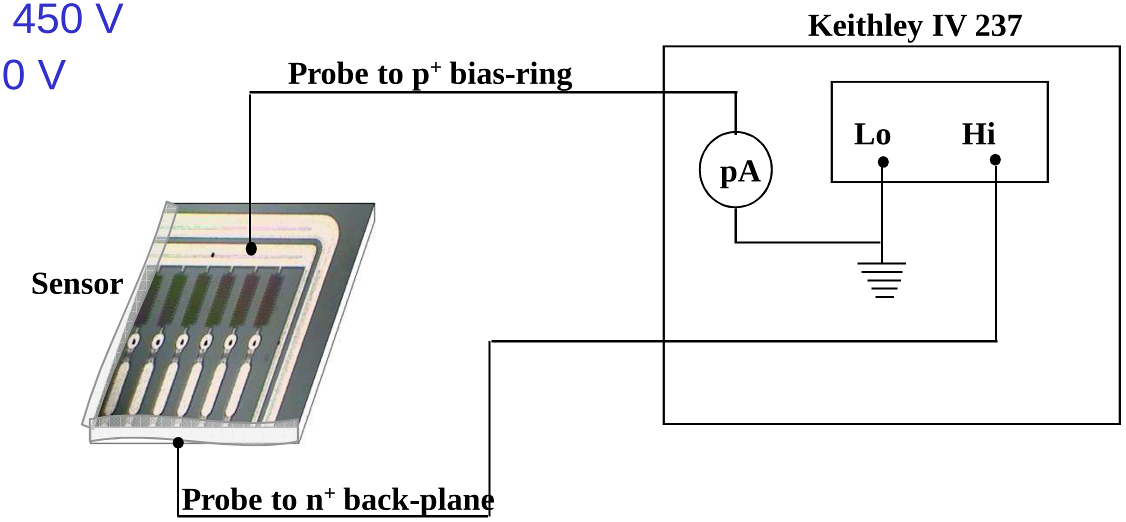
Electrical characterization - electrical parameters (10)

- Total leakage current I_{tot}
- Main sources of (unwanted) current flow:
  - Diffusion current
    - charges generated in the un-depleted zone adjacent to the depletion zone which diffuse into the depletion zone (otherwise they would quickly recombine)
    - should be negligible
  - Generation current
    - charge generated in the depletion zone by defects or contaminants
    - $J_g \propto \exp(-b/kT)$ – exponential dependence of temperature
    - rate determined by nature and concentration of defects
    - major contribution
  - Surface leakage currents
    - Take place at the edges of the sensor
    - n-type implants put around edge of the device and a proper distance maintained between p bias ring and edge ring
    - External guard-ring assures continuous potential drop over the edge


CMS sensor **AMS sensor**

Electrical characterization - electrical parameters (11)

- Total leakage current I_{tot}
  - measured between the p^+ bias-ring and the n^+ back-plane of the sensor
  - for the case of large number of sensors certification, total leakage current is a fairly good indicator of imperfections (the net current measured is the sum with the signs of all the contributions mentioned before)
- I_{tot} values:
  - CMS sensors: I_{tot} < 12 μA @ 450 V
  - AMS sensors: I_{tot} < 2 μA @ 80 V



  - Usually, all the strips are resistively connected to the bias-ring
  - I_{tot} – the sum of single-strip leakage currents contributions

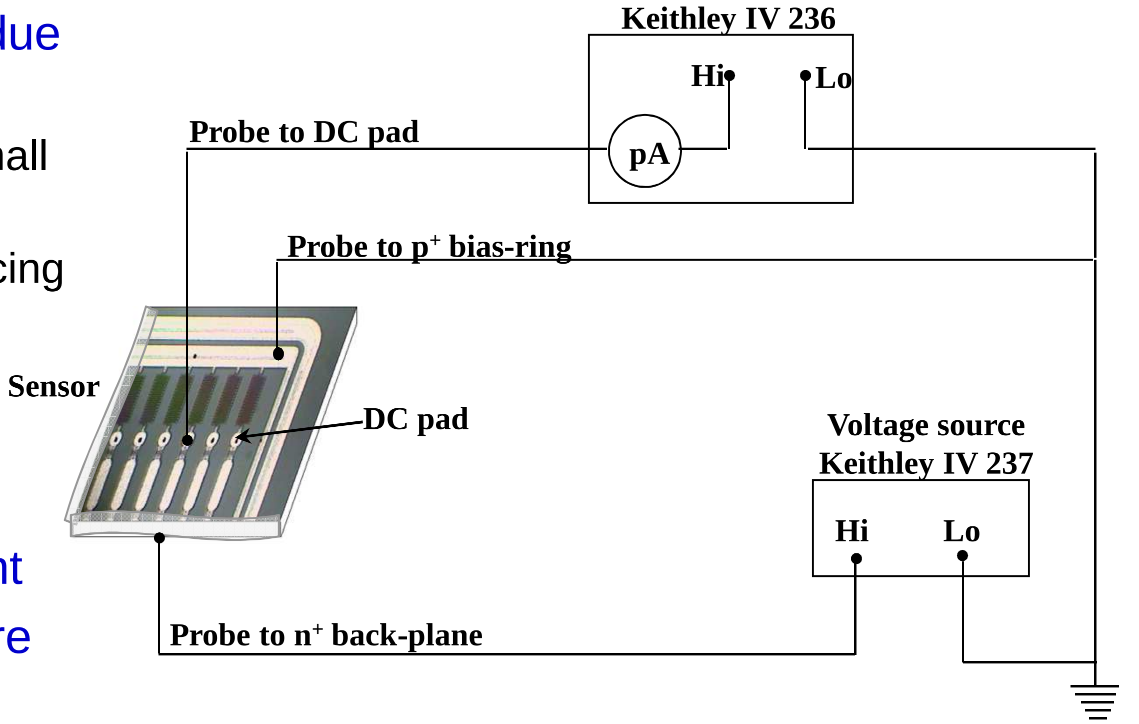
Electrical characterization - electrical parameters (12)

- Single strip leakage current I_{ss}
- Measured to find local defects due to:
  - fabrication process defects (small imperfections in the masks)
  - manipulation damages from dicing and transport (chipping, scratches)

- If I_{ss} > critical limit

  $\Rightarrow$ channel is noisy and inefficient
- Limited no. of noisy channels are allowed

