

Semiconductor Detectors in Particle Physics

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January 20, 2022



Regional E-conference on Physics

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.

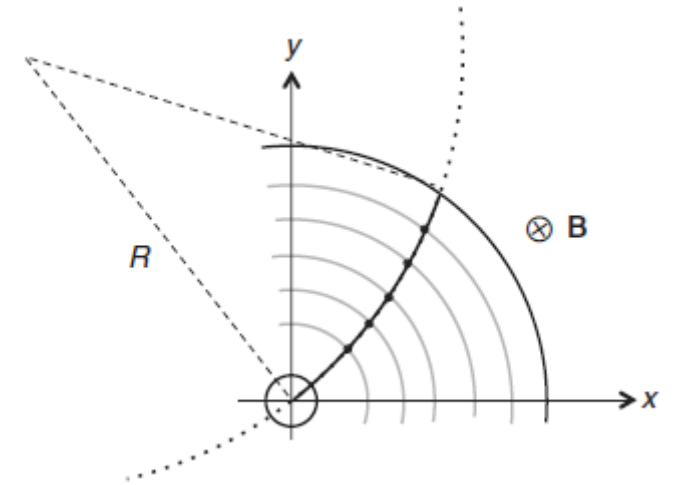
A charged particle travels through a certain medium and ionize atoms. By detecting this ionisation, it is possible to reconstruct the trajectory of a charged particle commonly known as the **Tracking**.

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

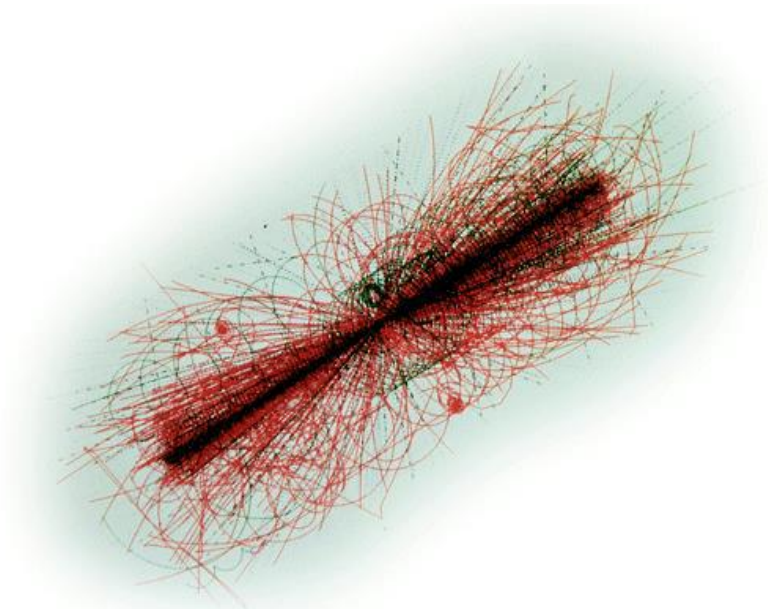
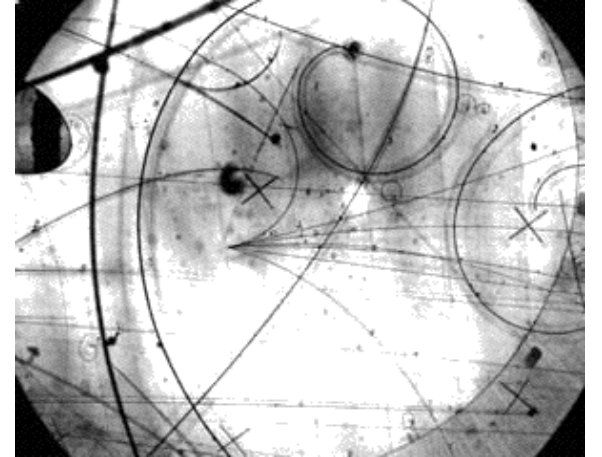
- Many bubbles along path; take stereo photos; measure trajectory by manual scanning of film

