Semiconductor Detectors in Particle Physics

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The **detection and measurement** of the **momenta** of **charged particles** is an essential aspect of any large particle physics experiment to study the physics processes.

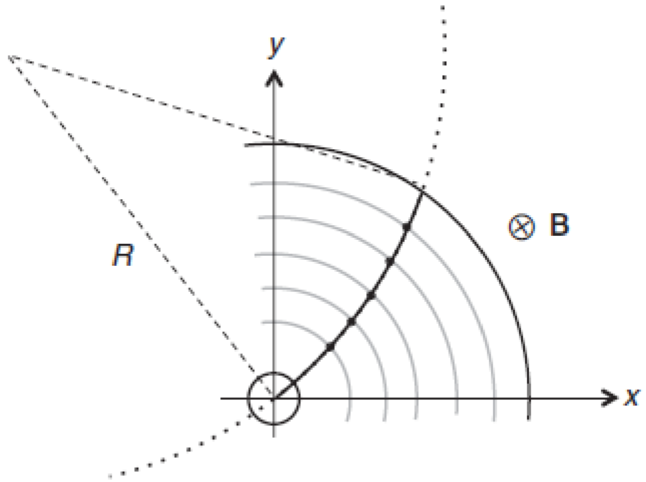
A charged particle travels through a certain medium and ionize atoms. By detecting this ionisation, it is possible to reconstruct the trajectory of a charged particle commonly knows as the **Tracking**.

Tracking in Particle Physics

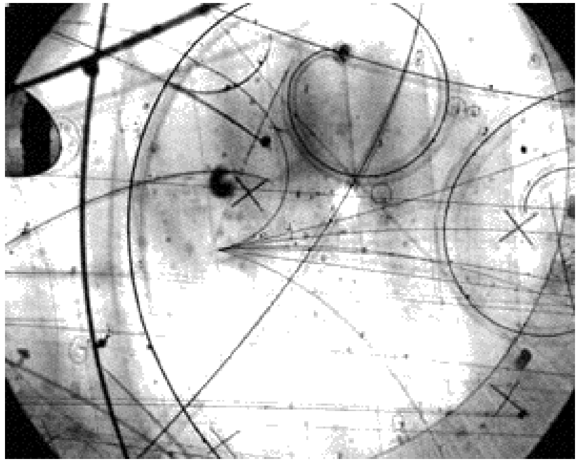
- Tracking is the act of measuring the direction and magnitude of **charged particles momenta**
- Use constant magnetic field ***B*** to curve particle trajectories in helixes, where particle momentum ***p*** measured from radius of curvature ***r***

$$r = \frac{P}{qB}$$

- Important to combine tracks and find **vertices**



Tracking Technologies

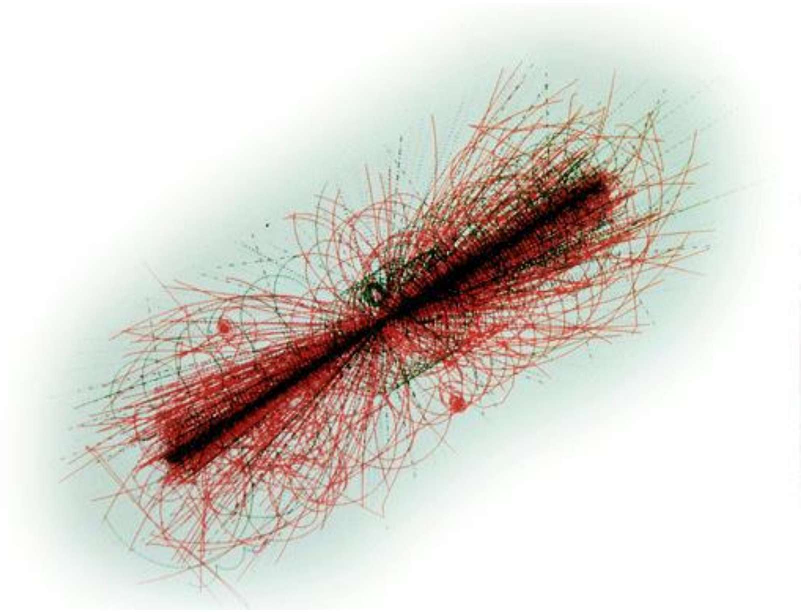


Bubble chambers ~1960s

- Many bubbles along path; take stereo photos; measure trajectory by manual scanning of film

Gas detectors >1970s

- A type of electronic detector, can digitally record “hits” at high rate without human intervention
- Software links hits together into helix sections called “tracks”
- Accuracy as good as ~200 μm per hit
- Used in CMS muon system



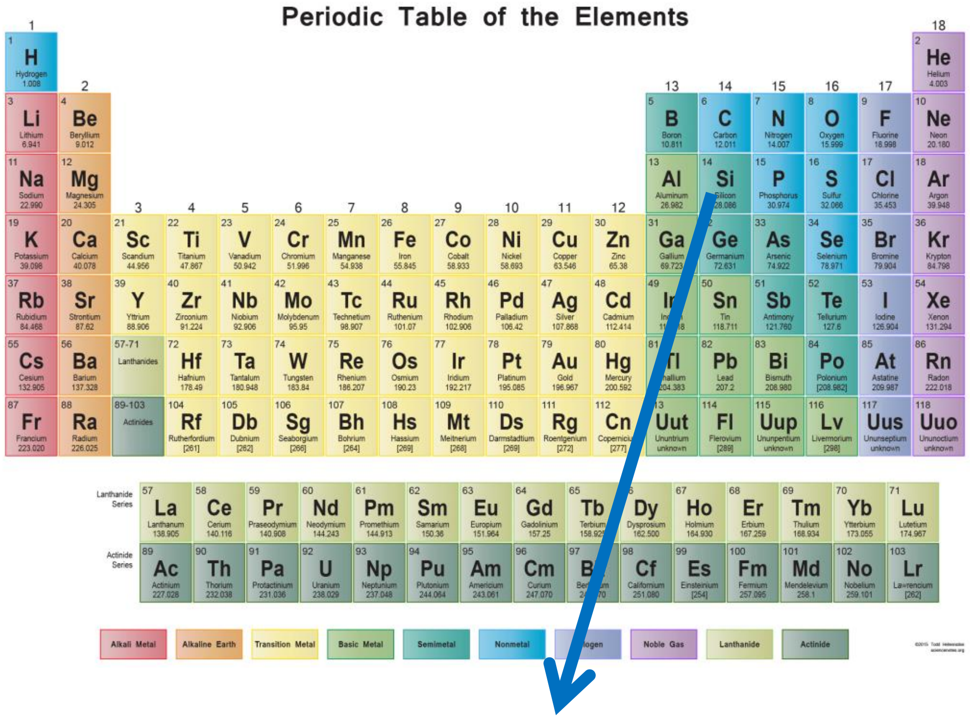
Silicon detectors (>1990s)

- Accuracy ~10 μm per hit and very radiation-hard but also more expensive
- Used in the CMS central tracker system

Why Silicon?

Advantages:

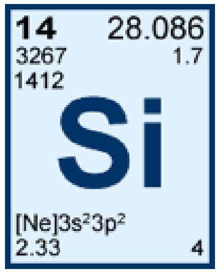
- large signal in thin layers (~24k e in 300 μm)
- fast signal: O(10 ns)
- no recovery time
- very good position resolution
- light: low Z, X0 = 9.36 cm



Disadvantages:

- needs lots of auxiliary electronics, services
- high channel density that leads to more power dissipation
- susceptible to radiation damage

Requires Cooling (high channel density, susceptible to radiation damage)



Silicon Properties

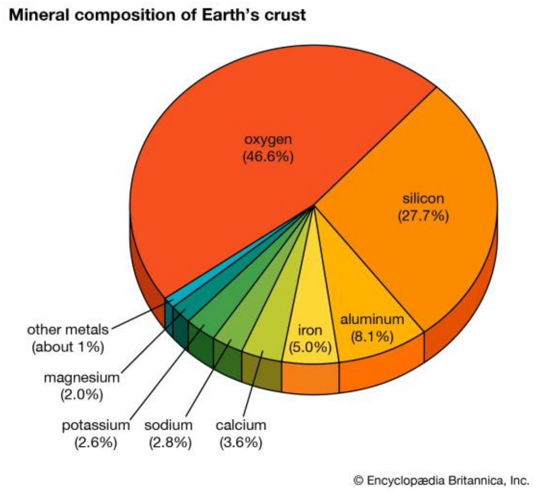
- Silicon is a **group IV** element -> 4 valence electrons that form covalent bonds

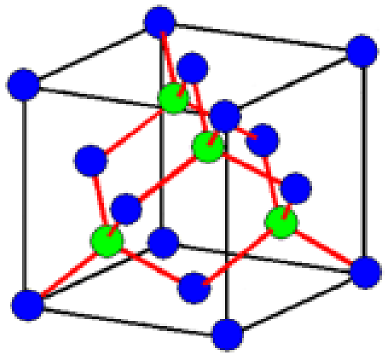
- Si is a **semiconductor** (isolator at T~ 0K and conductance between metal and insulator at RT)

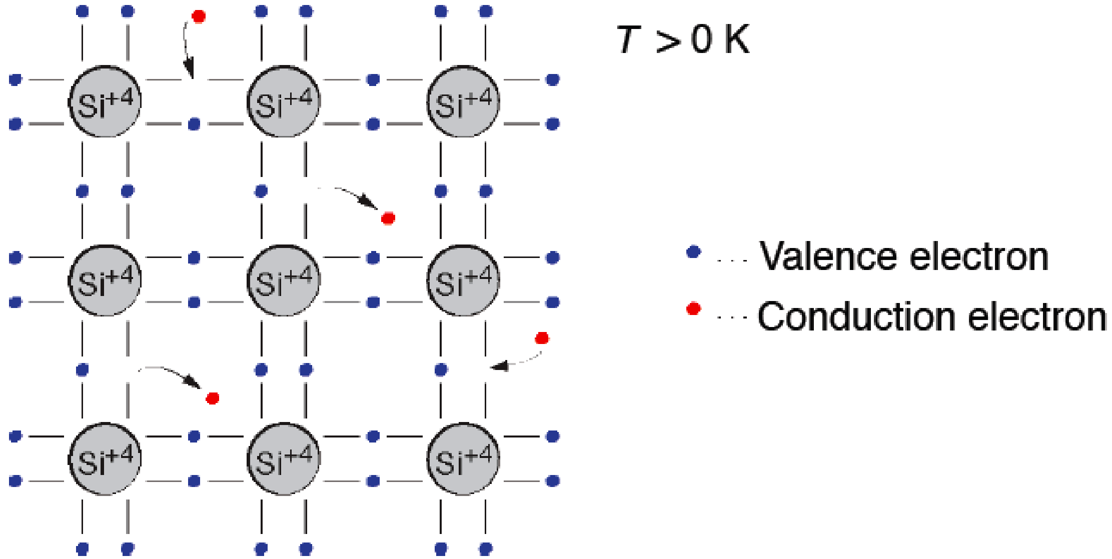
- can form **single crystals** (111 or 100 orientation)

- diamond cubic lattice (2 interleaved fcc sub-lattices)