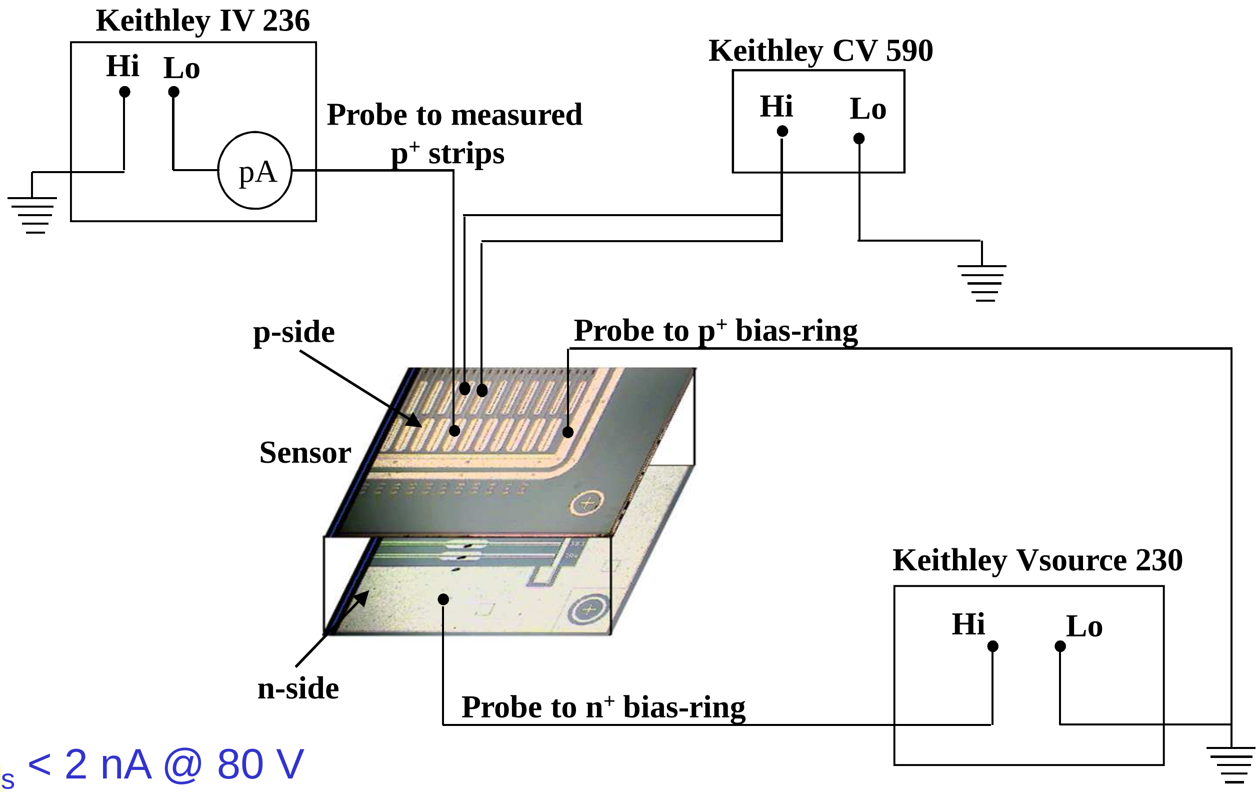
- I_{ss} values:
  - CMS sensors: I_{ss} < 100 nA @ 400 V



I_{ss} measurement set-up for
single-sided AC coupled poly-silicon resistor biased sensor

Electrical characterization - electrical parameters (13)

- Single strip leakage current I_{ss}

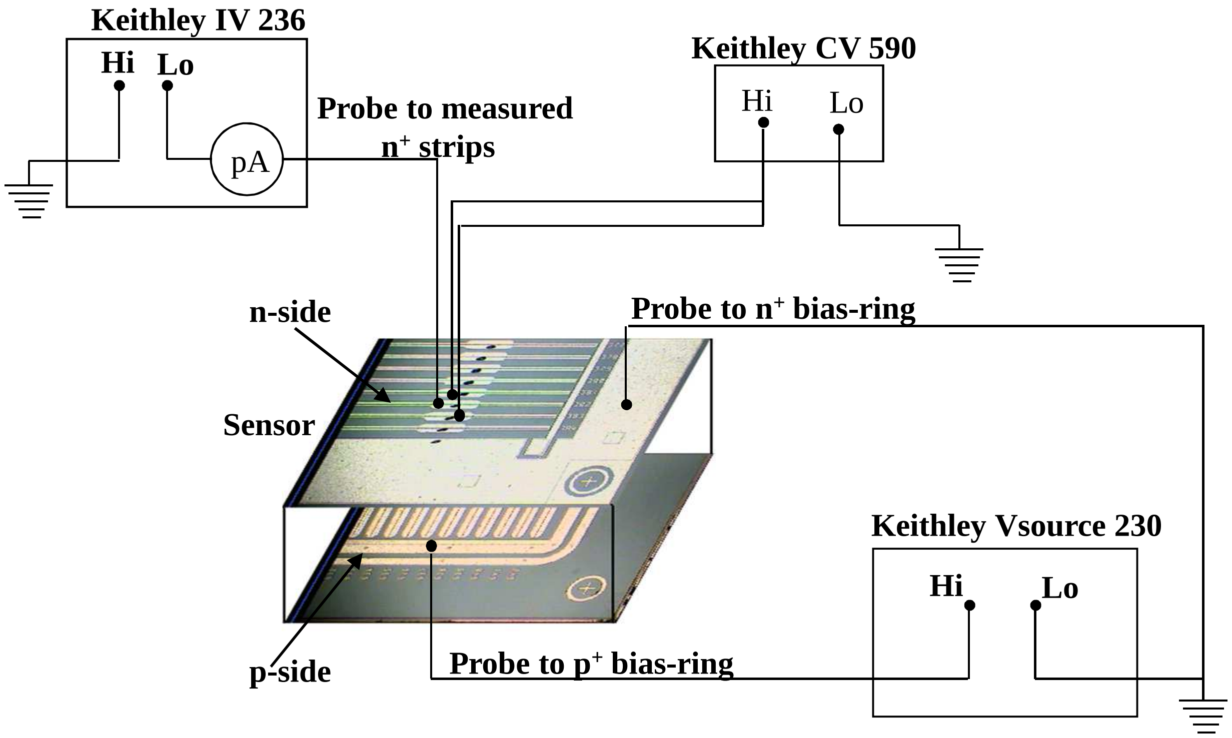


set-up for p-side I_{ss} measurement for
double-sided DC coupled punch-through biased sensor
(allows determination of Al-Al or p^+-p^+ shorts)

- I_{ss} values:
  - p-side, AMS sensors: I_{ss} < 2 nA @ 80 V

Electrical characterization - electrical parameters (14)

- Single strip leakage current I_{ss}



set-up for n-side I_{ss} measurement for
double-sided DC coupled punch-through biased sensor
(allows determination of Al-Al or p^+-p^+ shorts)

- I_{ss} values:
  - n-side, AMS sensors: $I_{ss} < 20$ nA @ 80 V

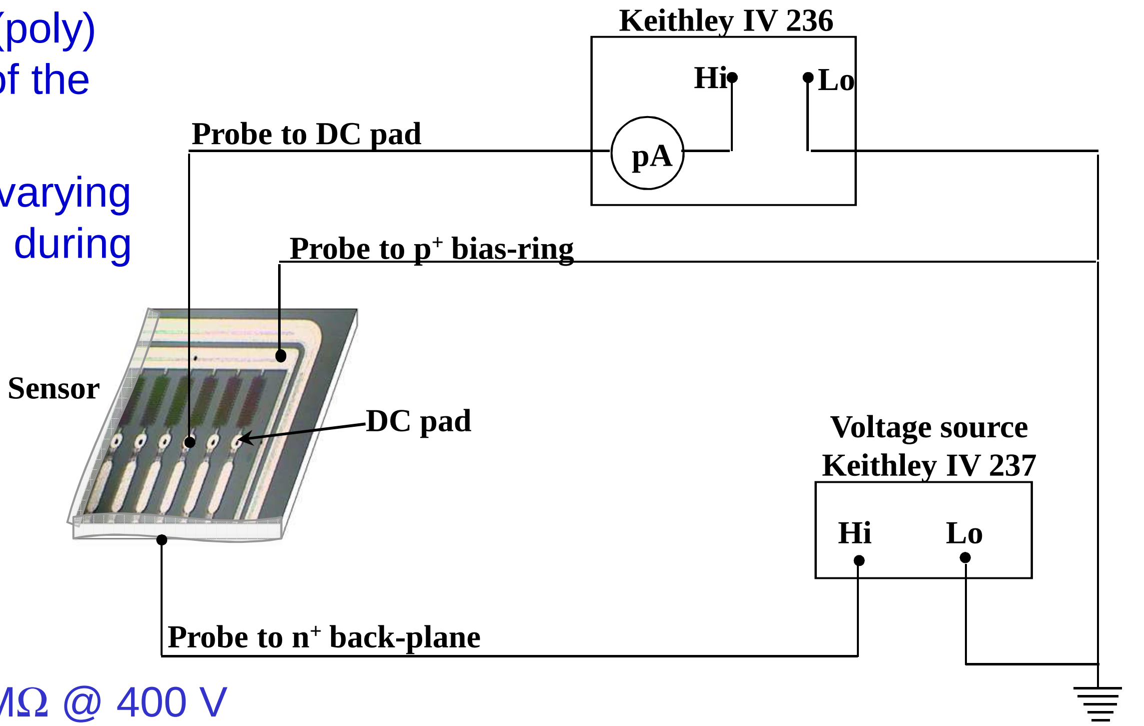
Electrical characterization - electrical parameters (15)