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 $\sim 200 \mu\text{m}$ per hit
- Used in CMS muon system

Silicon detectors (>1990s)

- Accuracy $\sim 10 \mu\text{m}$ 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

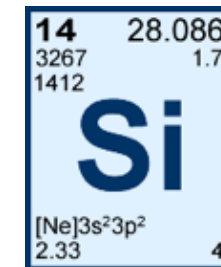
Disadvantages:

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

Requires Cooling

Periodic Table of the Elements

1																	18
H Hydrogen 1.008																	He Helium 4.003
3	4											13	14	15	16	17	18
Li Lithium 6.941	Be Beryllium 9.012											B Boron 10.811	C Carbon 12.011	N Nitrogen 14.007	O Oxygen 15.999	F Fluorine 18.998	Ne Neon 20.180
11	12											13	14	15	16	17	18
Na Sodium 22.990	Mg Magnesium 24.305											Al Aluminum 26.982	Si Silicon 28.086	P Phosphorus 30.974	S Sulfur 32.065	Cl Chlorine 35.453	Ar Argon 39.948
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
K Potassium 39.098	Ca Calcium 40.078	Sc Scandium 44.956	Ti Titanium 47.867	V Vanadium 50.942	Cr Chromium 51.996	Mn Manganese 54.938	Fe Iron 55.845	Co Cobalt 58.933	Ni Nickel 58.693	Cu Copper 63.546	Zn Zinc 65.38	Ga Gallium 69.723	Ge Germanium 72.631	As Arsenic 74.922	Se Selenium 78.971	Br Bromine 79.904	Kr Krypton 84.796
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rb Rubidium 84.468	Sr Strontium 87.62	Y Yttrium 88.906	Zr Zirconium 91.224	Nb Niobium 92.906	Mo Molybdenum 95.95	Tc Technetium 98.907	Ru Ruthenium 101.07	Rh Rhodium 102.905	Pd Palladium 106.42	Ag Silver 107.868	Cd Cadmium 112.414	In Indium 114.818	Sn Tin 118.710	Sb Antimony 121.760	Te Tellurium 127.6	I Iodine 126.905	Xe Xenon 131.294
55	56	57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
Cs Cesium 132.905	Ba Barium 137.327	Lanthanides	Hf Hafnium 178.49	Ta Tantalum 180.948	W Tungsten 183.84	Re Rhenium 186.207	Os Osmium 190.23	Ir Iridium 192.222	Pt Platinum 195.084	Au Gold 196.967	Hg Mercury 200.592	Tl Thallium 204.383	Pb Lead 207.2	Bi Bismuth 208.980	Po Polonium [209]	At Astatine [209]	Rn Radon [222]
87	88	89-103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
Fr Francium [223]	Ra Radium [226]	Actinides	Rf Rutherfordium [261]	Db Dubnium [262]	Sg Seaborgium [266]	Bh Bohrium [264]	Hs Hassium [265]	Mt Meitnerium [268]	Ds Darmstadtium [271]	Rg Roentgenium [272]	Cn Copernicium [285]	Uut Ununtrium [288]	Fl Flerovium [289]	Uup Ununpentium [294]	Lv Livermorium [293]	Uus Ununseptium [294]	Uuo Ununoctium [294]
Lanthanide Series																	
57	58	59	60	61	62	63	64	65	66	67	68	69	70	71			
La Lanthanum 138.905	Ce Cerium 140.119	Pr Praseodymium 140.908	Nd Neodymium 144.242	Pm Promethium [144.913]	Sm Samarium 150.36	Eu Europium 151.964	Gd Gadolinium 157.25	Tb Terbium 158.925	Dy Dysprosium 162.500	Ho Holmium 164.930	Er Erbium 167.259	Tm Thulium 168.934	Yb Ytterbium 173.055	Lu Lutetium 174.967			
Actinide Series																	
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103			
Ac Actinium [227.028]	Th Thorium 232.038	Pa Protactinium 231.036	U Uranium 238.029	Np Neptunium [237.048]	Pu Plutonium 244.064	Am Americium [243.061]	Cm Curium [247.070]	Bk Berkelium [247.070]	Cf Californium [251.082]	Es Einsteinium [254]	Fm Fermium [257.095]	Md Mendelevium [258.1]	No Nobelium [259.101]	Lr Lawrencium [262]			
Alkali Metal Alkaline Earth Transition Metal Basic Metal Semimetal Nonmetal Halogen Noble Gas Lanthanide Actinide																	