- one of the **most abundant elements** in earth crust - mostly in the form of SiO_2 - aka sand







Band Gap

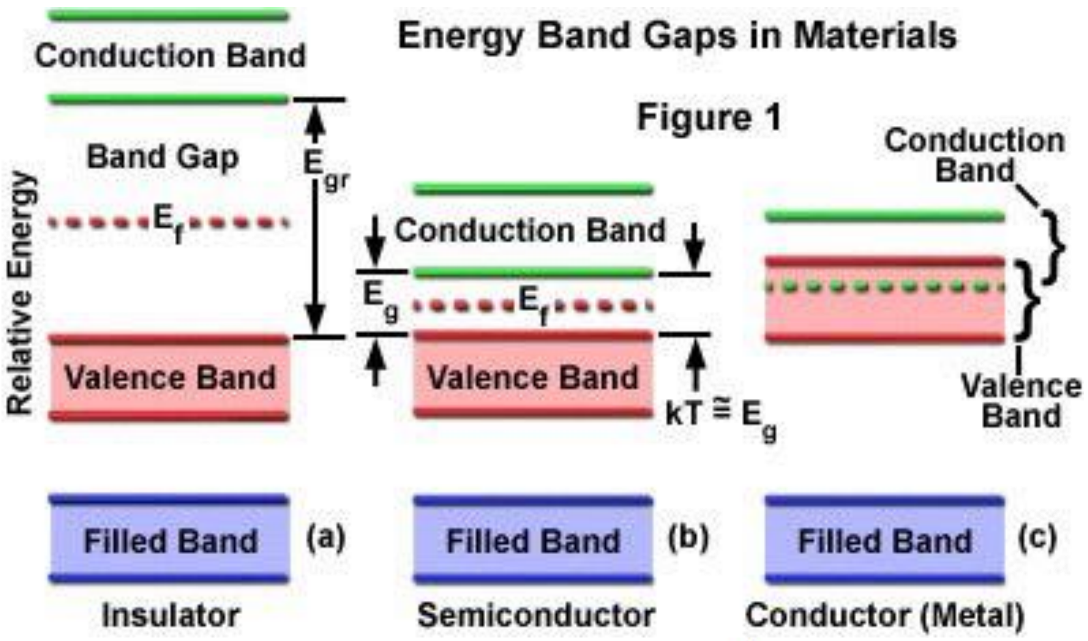
- due to the **regular lattice** of the Si atoms in a single crystal, **energy levels form bands**: valence-band & conduction-band

- at lower temperatures, the valence band is filled and the conduction band empty

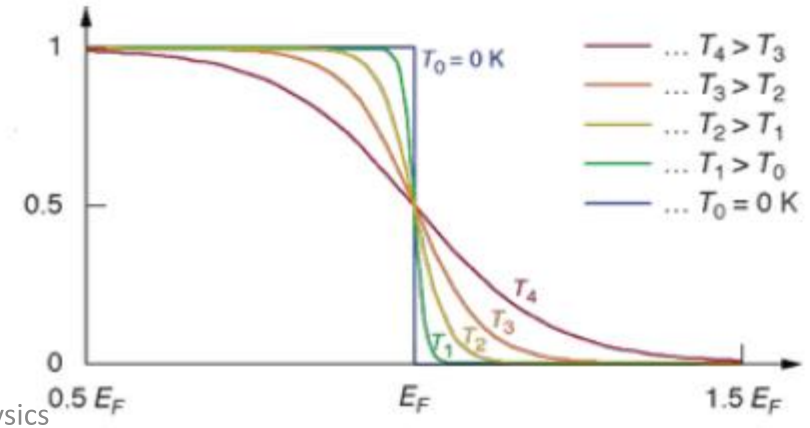
- electrons in the v-band can be (thermally) excited to the c-band leaving empty bonds (holes)- the **band-gap is 1.12 eV**

- E_f denotes the Fermi-level, where the occupation of states = 50%

- conductivity behavior can be altered by introducing additional levels in the band gap -> **“doping”**



$$f(E) = \frac{1}{1 + \exp \frac{E - E_f}{k_B T}}$$



Doping

typical **dopants** are:

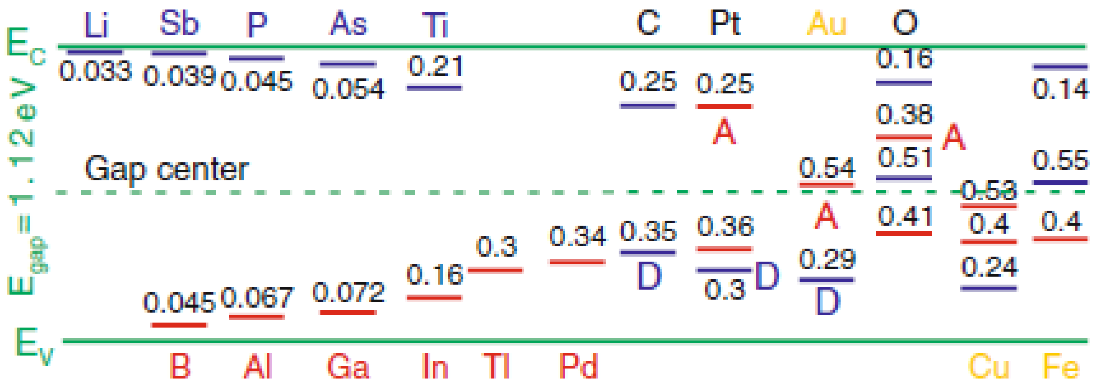
- **group III elements** like Boron with 3 valence electrons, leaving a **“hole” acceptor level**, p-type silicon

- **group V elements** like Phosphorous with 5 valence **electrons -> donor level**, n-type silicon

- additional levels increase probability of electron excitation thus changing the Conductivity

- **doping shifts the Fermi level** in the band-gap

- doping changes the electrical conductivity σ & resistivity ρ:



$$n_i = \sqrt{N_C N_V} \exp - \frac{E_g}{2k_b T}$$

n_i … intrinsic charge carrier density
E_g … band gap
N_C … density in the c band
N_V … density in the v band
k_B … Boltzmann's constant

$$\sigma = e_0(\mu_e n_e + \mu_h n_h)$$

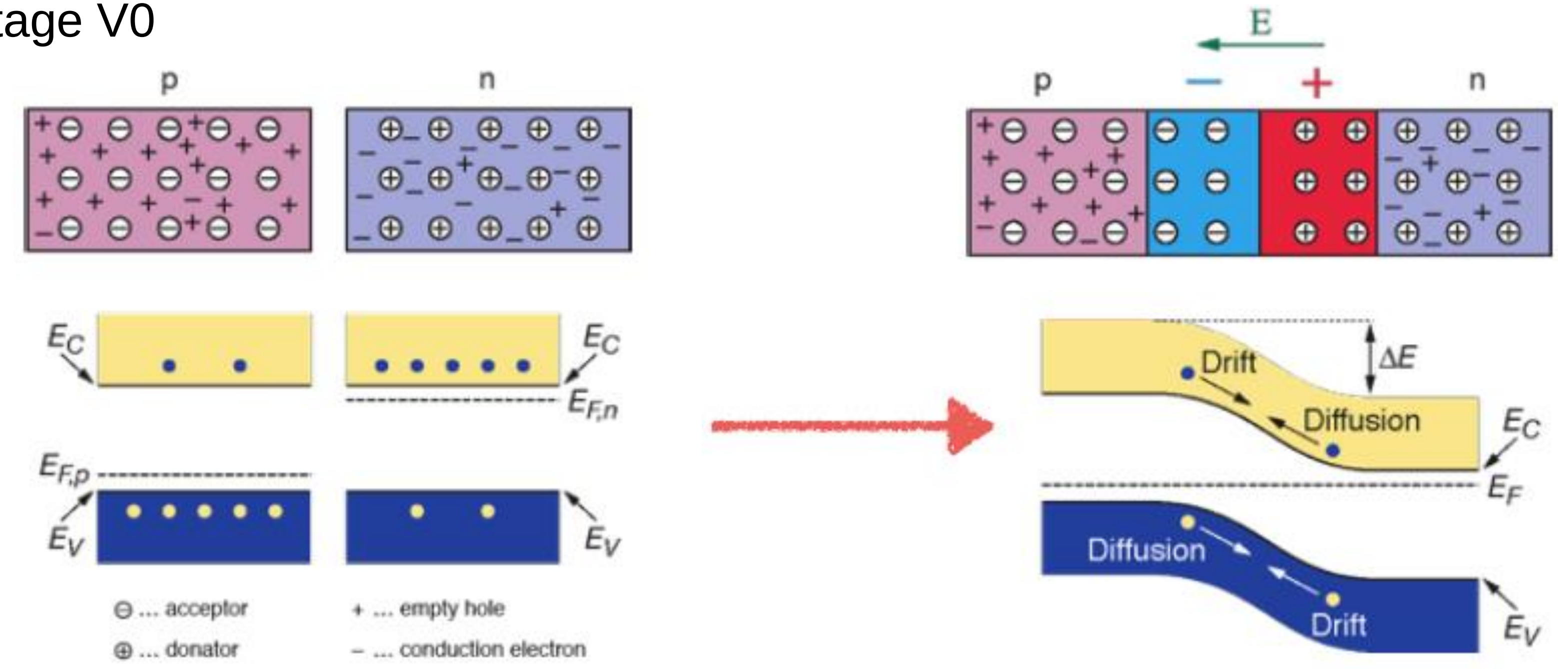
in practice, only the dopants matter

μ … charge carrier mobility determined by the time between scattering processes
e_0 … elementary charge
$n_{e,h,d}$ … charge carrier density

$$\rho = \frac{1}{e_0 \mu n_d}$$

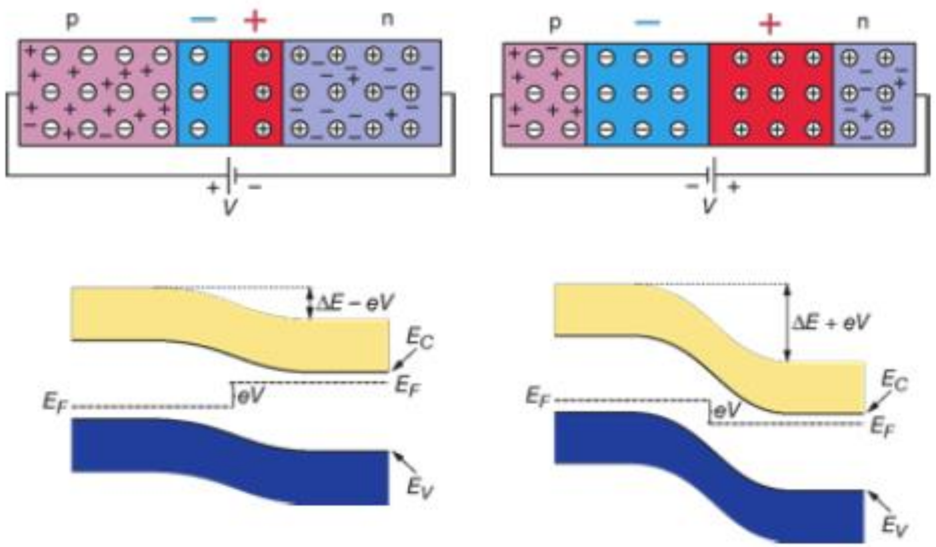
The PN Junction - I

- if **p- and n- doped materials** are **brought in contact**, the majority carriers start diffusing in the other region building up a potential barrier
- leads to **creation of a space-charge region** (electric field) that stops further diffusion
- leads to a stable, charge carrier free region -> **depletion region**
- contact voltage V0