- Poly-silicon resistor R_{poly}

(for poly-silicon biasing structure)

  - bias resistor - source of thermal noise
  - obtained by doping (implantation or diffusion) of non-single crystal (poly) silicon between the metal line of the bias-ring and the p^+ strip
  - desired resistance is obtained varying the length to width aspect ratio during processing

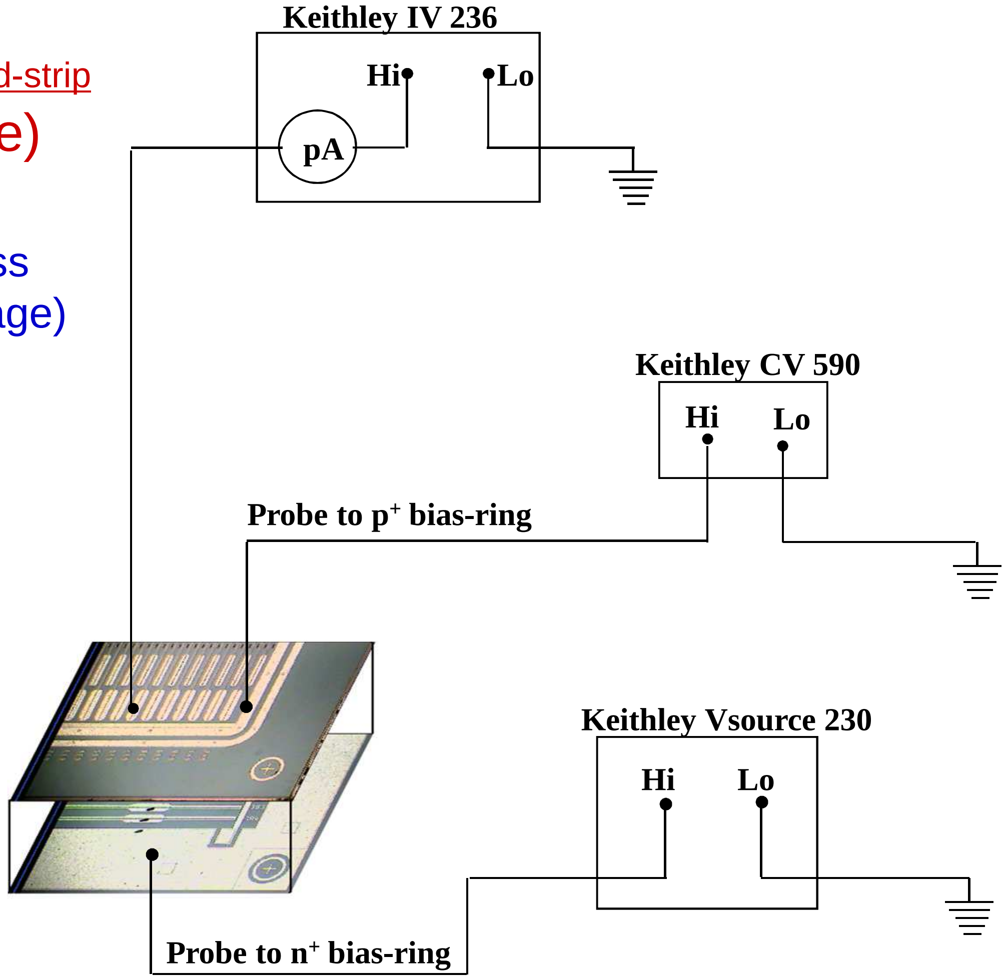
- R_{poly} values:
  - CMS sensors: $R_{poly} = 1.5 \pm 0.3$ MΩ @ 400 V



R_{poly} measurement set-up for single-sided AC coupled poly-silicon resistor biased sensor

Electrical characterization - electrical parameters (16)

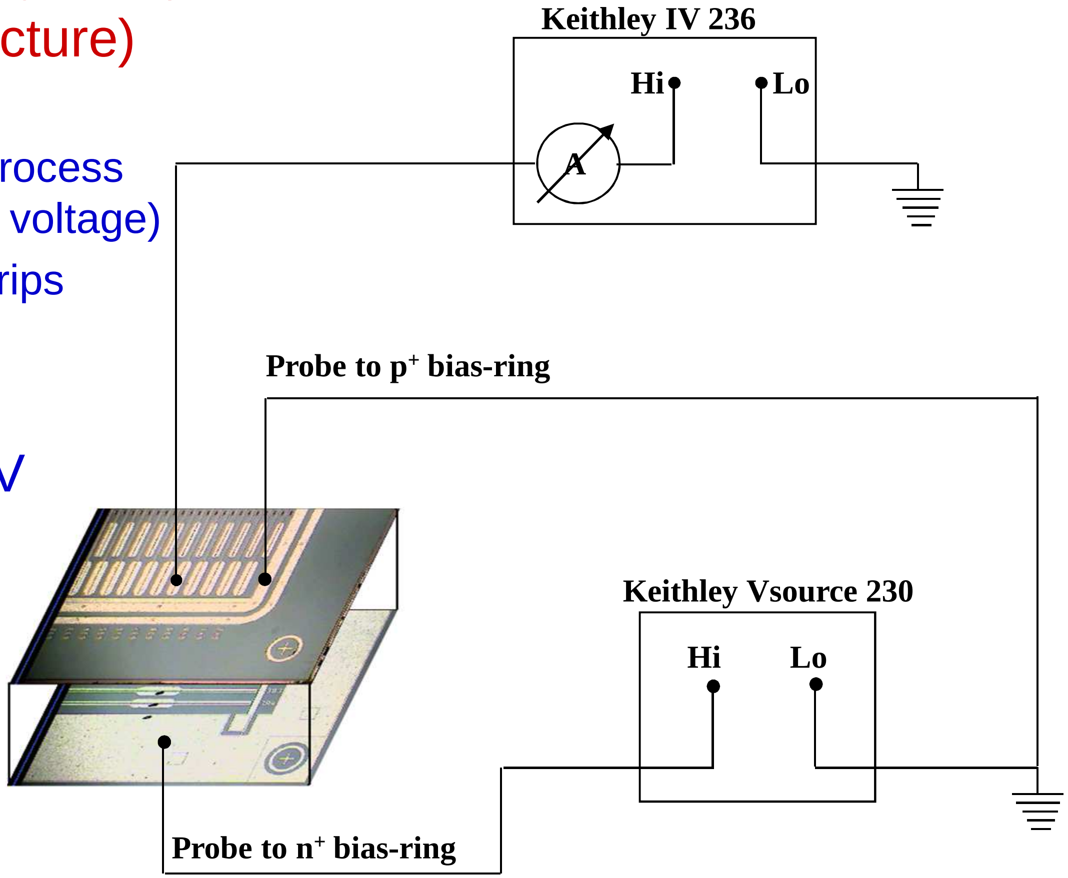
- Resistance to the bias-ring $R_{guard\text{-}strip}$ (for punch-through biasing structure)
  - source of thermal noise
  - optimized through fabrication process (sensor geometry, doping, bias voltage)
  - allows uniform bias of all the strips
    - p-side – punch-through
    - n-side – surface-through
  - $R_{gs} I_{ss} \approx 2\ V_{drop}$; $V_{drop} \sim 2$ V