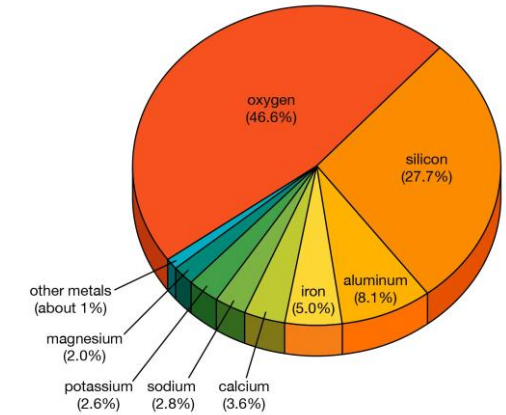


Silicon Properties

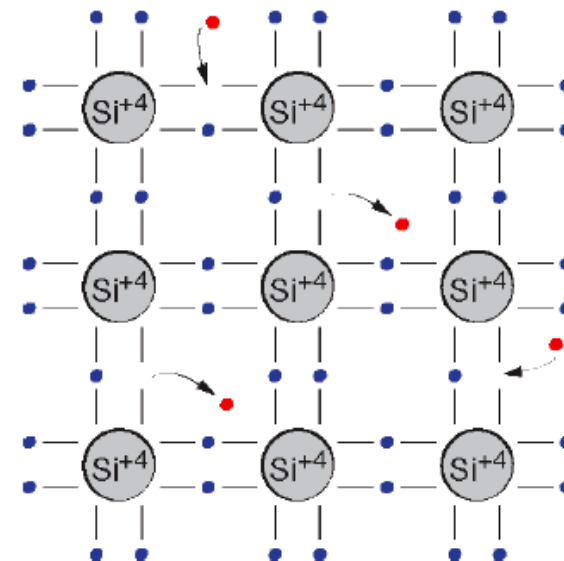
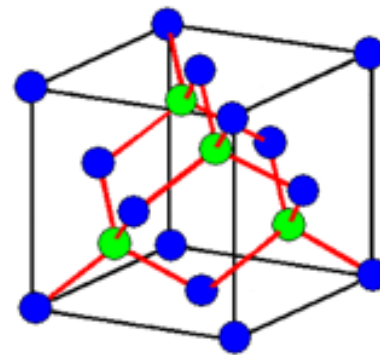
- Silicon is a **group IV** element -> 4 valence electrons that form covalent bonds
- Si is a **semiconductor** (isolator at $T \sim 0K$ and conductance between metal and insulator at RT)
- can form **single crystals** (111 or 100 orientation)
- diamond cubic lattice (2 interleaved fcc sub-lattices)
- one of the **most abundant elements** in earth crust - mostly in the form of SiO_2 - aka sand