The PN Junction - II

- applying an **external voltage** can alter the behavior of the depleted region depending on the **polarity**:
- V_{ext} **in forward direction** decreases the potential barrier and thus the width of the depleted region -> diffusion currents drastically increase
- V_{ext} **in reverse direction** increases the width of the depleted region -> very small leakage current



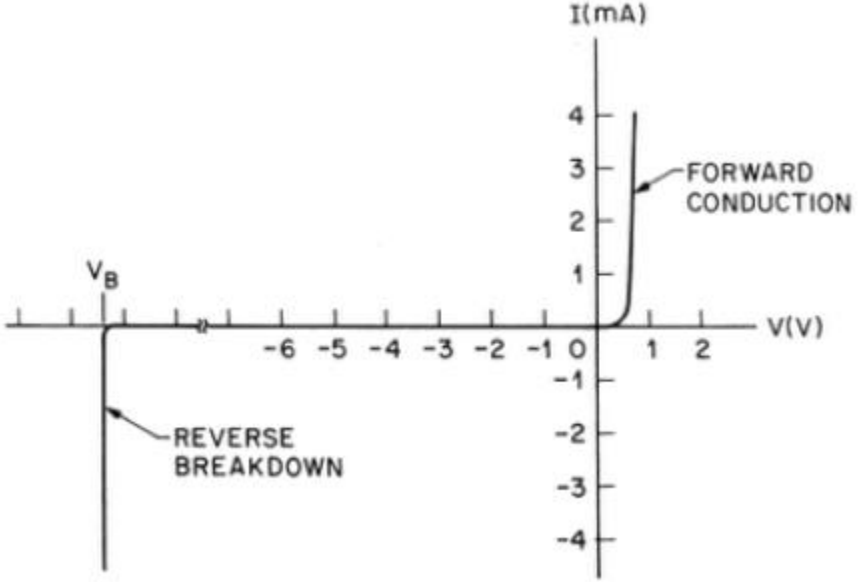
width W of the depleted region:

$$W = \sqrt{\frac{2\epsilon_0\epsilon_r}{e_0}(V_0 - V)(\frac{1}{N_d} + \frac{1}{N_a})}$$

ε … dielectric constants
$N_{a/d}$ … acceptor/donor concentrations
V_0 … contact voltage
V … external voltage
e_0 … elementary charge

The PN Junction - III

- applying an **external voltage** can alter the behaviour of the depleted region depending on the **polarity**:
- **V_{ext} in forward direction** decreases the potential barrier and thus the with of the depleted region -> diffusion currents drastically increase
- **V_{ext} in reverse direction** increases the width of the depleted region -> very small leakage current until breakdown (avalanche effect in E-field)



width W of the depleted region:

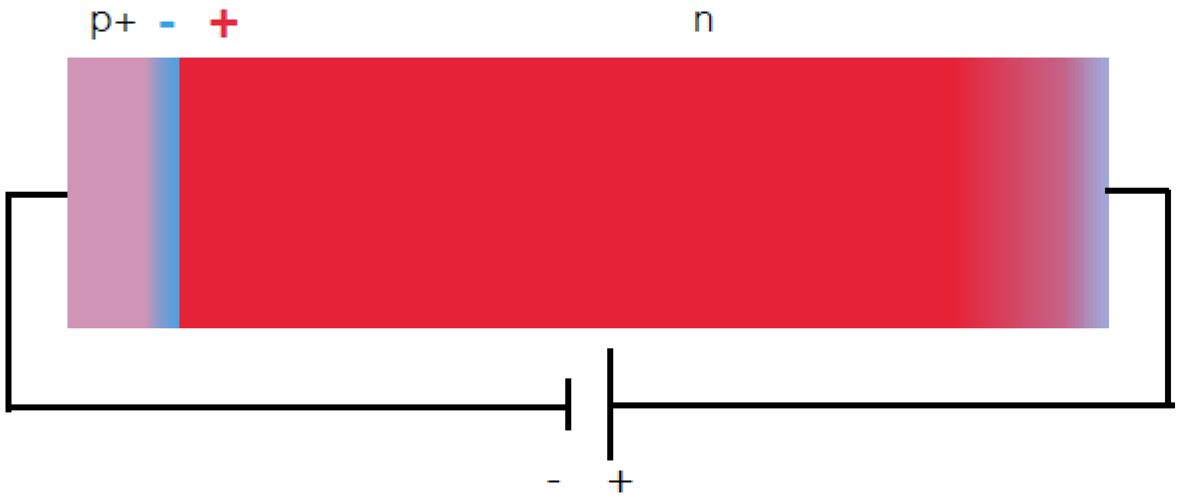
$$W \approx \sqrt{2\epsilon_0\epsilon_r\mu\rho|V|}\ for\ V >> V_0$$

ε … dielectric constants
ρ … resistivity
μ … charge carrier mobility
V … external voltage

PN Junction of a Detector

- use one thin but highly doped region ($O(10^{15})$) - electrode
- one thick region ($O(10^{12})$) - bulk
- width W of depleted region:
- V_{ext}=0V: Wp = 0.02µm, Wn = 23µm
- V_{ext}, reverse = 100V: Wp = 0.4µm, Wn = 363µm

This is how to operate PN junction as detector

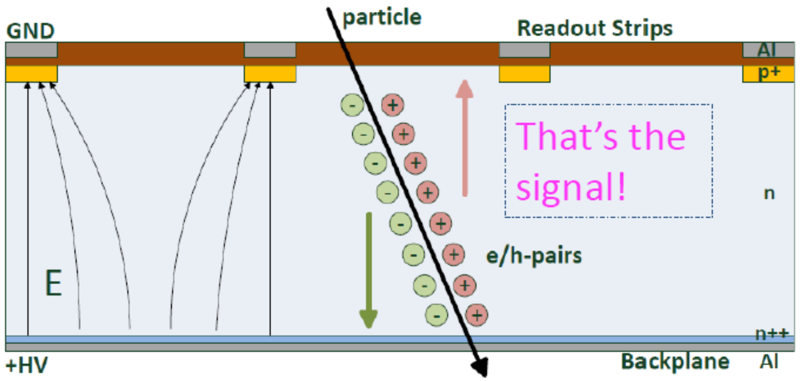


Possible to use:
P+ contact in n bulk
N+ contact in p bulk

Typical detector thickness: 50 – 500 µm

Detection Principle

- the depleted region (free of charge carriers) acts in a similar manner to a gaseous detector
- instead of e^--ion pairs, **electron - hole pairs are created by traversing particles** (an e^- from the valence band is excited to the conduction band leaving a hole)
- $e^- h^+$ pairs drift in the E-field inducing a signal at the contacts
- the required average energy loss for the creation of e/h pair is only 3.6eV (~30eV for gases)→ very thin produce high signals



No free charge is present in the depleted region to extinguish the generated electron-hole pair

Signal Vs intrinsic charge carriers

- ionization E in intrinsic silicon E_0=3.62 eV
- average dE/dx in Si: 3.87 MeV/cm
- intrinsic charge carrier density @ T=300K: $n_i = 1.45 \times 10^{10}$ cm^{-3}
- created $e^- h^+$ pairs for detector with d= 300µm and A=1cm^2:

$$\frac{dE/dx \times d}{I_0} = \frac{3.87 \times 10^6 eV/cm 0.03 cm}{3.62 eV} \approx \boxed{3.2 \times 10^4}$$

- thermally generated e-h+ pairs in undepleted detector:

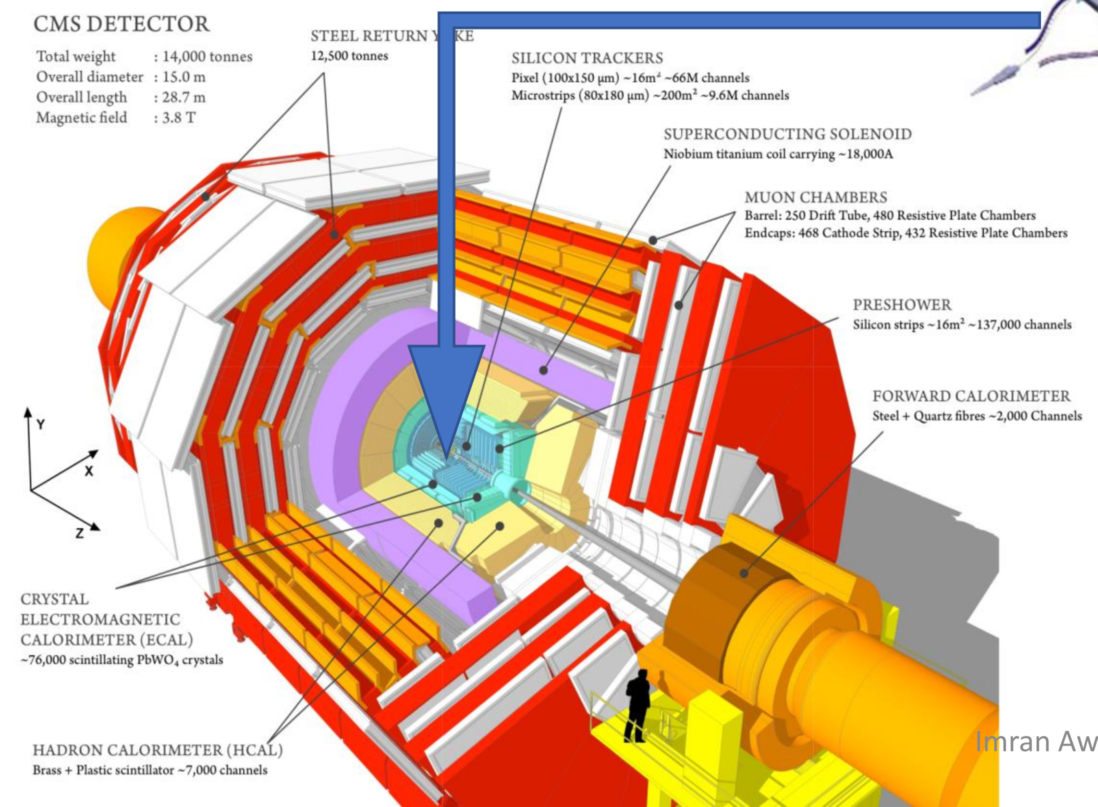
$$n_i dA = 1.45 \times 10^{10}\ \text{cm}^{-3} \times 0.03\ \text{cm} \times 1\ \text{cm}^2 \approx \boxed{4.35 \times 10^8}$$