set-up for $R_{guard\text{-}strip}$ measurement for double-sided DC coupled punch-through biased sensor

Electrical characterization - electrical parameters (16)

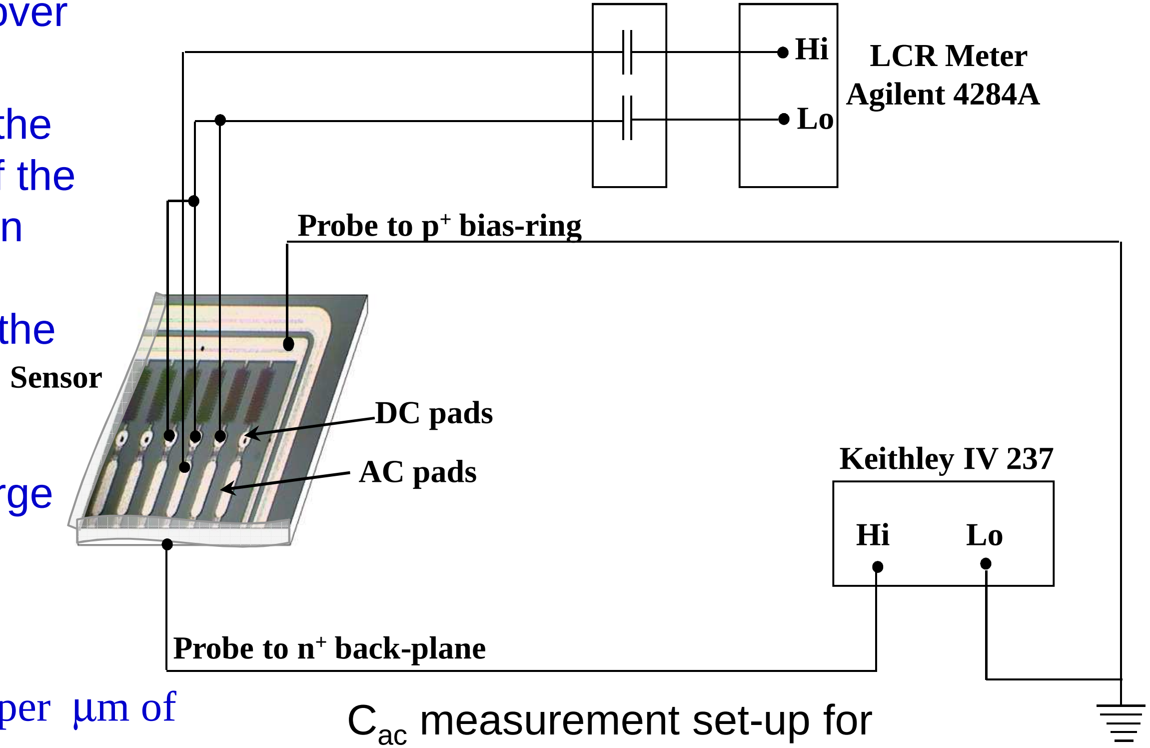
- Resistance to the bias-ring $R_{guard\text{-}strip}$ (for punch-through biasing structure)
  - source of thermal noise
  - optimized through fabrication process (sensor geometry, doping, bias voltage)
  - allows uniform bias of all the strips
    - p-side – punch-through
    - n-side – surface-through
  - $R_{gs}I_{ss} \approx 2\ V_{drop}$; $V_{drop} \sim 2$ V
- Voltage drop →



set-up for V_{drop} measurement for double-sided DC coupled punch-through biased sensor

Electrical characterization - electrical parameters (17)

- Coupling capacitance C_{ac}
  (for AC coupled sensor)
  - given by a capacitor made by a sandwich of aluminium strip over oxide layer over p-strip
  - depends on the geometry of the strips, length and the width of the implantation and aluminization
  - C_{ac} measurement - monitors the uniformity of the oxide layer
  - gives confidence about the resulting homogeneity in charge collection
- C_{ac} values:
  - CMS sensors: C_{ac} > 1.2pF/cm per µm of implanted strip width



C_{ac} measurement set-up for single-sided AC coupled poly-silicon resistor biased sensor (allows determination of Al-Al or p^+-p^+ shorts)

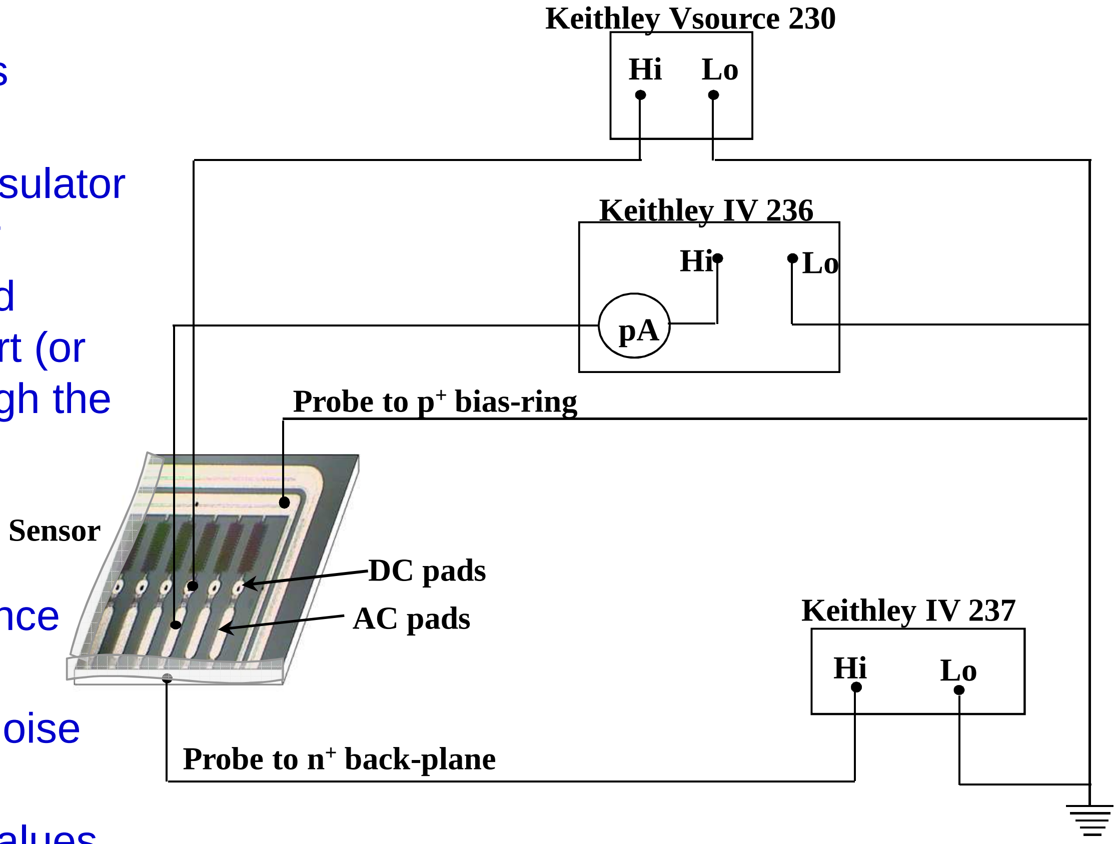
Electrical characterization - electrical parameters (18)