Mineral composition of Earth's crust



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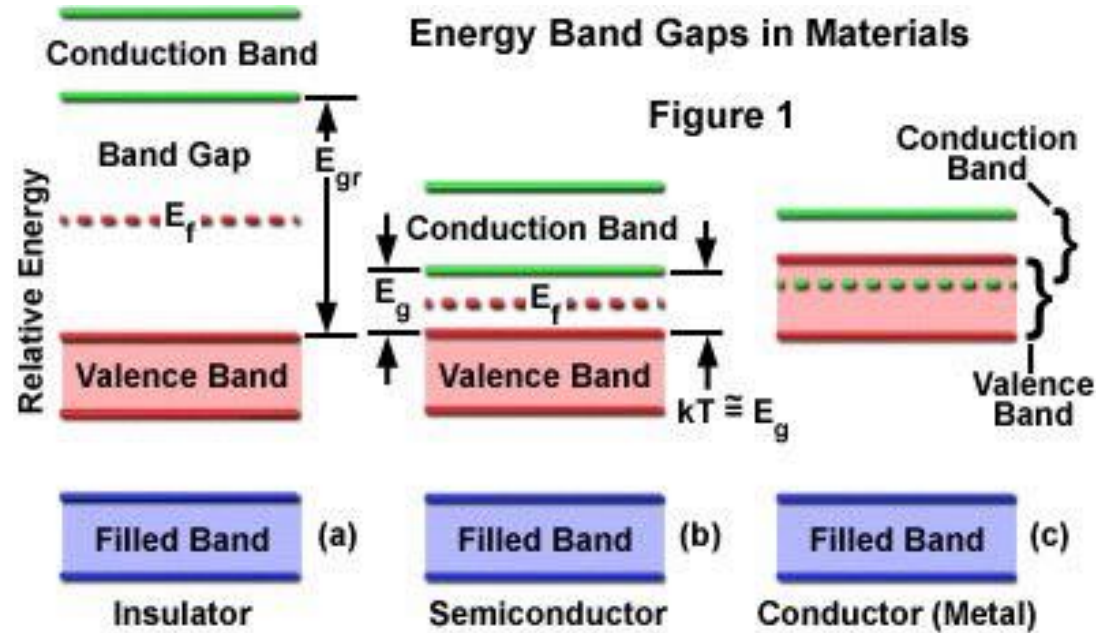


$T > 0 K$

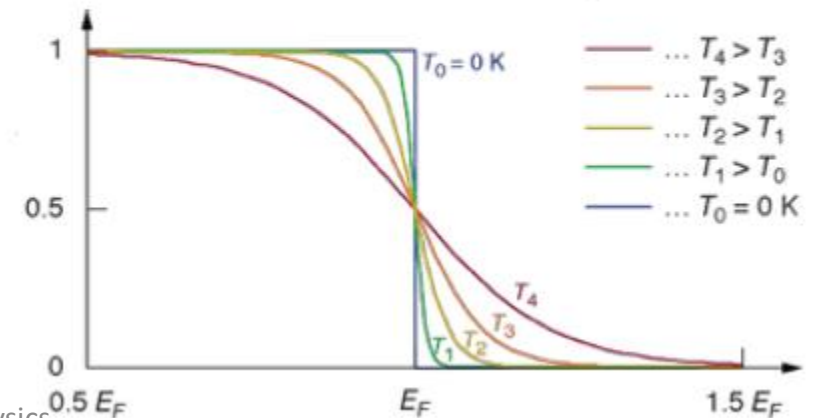
- ... Valence electron
- ... Conduction electron

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**”



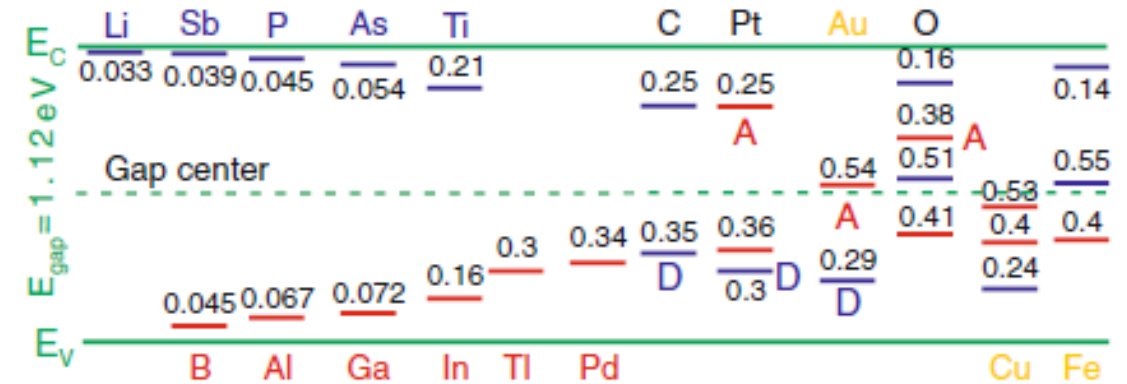
$$f(E) = \frac{1}{1 + \exp \frac{E - E_f}{k_B T}}$$