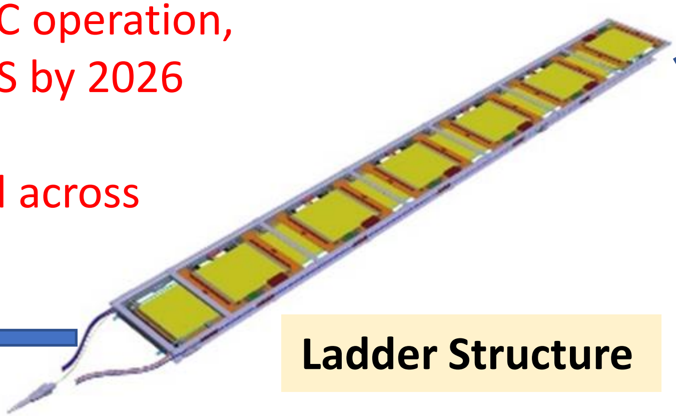
- signal drowned in thermally generated “noise” by 4 orders of magnitude
- absolutely **vital** to operate the detector **depleted**

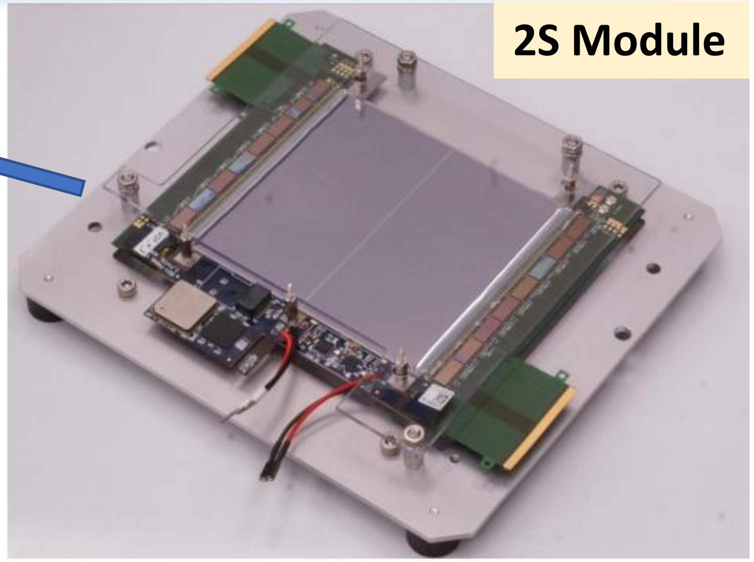
Phase-2 Upgrade of CMS Outer Tracker

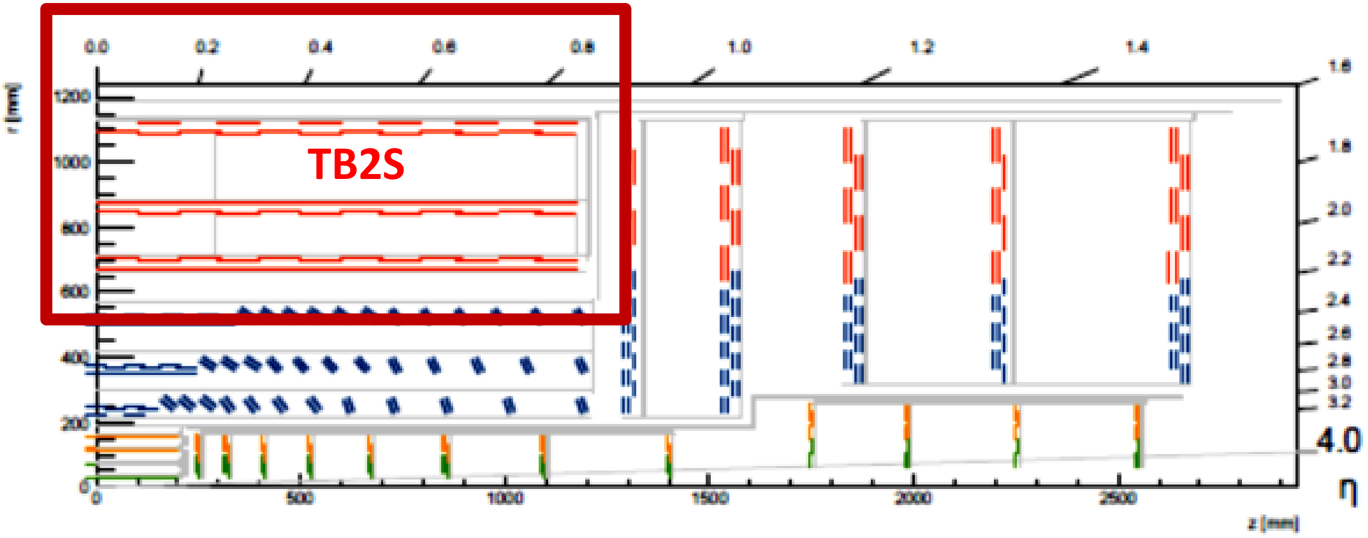
- To cope with the High Luminosity LHC operation, A new tracker will be installed at CMS by 2026

- ~11000 2S Modules will be produced across worldwide assembly centres







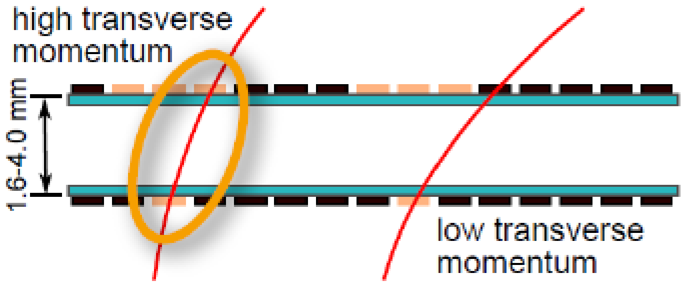


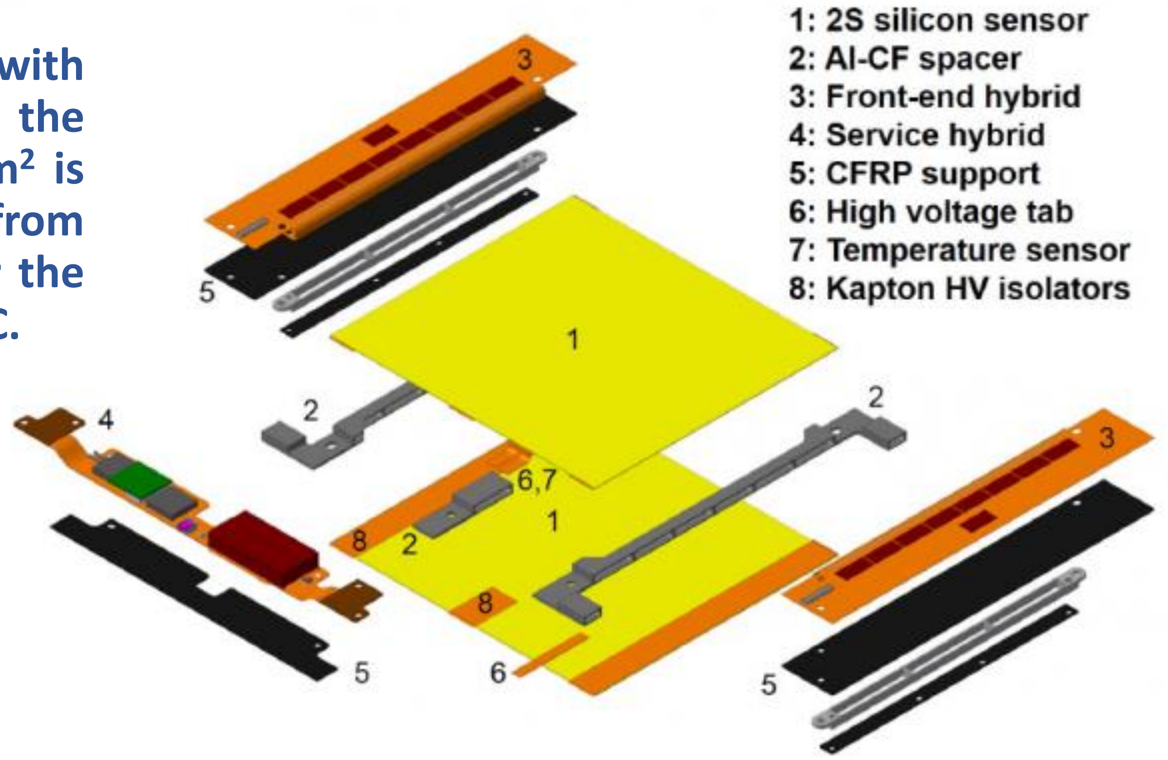
NCP is one of the Module Assembly and sensor qualification centre.

A dedicated lab for semiconductor detector technology has been developed

CMS Outer Tracker 2S Module

The 2S modules are built from two silicon strip sensors with 1.8 mm or 4 mm spacing, depending on the region in the CMS detector. The active area of approximately 92 cm^2 is read out by 16 CBC3 front-end chips forming hit pairs from the two sensors. The power consumption is 5.0 W for the front-end electronics and 1.0 W for the sensors at -20 ^{0}C.





- Pair of hits = Stubs (Hit Position + Bend Info)
- 2 Hits per Module

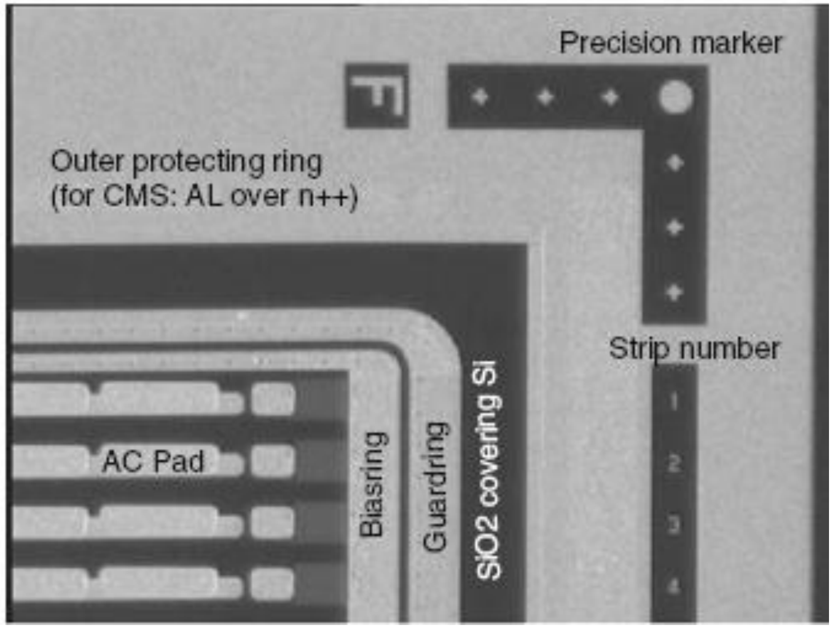
Module will have on board pT discrimination:

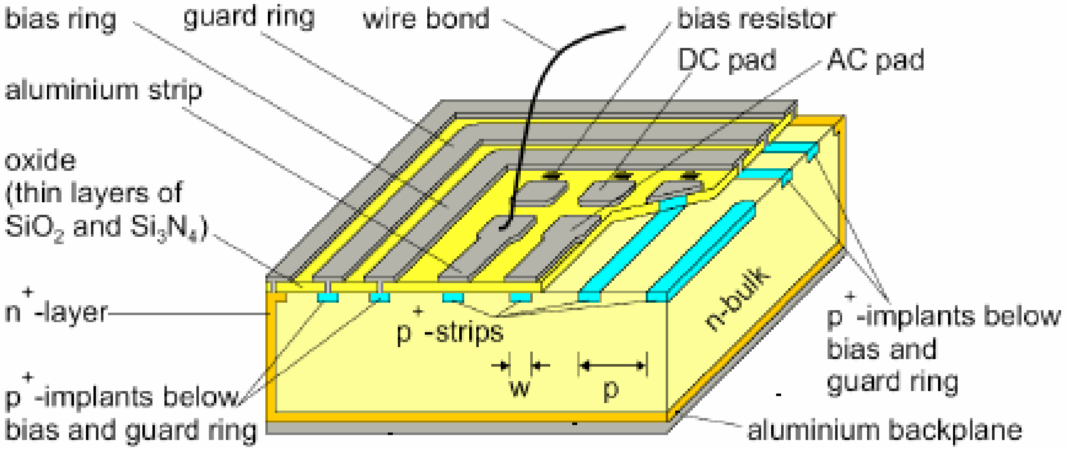
- Signals from two closely spaced sensors are correlated
- Exploit strong magnetic field for local pT measurement
- Local rejection of low pT tracks to minimize data volume

2S Module Silicon Sensor

- **Dimension of Sensor 102.7 x 94.183 mm**
- **Thickness of Sensor 320 µm**
- **Number of Strips 2032 (2 x 1016)**
- **Length of Single Strip 5cm**
- **Strip Pitch 90µm**
- **Standard Wafer Material Float Zone (FZ)**

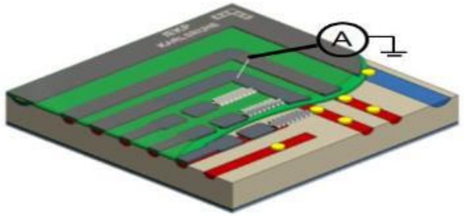
N in P sensor for phase-2 HL-LHC i.e., bulk material is p-type with n-implants



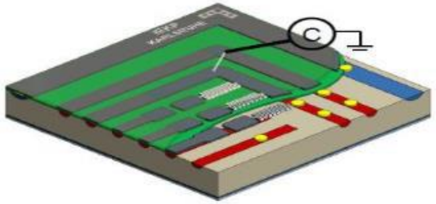


Electrical Characterization of Silicon Sensors

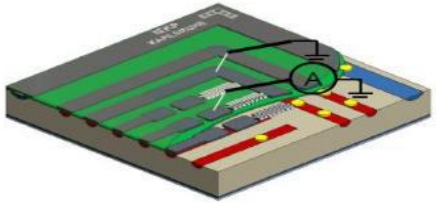
1. IV
Sensor current vs Bias



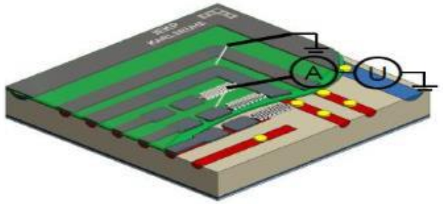
2. CV
Sensor capacitance vs Bias



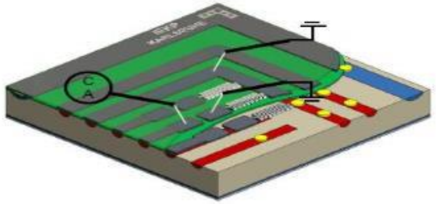
3. I_{leak}
Strip leakage current



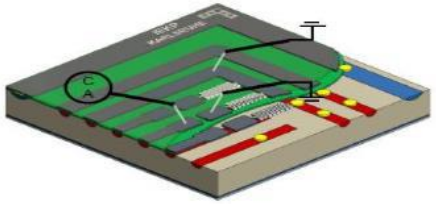
4. R_{bias}
Strip bias resistor



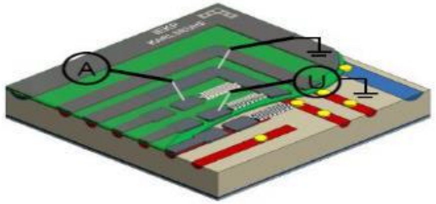
5. C_{Coup}
Coupling capacitance



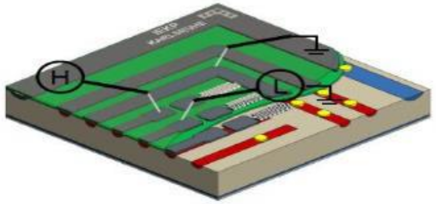
6. I_{diel}
Dielectric current



7. R_{int}
Interstrip resistance



8. C_{int}
Interstrip capacitance

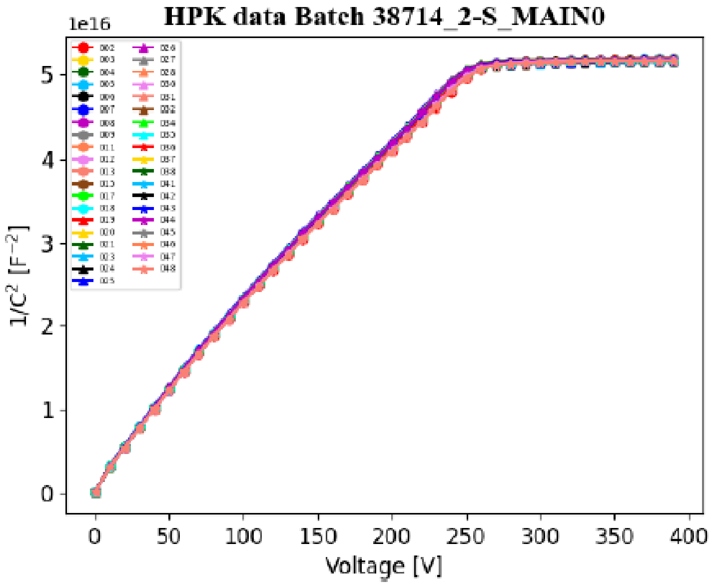


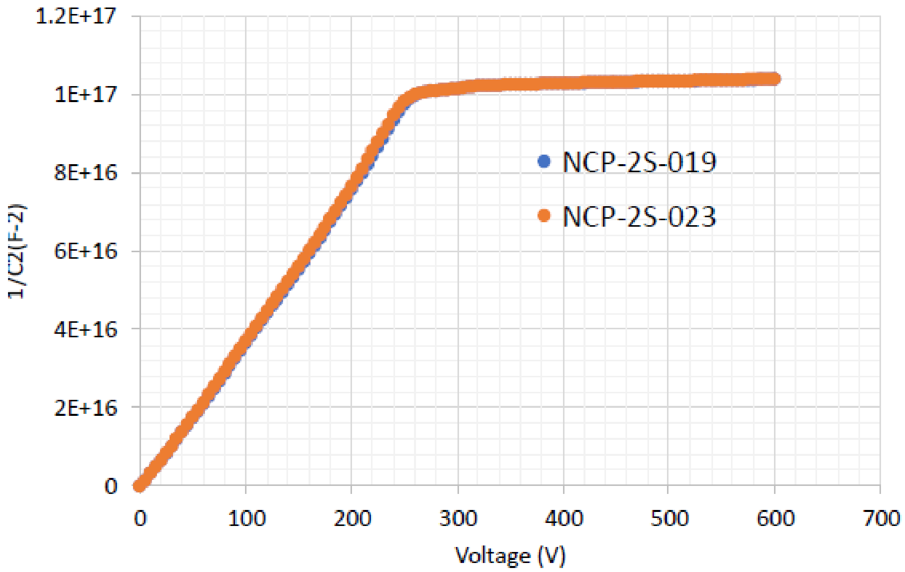
Sensor Qualification Setup at NCP

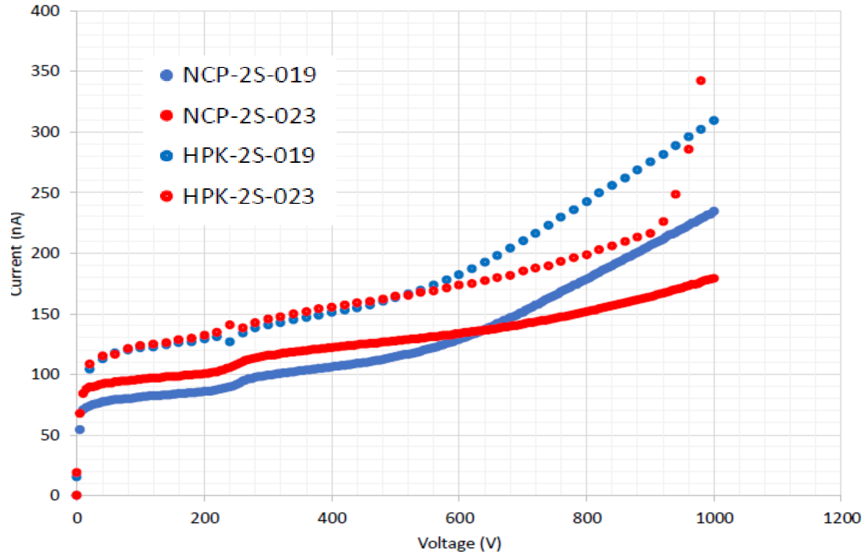
Software has been developed locally to automatize the electrical characterization

CV and IV measurements

The current increases while capacitance decreases linearly with the width of PN junction until the sensor is fully depleted. The kinks determines the depletion voltage.