- Current through dielectric layer I_{diel}

  (for AC coupled sensor)

  - oxide thickness of 0.1÷0.2 µm is usually required
  - difficult to make perfect oxide insulator over large surface of the sensor
  - most common defects are called ***"pinholes"***, representing a short (or low resistivity connection) through the oxide

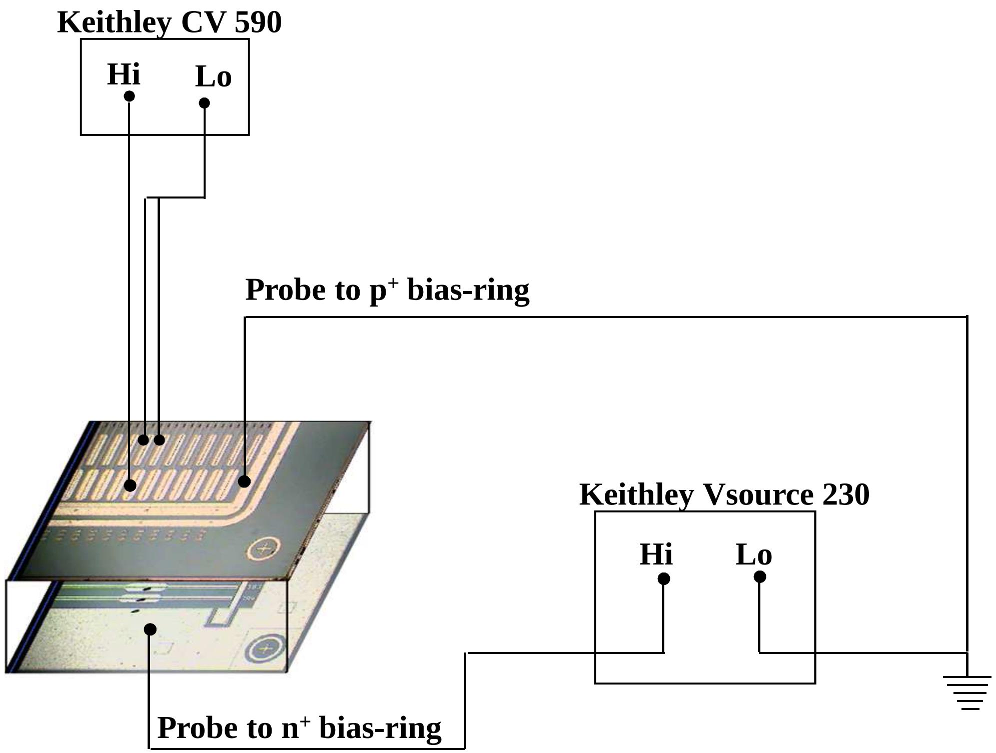
  - I_{diel} measurement - puts in evidence the pinholes
  - good capacitor - I_{diel} equals the noise of the set-up (in the order of pA)
  - pinhole - I_{diel} exceeds a certain values (e.g. 1 nA)



I_{diel} measurement set-up for
single-sided AC coupled poly-silicon resistor biased sensor

Electrical characterization - electrical parameters (19)

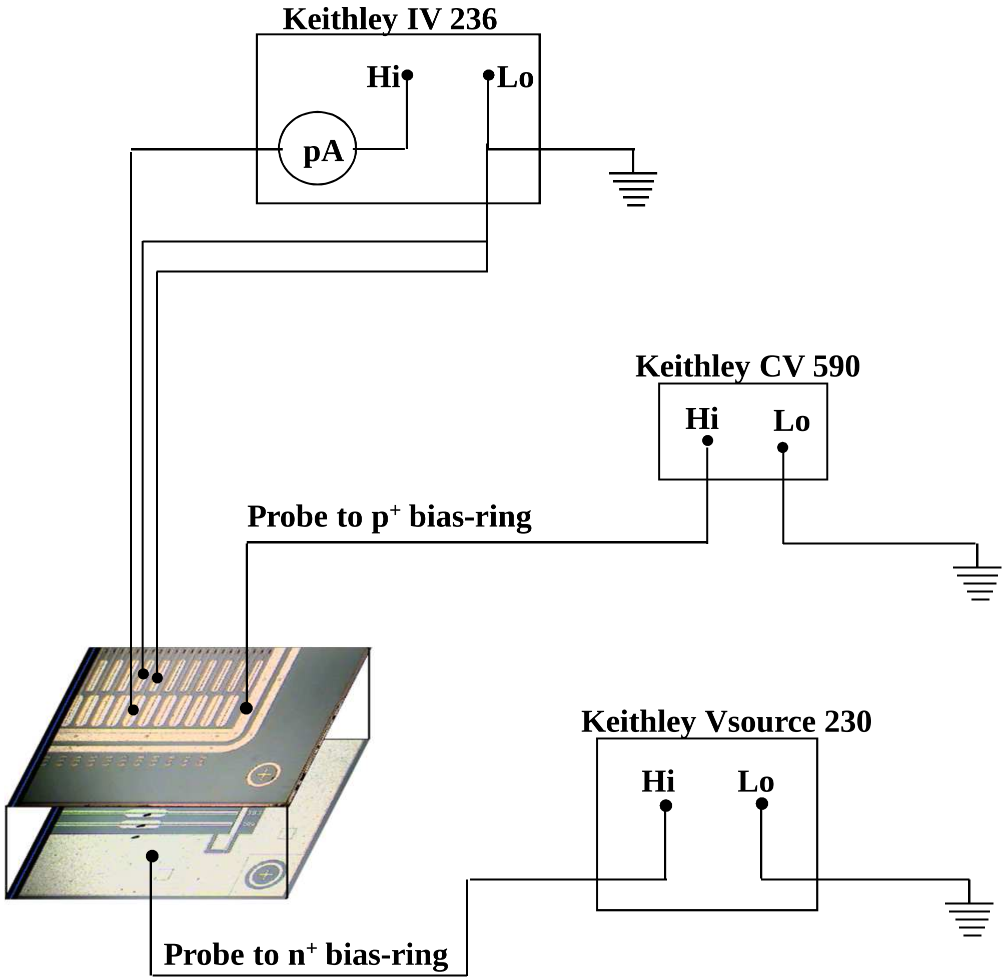
- Interstrip capacitance $C_{interstrip}$
  - Depends on the geometry of the strips, length and the width of the implantation and aluminization



set-up for $C_{interstrip}$ measurement for
double-sided DC coupled punch-through biased sensor