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 :



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

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

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

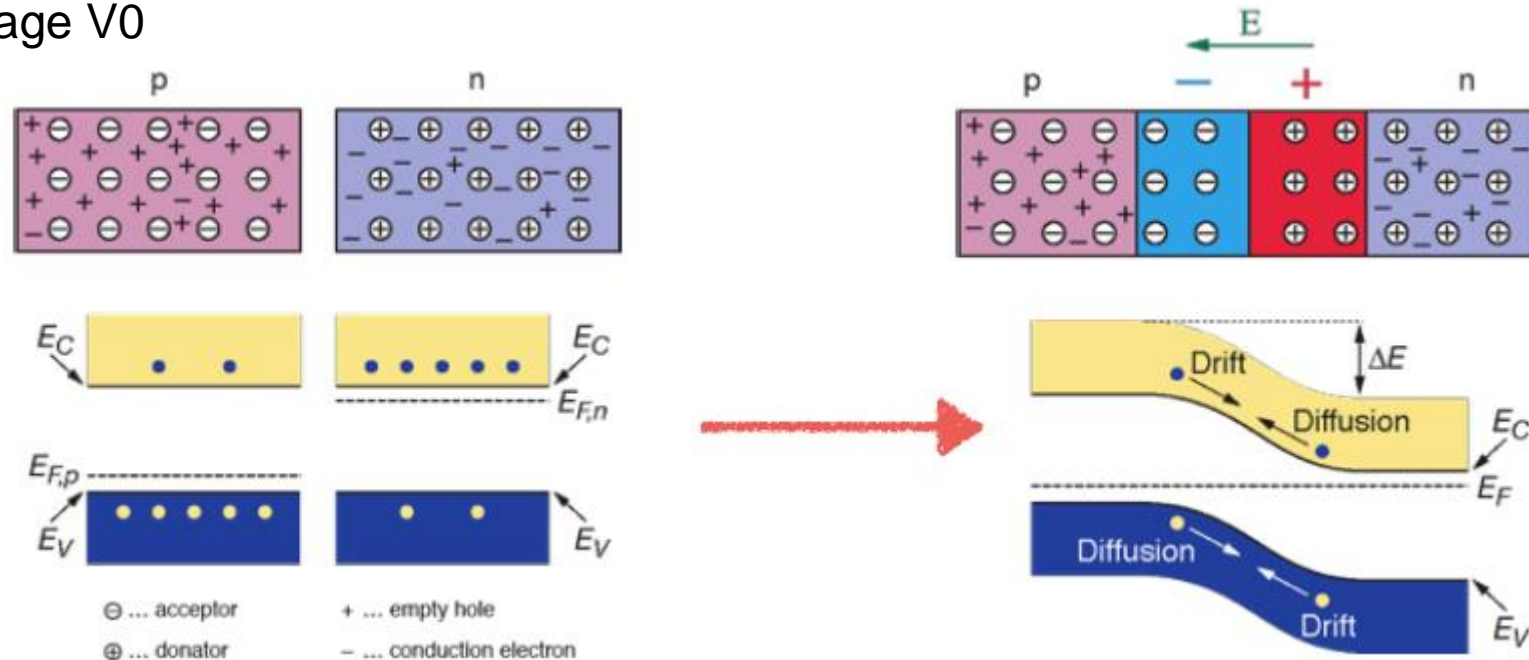
**in practice,
only the
dopants
matter**