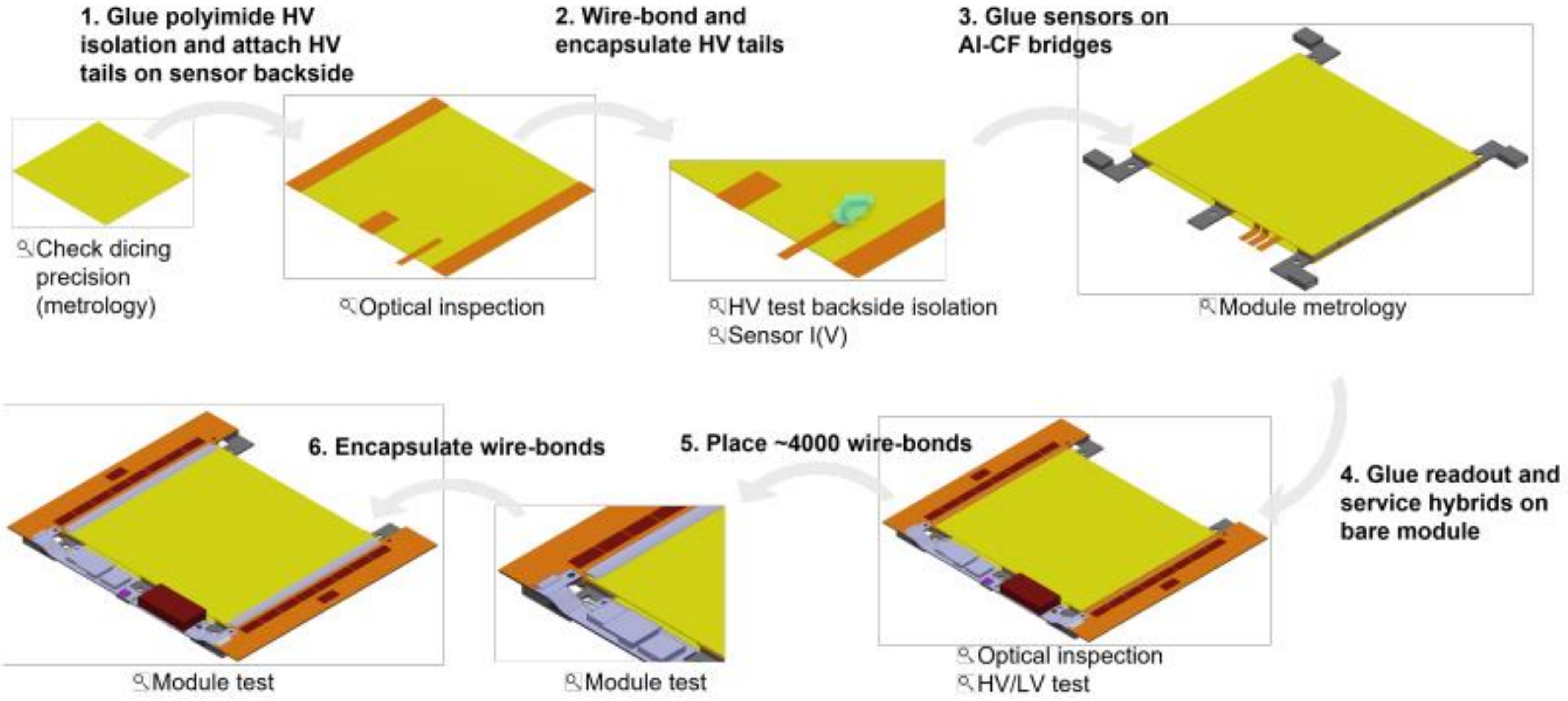


$$C_{bulk} = \begin{cases} A\sqrt{\dfrac{\varepsilon_{Si}}{2\varrho\mu V_{bias}}} & V_{bias} \leq V_{FD} \\ A\dfrac{\varepsilon_{Si}}{D_{depletion}} = const. & V_{bias} > V_{FD} \end{cases}$$

HPK: Temp = 25 C, RH = 40%

NCP: Temp = 20 C, RH = 10%

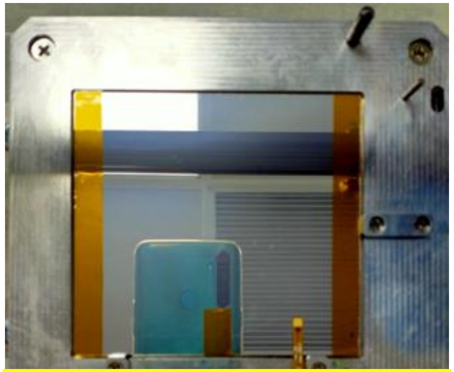
2S Tracker Module Assembly Steps



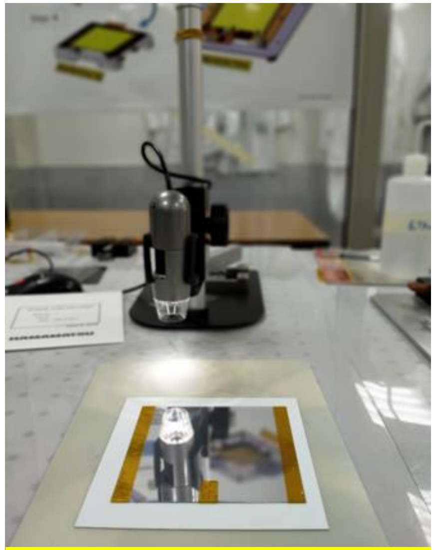
Dedicated Fixtures for Each Assembly Step

Kapton Strips Positioning

Kapton Strips pasting

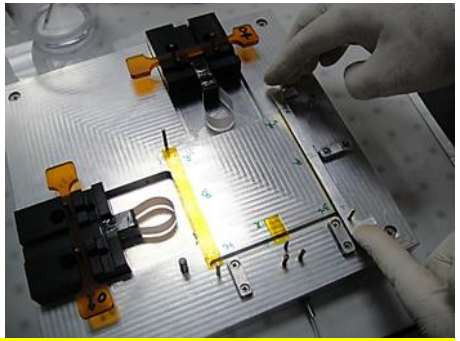


Kapton Strips Gluing

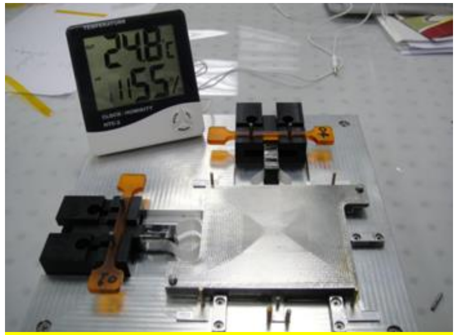


Metrology Setup

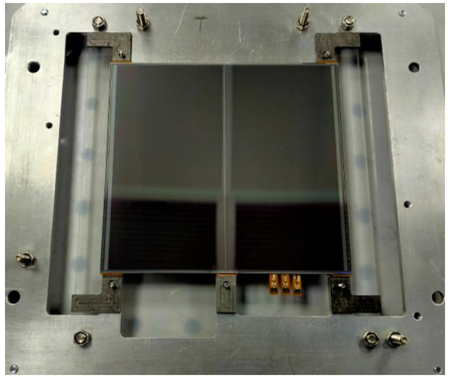
Glue Transfer Plate



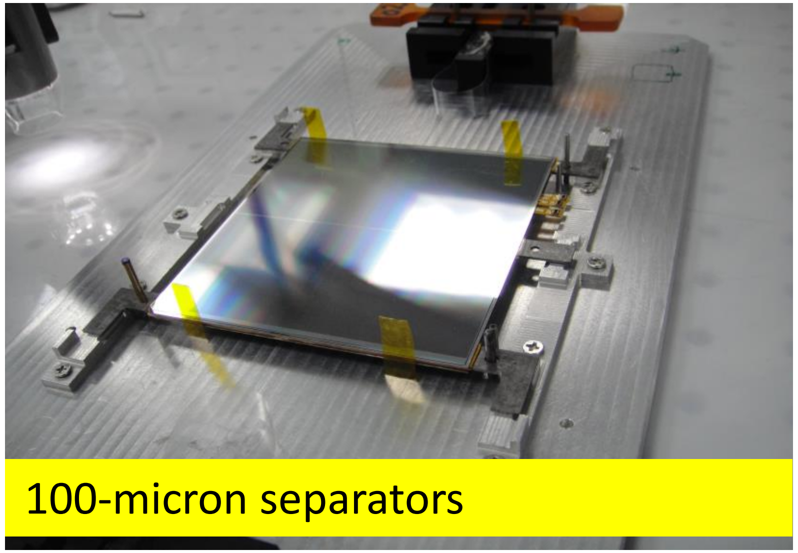
Sensors Sandwich Assembly



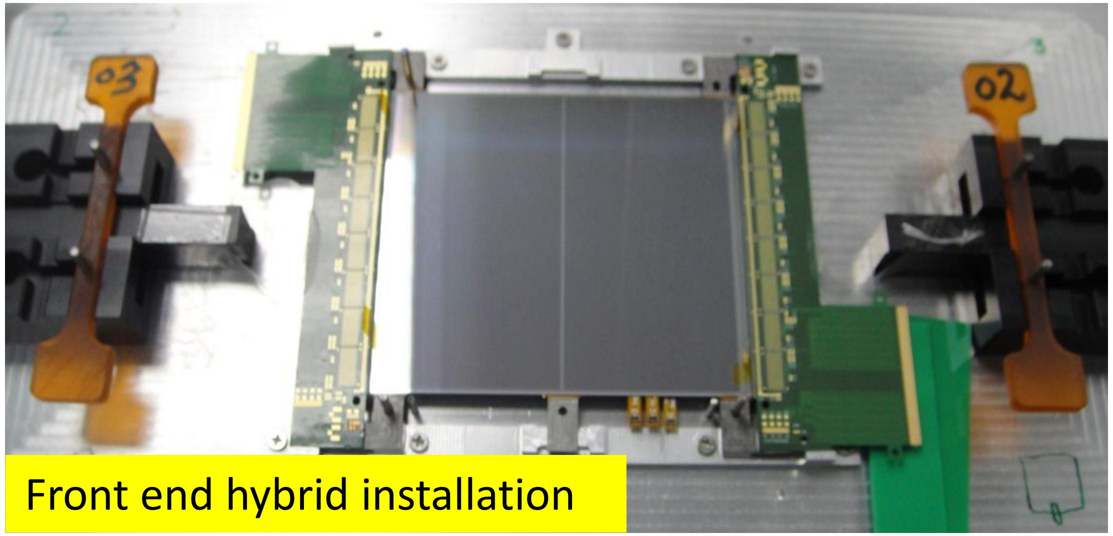
Glue curing for 24 hours



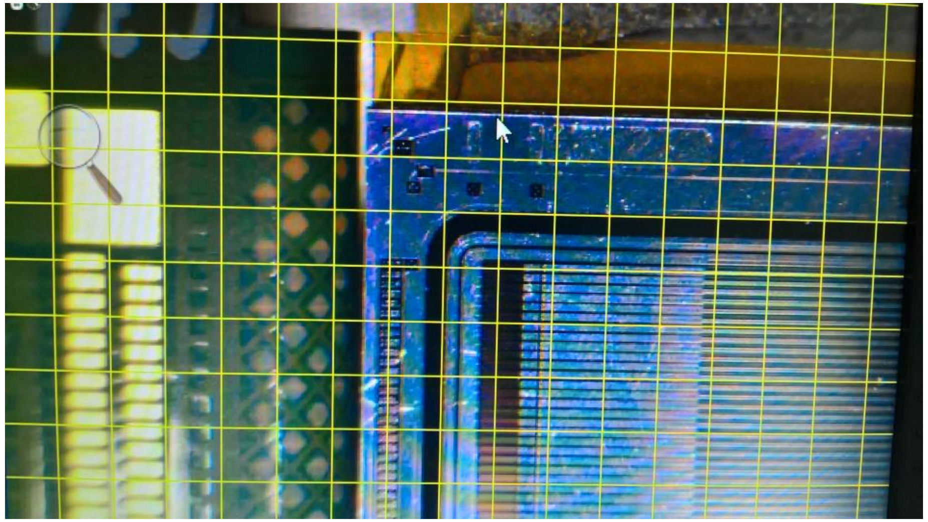
Dedicated Fixtures for Each Assembly Step