Electrical characterization - electrical parameters (20)

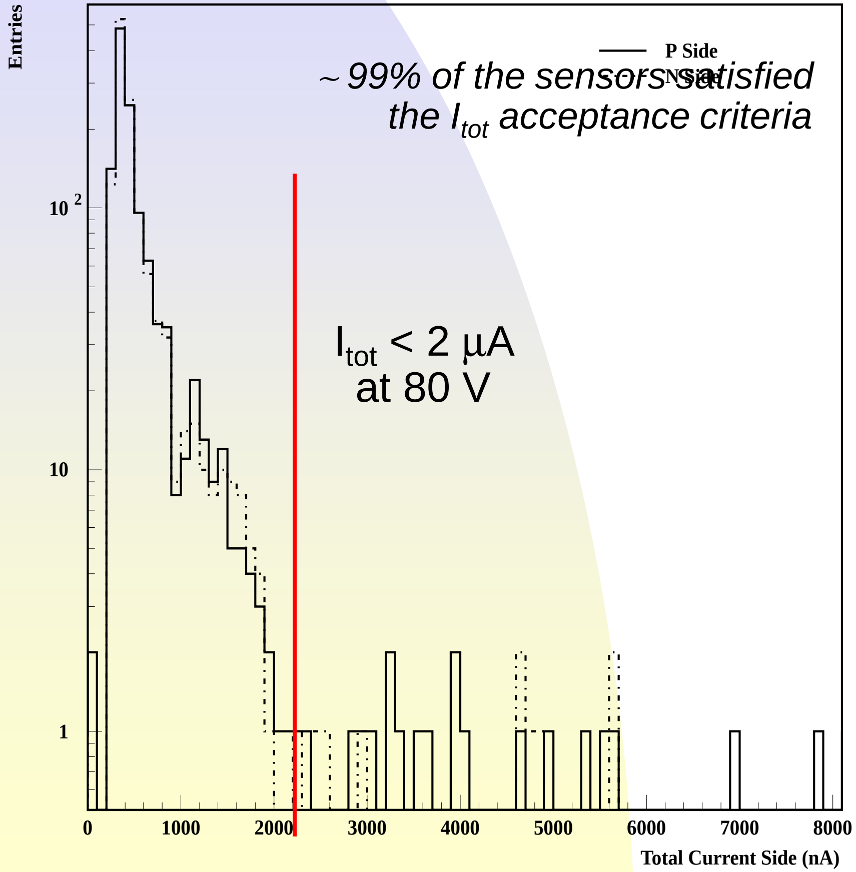
- Interstrip resistance $R_{interstrip}$
  - optimized through fabrication process and geometric dimensions of implantation



set-up for $R_{interstrip}$ measurement for double-sided DC coupled punch-through biased sensor

Electrical characterization - characteristic defects (21)

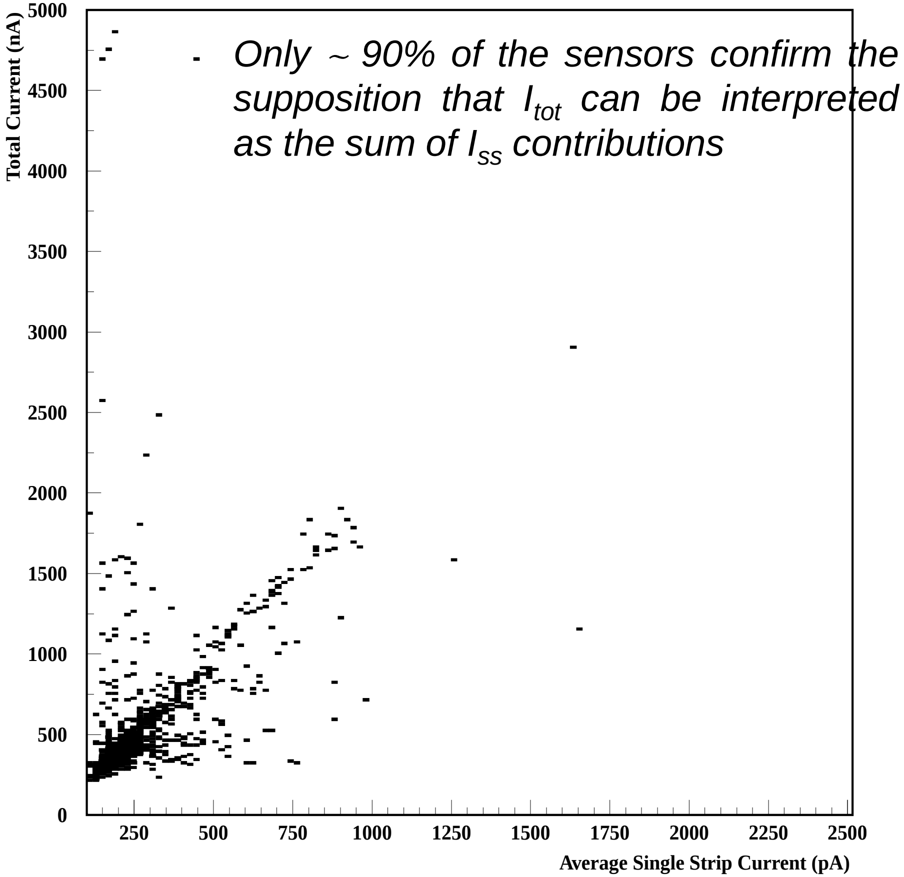
Cumulative distribution of I_{tot} at 80 V for ~ 1500 AMS production sensors



~ 99% of the sensors satisfied the I_{tot} acceptance criteria

$I_{tot} < 2$ µA at 80 V

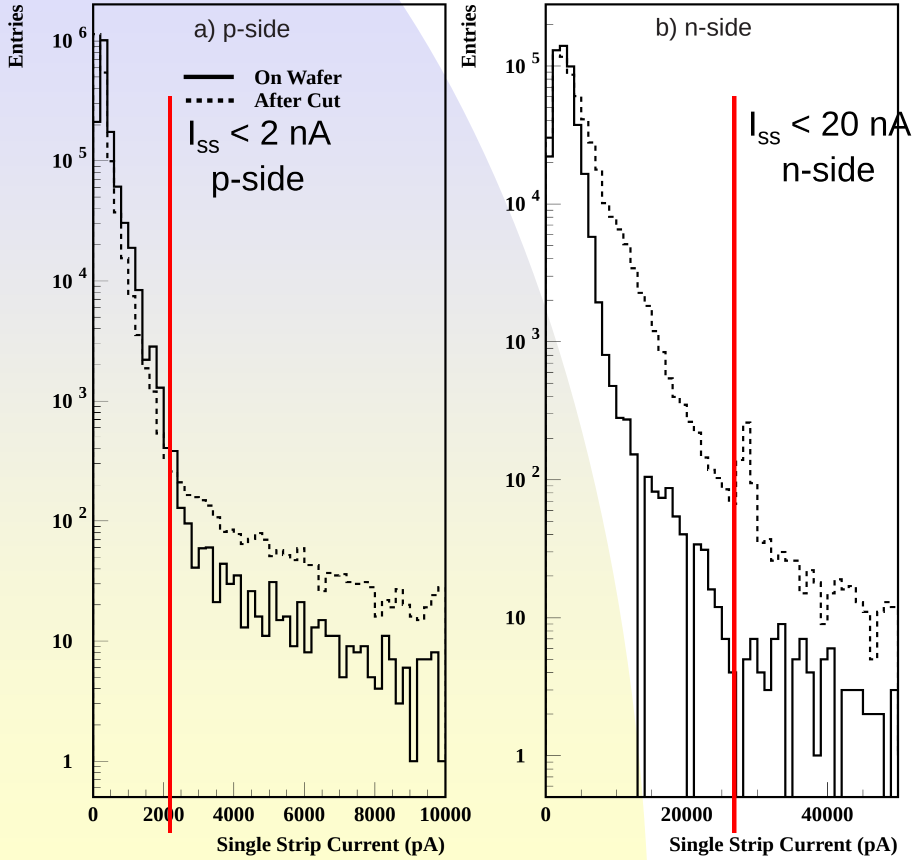
Correlation between I_{tot} and p-side average I_{ss} for each AMS production sensor (~ 1500 units)