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

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

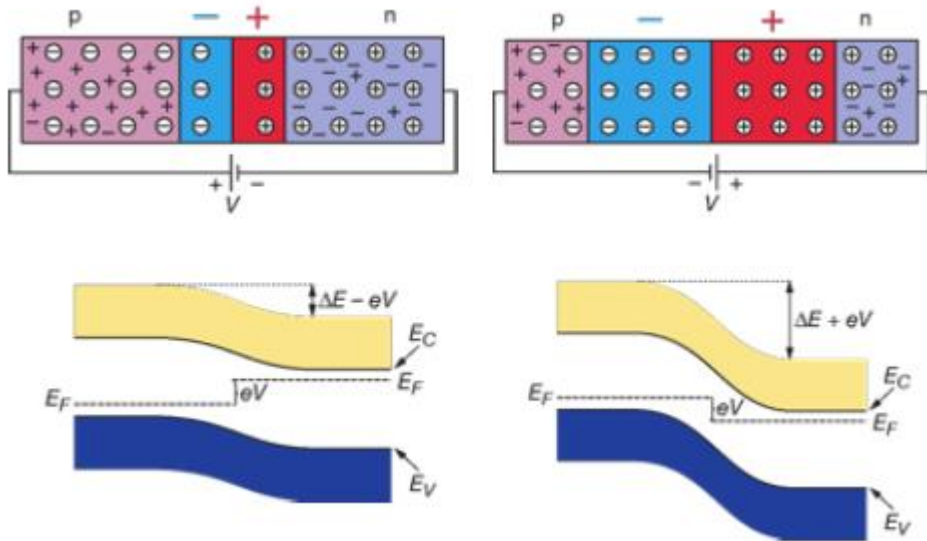
The PN Junction - I

- 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 V_0



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



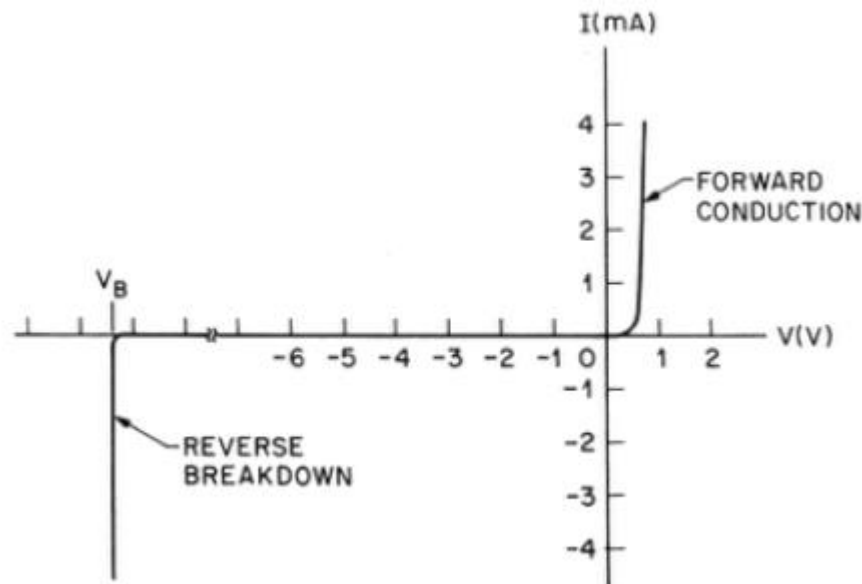
width W of the depleted region:

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

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 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 until breakdown (avalanche effect in E-field)



width W of the depleted region:

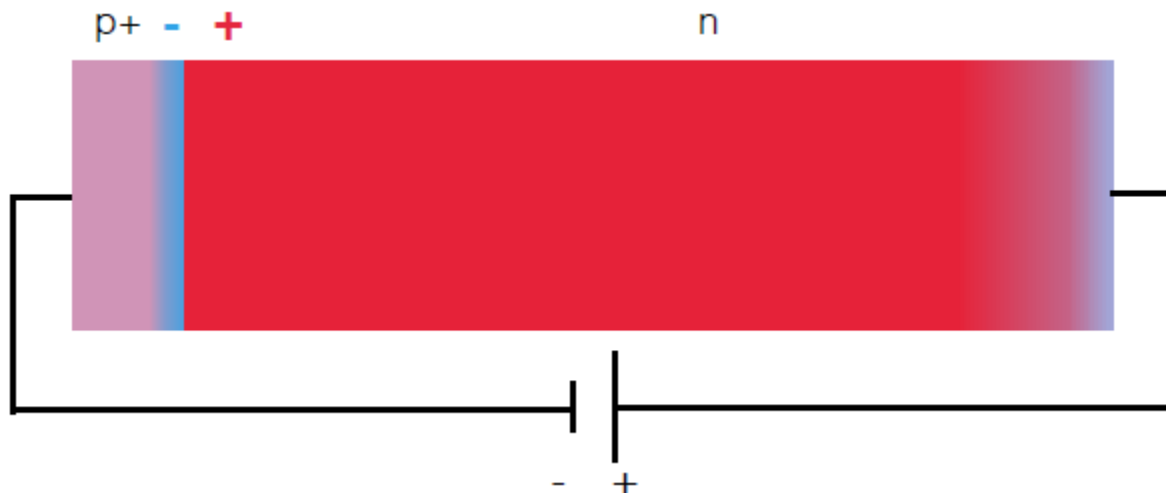
$$W \approx \sqrt{2\epsilon_0\epsilon_r\mu\rho|V|} \text{ for } V \gg V_0$$

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:
- $V_{\text{ext}}=0\text{V}$: $W_p = 0.02\mu\text{m}$, $W_n = 23\mu\text{m}$
- V_{ext} , reverse = 100V : $W_p = 0.4\mu\text{m}$, $W_n = 363\mu\text{m}$

This is how to operate PN junction as detector

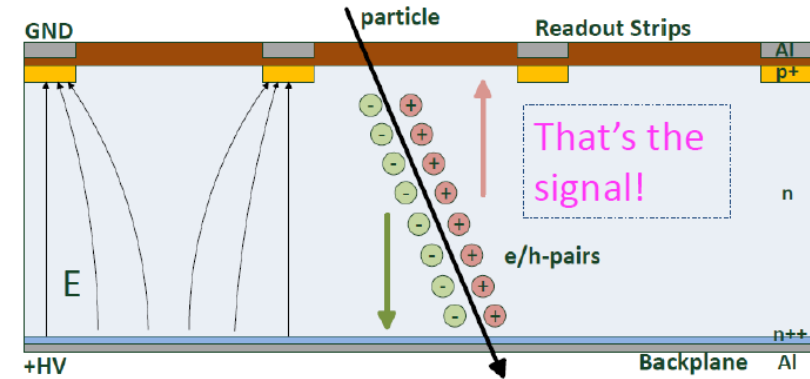


Possible to use:
P+ contact in n bulk
N+ contact in p bulk

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 ($\sim 30\text{eV}$ for gases) \rightarrow 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: $n_i = 1.45 \times 10^{10} \text{ cm}^{-3}$
- created $e^- h^+$ pairs for detector with $d= 300\mu\text{m}$ and $A=1\text{cm}^2$:

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

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

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

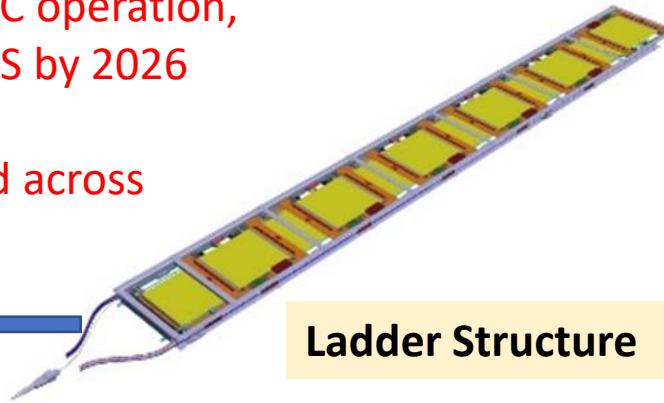
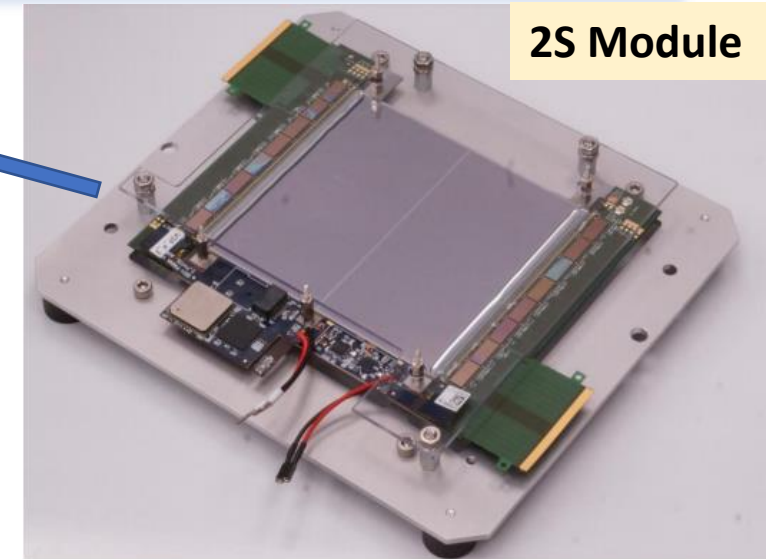
- signal drowned in thermally generated “noise” by 4 orders of magnitude
- absolutely **vital** to operate the detector **depleted**