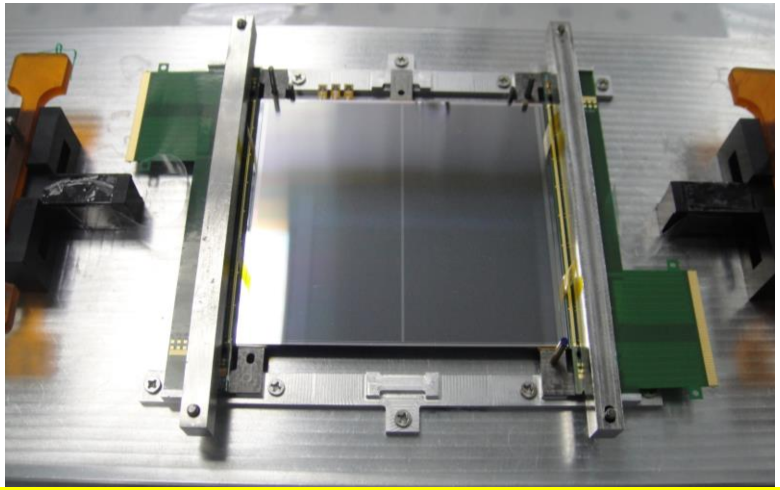
100-micron separators



Front end hybrid installation



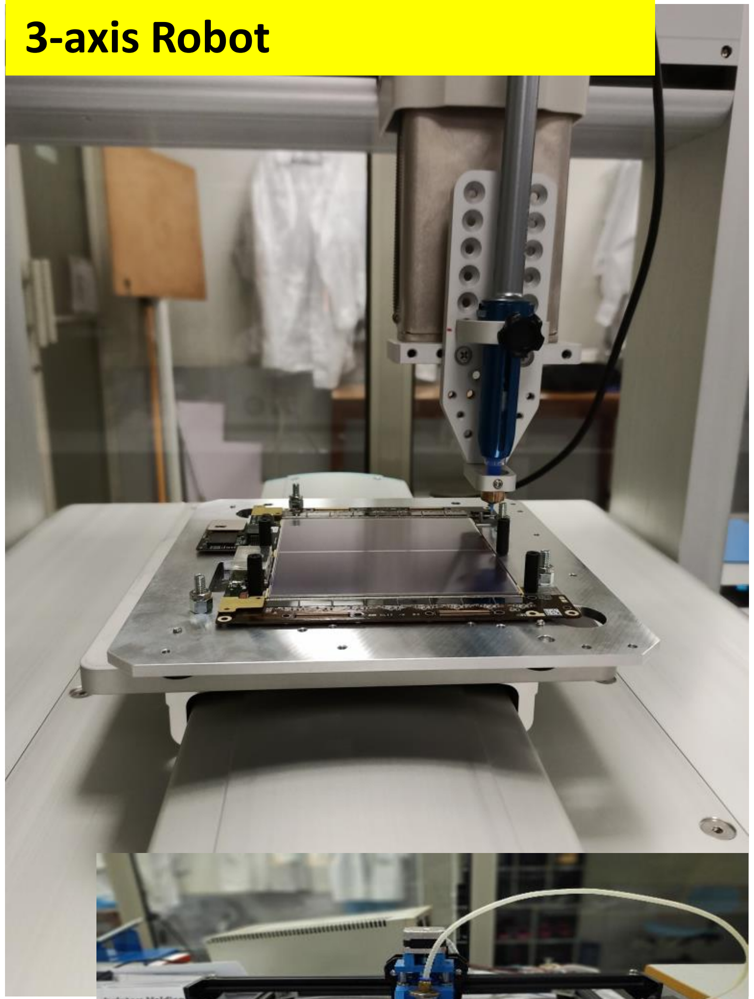
Alignment of sensor strips with the bond pads of Front-End Hybrid

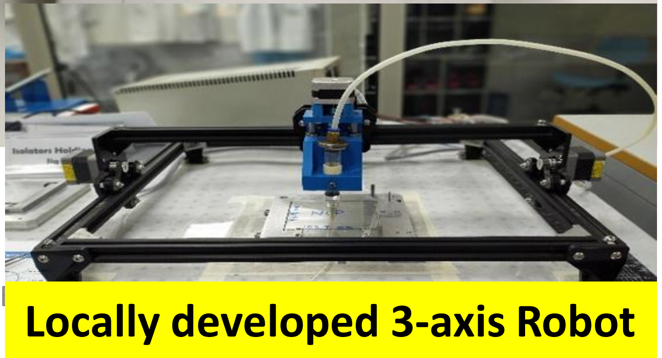


Weight bars for uniformity of the glue and curing

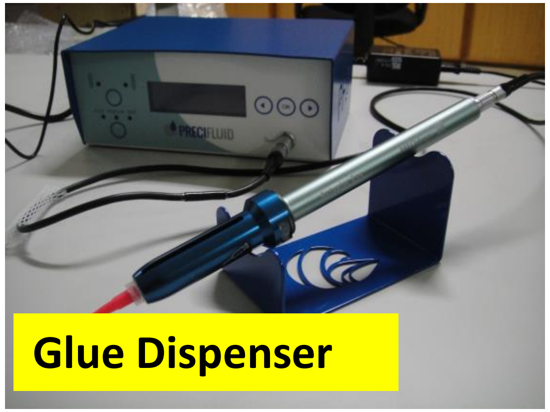
Glue Preparation and Dispensing Setup

- Glue is mixed in vacuum with controlled speed (SmartMix X2)
- The glue dispenser can be programmed for speed and quantity for controlled dispensing of glues (Precifluid)
- 3-axis robot can be programmed to dispense the glue at desired location on the modules
- The glue is passed through an independent vacuum chamber for the removal of air before using for the module assembly


3-axis Robot

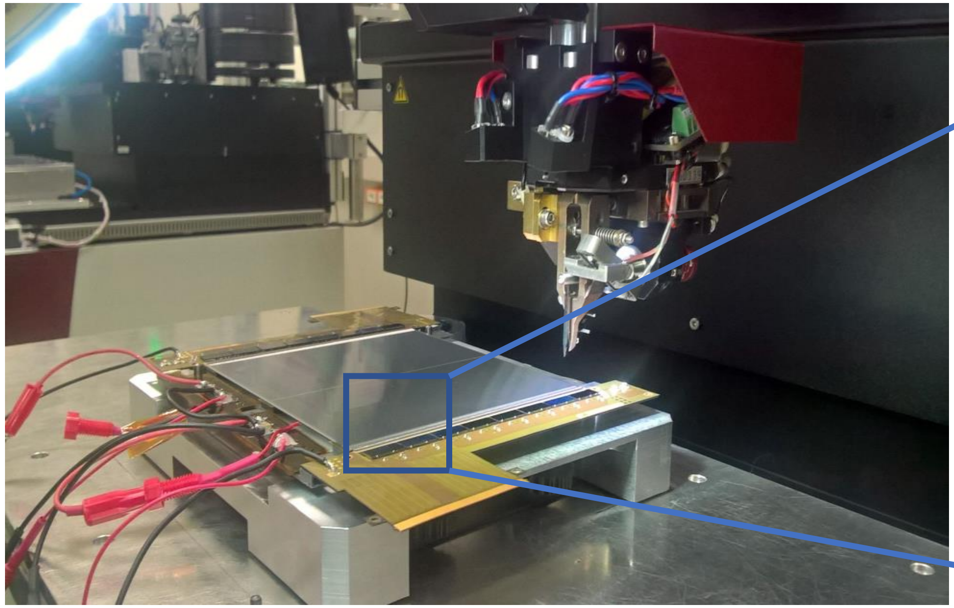

Locally developed 3-axis Robot

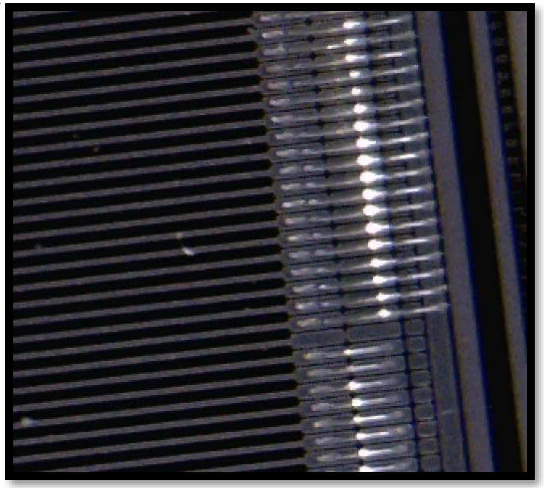

Glue Mixer


Glue Dispenser

Vacuum chamber

Wire Bonding and Encapsulation

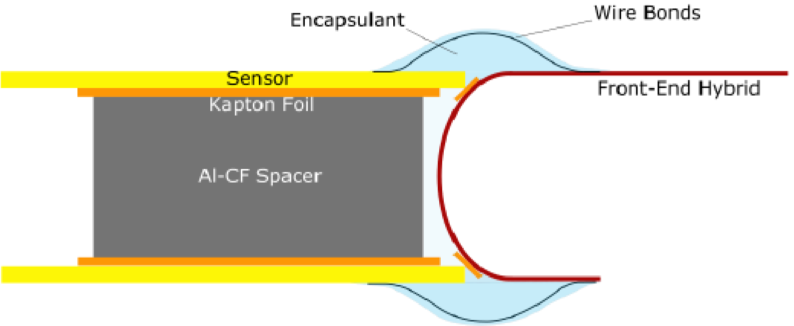


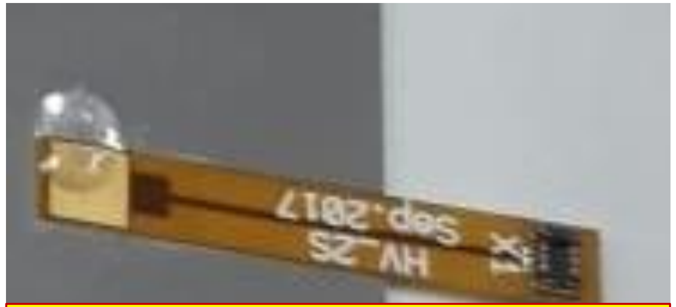


Wire bonds on Silicon Sensor

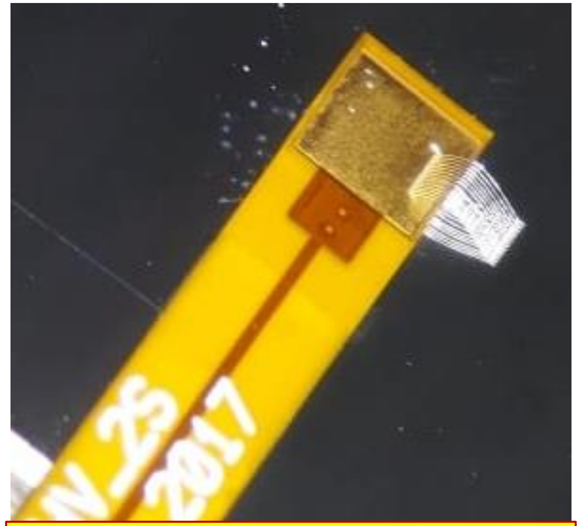
- Delvotec wire bonder model G5 64000
- Speed of 2 to 3 wires per second (depending on application)
- Fine wire Ø 25 µm (Al/Si Alloy)