Only ~ 90% of the sensors confirm the supposition that I_{tot} can be interpreted as the sum of I_{ss} contributions

Electrical characterization - characteristic defects (22)

Cumulative distributions of I_{SS} at 80 V for
~ 1500 AMS production sensors
before and after dicing

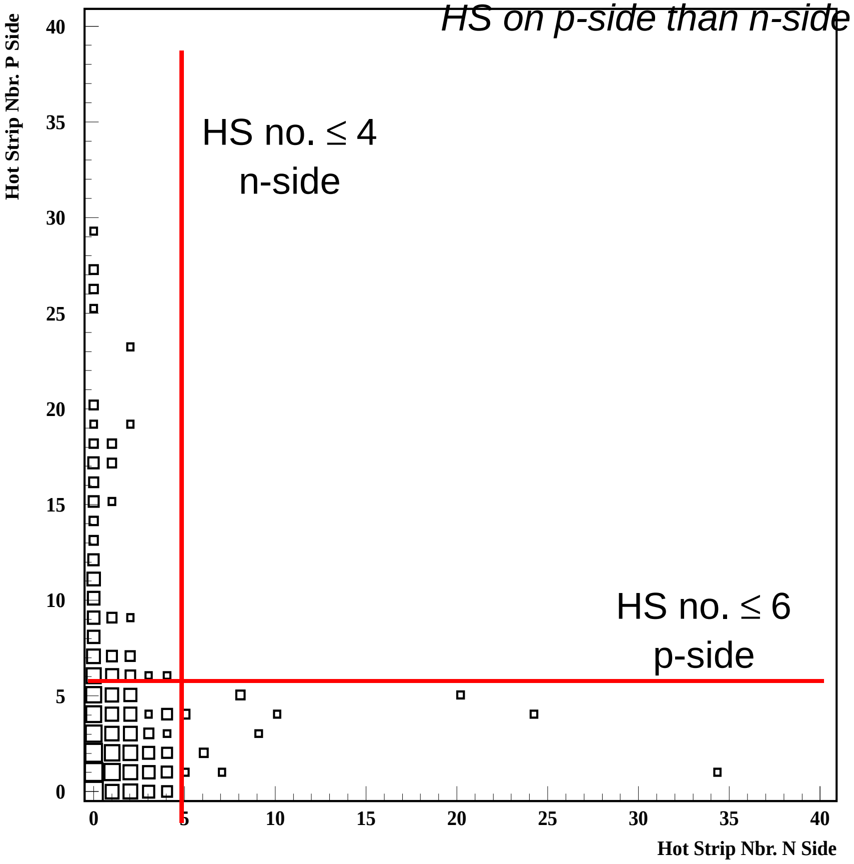


I_{SS} < 2 nA
p-side

I_{SS} < 20 nA
n-side

Correlation of p- and n-side HS number
for each AMS production sensor
after dicing (~ 1500 units)