- 4064 wire bonds / Module
- 10 wire bonds / HV tail



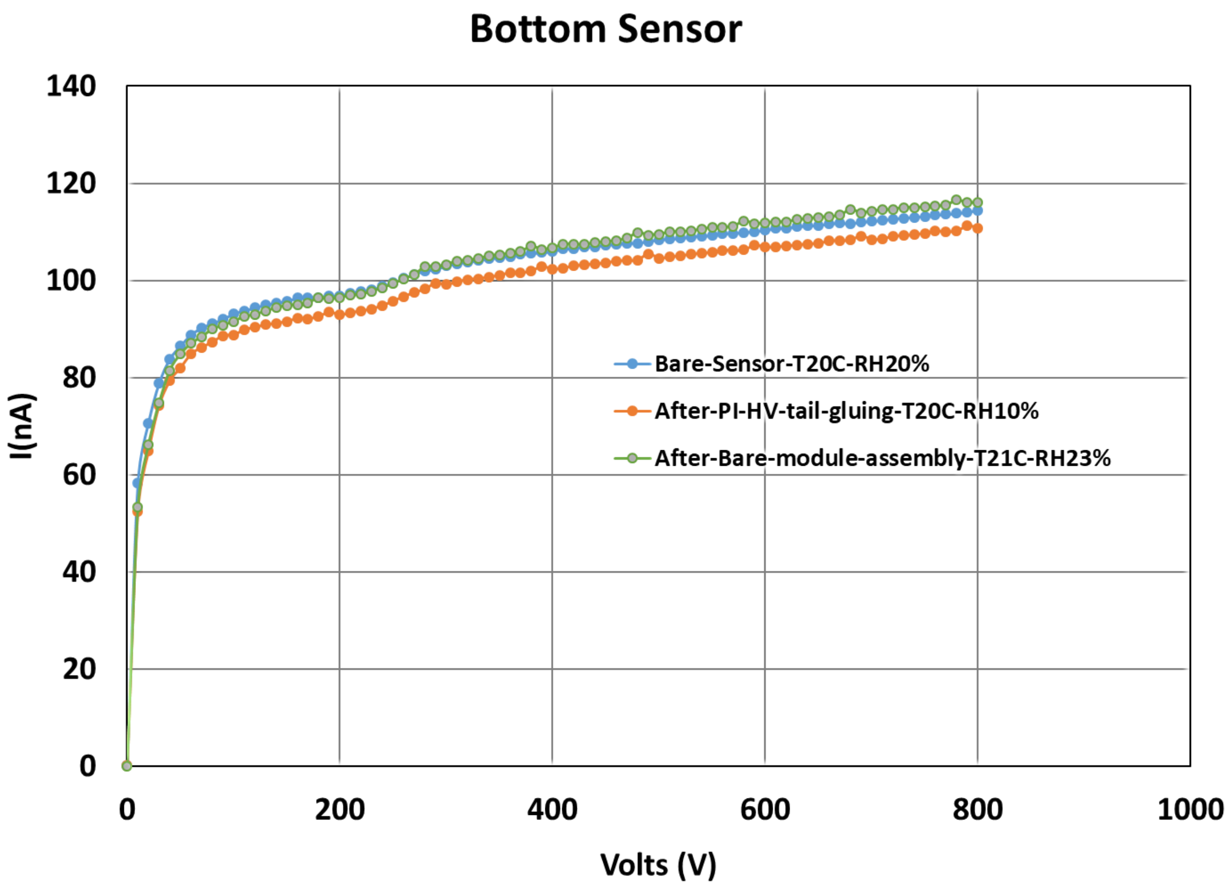


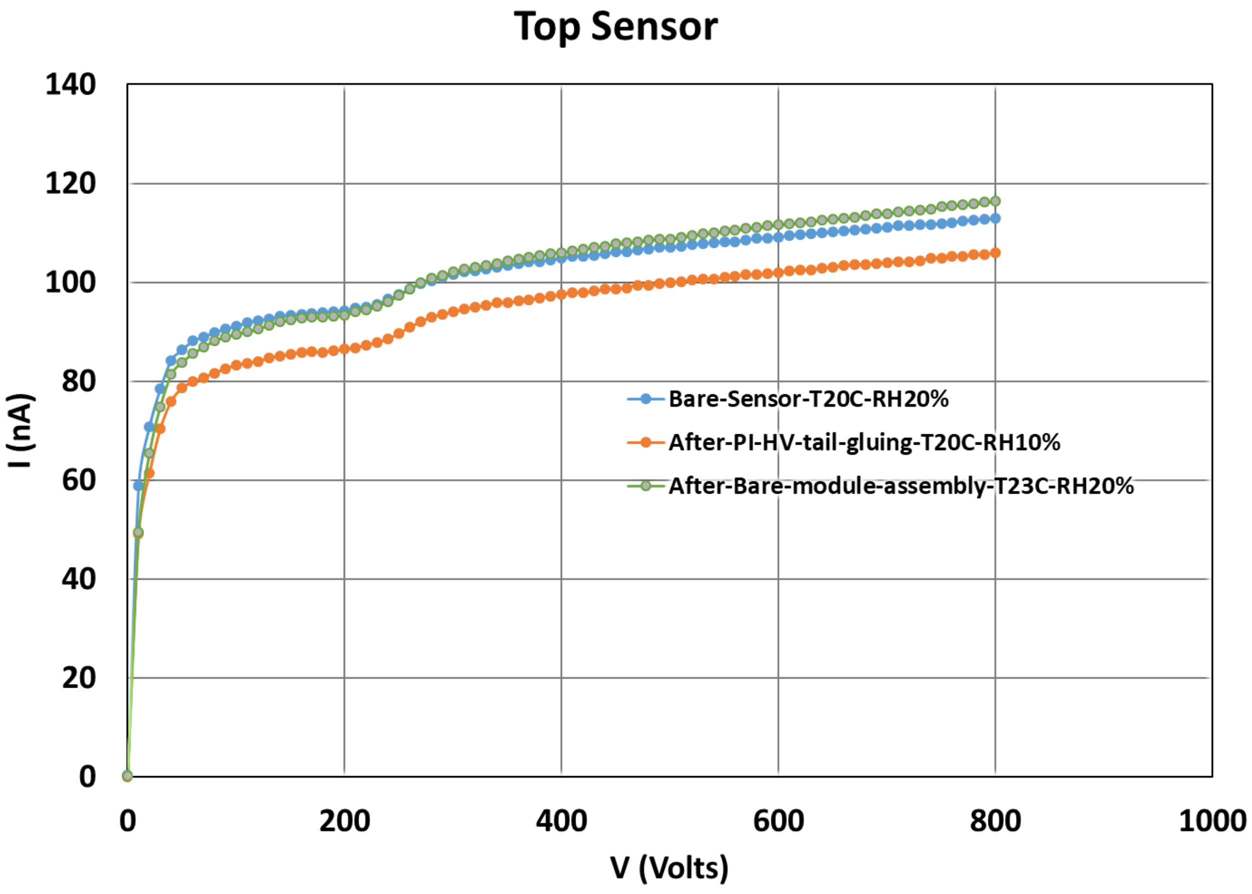
Sylgaurd 186 silicon elastomer is used to protect the wires



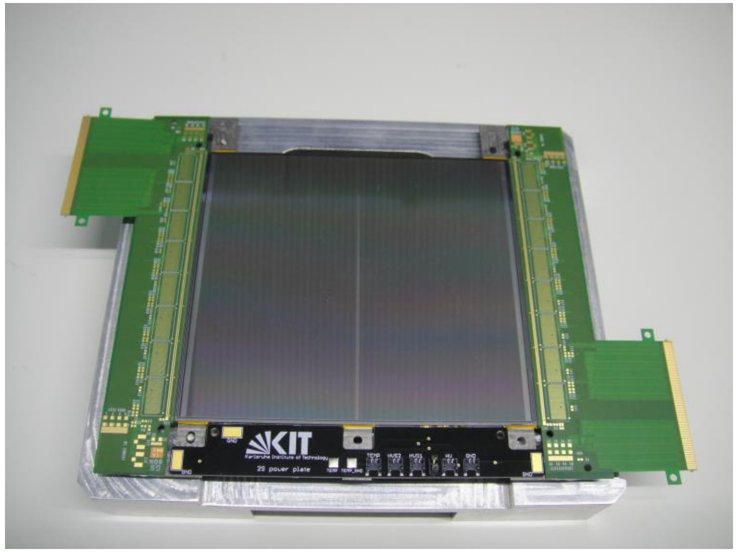
Wire bonds with height of **< 500 µm** is made between HV tail bond pad and sensor backside for biasing of the sensor

2S Module with 8CBC3 Assembly – IV Measurements

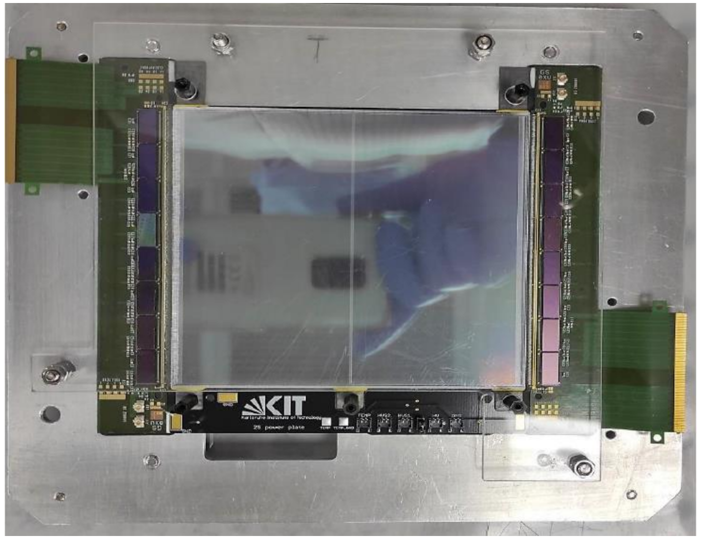




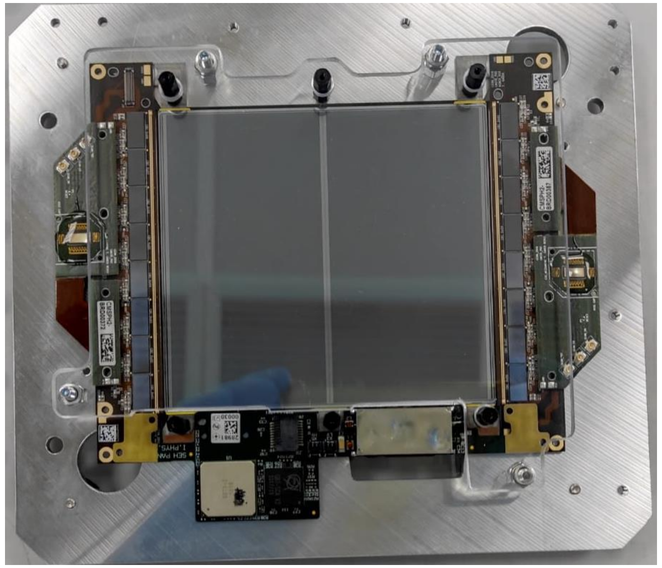
Tracker 2S Outer Tracker Module Assembled at NCP



1st Silicon Dummy Module
Without CBC chips



2nd Silicon Functional Module
8CBC2 Front End Hybrids



3rd Silicon Functional Module
8CBC3 Front End Hybrids

$\Delta X = -12.9\ \mu m$
$\Delta Y = -4.0\ \mu m$
Angle = $-21.9\ \mu rad$

Thank You !