Higher accumulation of HS on p-side than n-side

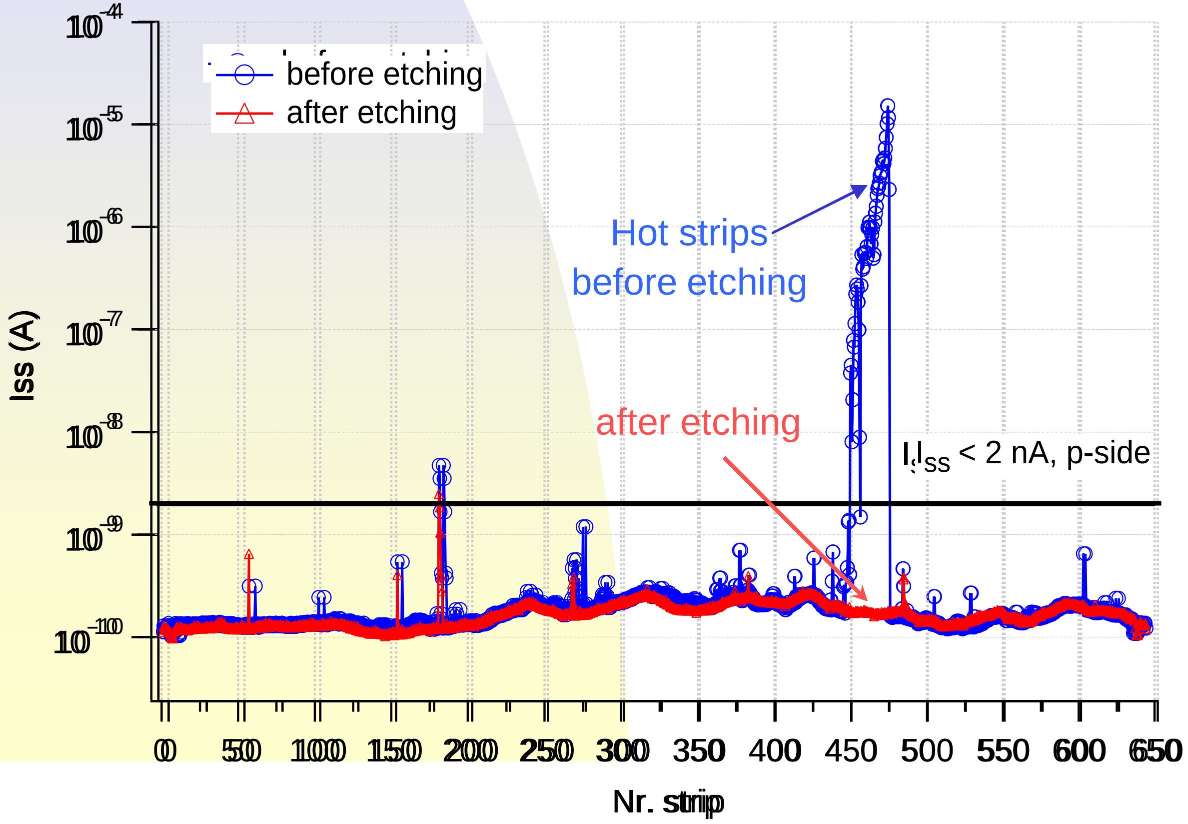


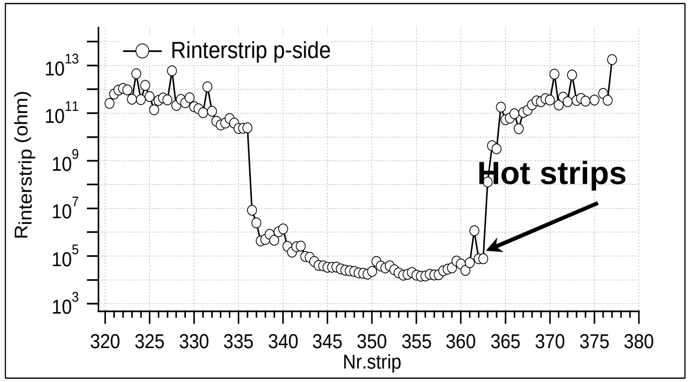
HS no. ≤ 4
n-side

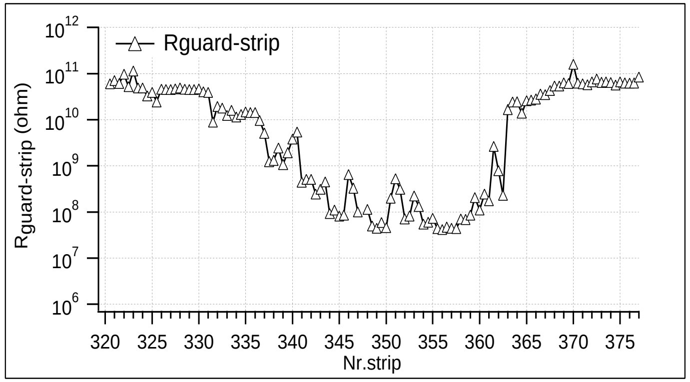
HS no. ≤ 6
p-side

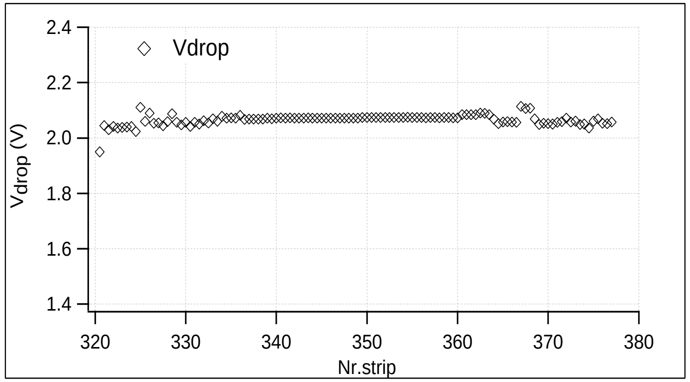
Electrical characterization - characteristic defects (23)

- Small fraction of sensors (~10%) with HS no. >> threshold
- surface chemical contamination produced during dicing and transport
- Removing few Å from passivation oxide by a wet etching procedure, the I_{ss} of the corresponding HS decreased to normal values for 70% of the sensors



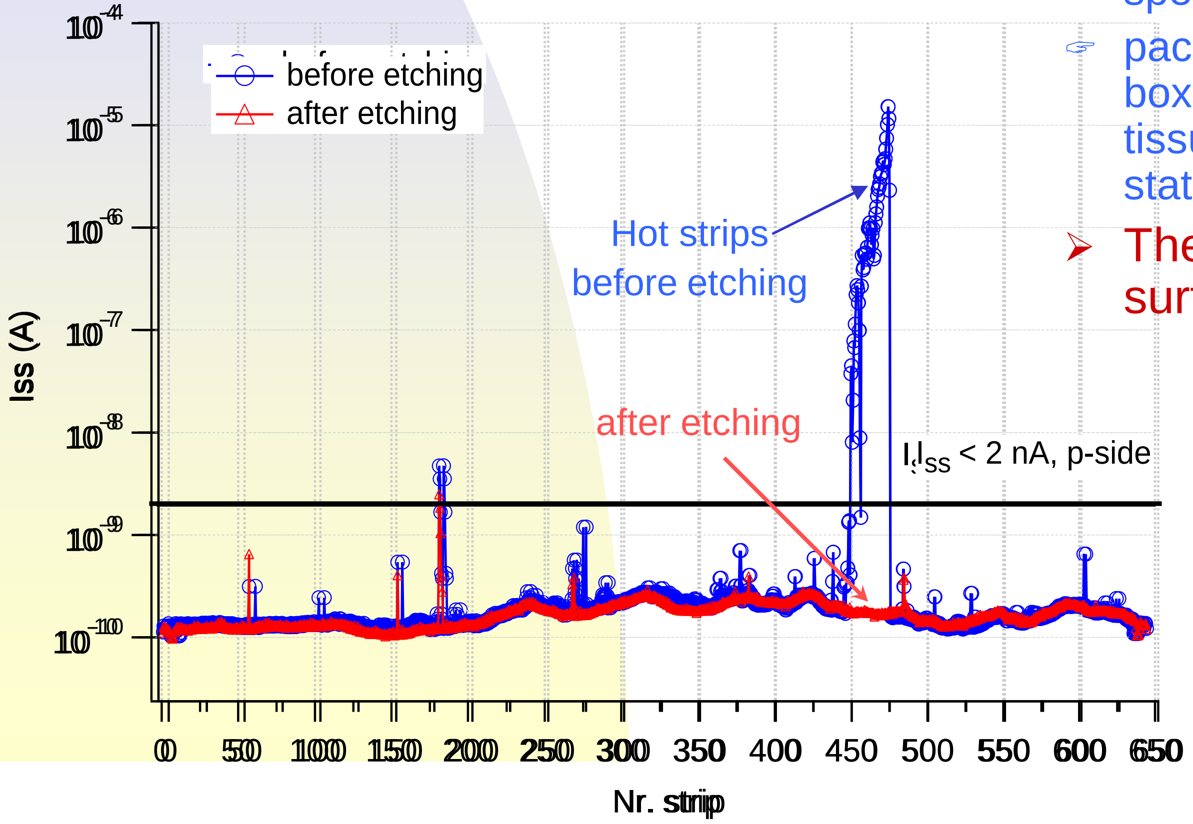






Electrical characterization - characteristic defects (23)

- Small fraction of sensors (~10%) with HS no. >> threshold
- surface chemical contamination produced during dicing and transport
- Removing few Å from passivation oxide by a wet etching procedure, the I_{ss} of the corresponding HS decreased to normal values for 70% of the sensors



Hot strips before etching

after etching

I_{ss} < 2 nA, p-side

- Stringent conditions imposed on dicing procedure and transport:
    - UV adhesive tape for dicing
    - during and after dicing, rinsing with a shower of low-res. de-ionized H_2O (1÷2 MΩ x cm)
    - drying with hyper-pure N_2 flow and special clean-room tissues
    - package – each sensor in small special box, covered by special clean-room tissue and fixed by two pieces of anti-static sponge
- These conditions eliminated the surface contamination

Conclusions

- Electrical characterization of silicon micro-strip silicon sensors has been presented
  - ☞ General considerations on hardware set-up
  - ☞ Description of all parameters with contribution to the noise at the input of the read-out electronics
    - Leakage currents
    - Poly-silicon resistance (polysilicon resistor biasing)
    - Resistance to the bias-ring (punch-through biasing)
    - Coupling capacitance and dielectric current (for AC coupled sensors)
    - Interstrip capacitance
    - Interstrip resistance

- Characteristic defects detected during electrical characterization have been shown (produced during dicing and transport)
  - ☞ Surface chemical contamination (70% of the sensors cured by wet etching procedure)