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



CMS DETECTOR

Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T

STEEL RETURN YUKE
 12,500 tonnes

SILICON TRACKERS

Pixel (100x150 μm) ~16m² ~66M channels
 Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
 Niobium titanium coil carrying ~18,000A

MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
 Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

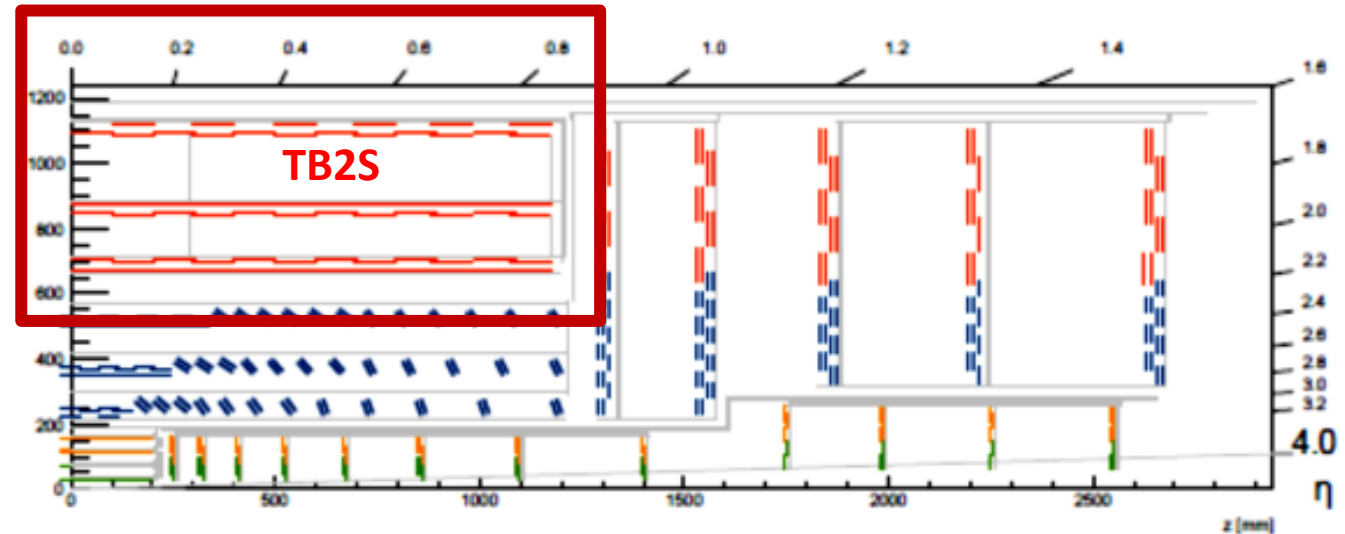
PRESHOWER


Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
 Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
 ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
 Brass + Plastic scintillator ~7,000 channels

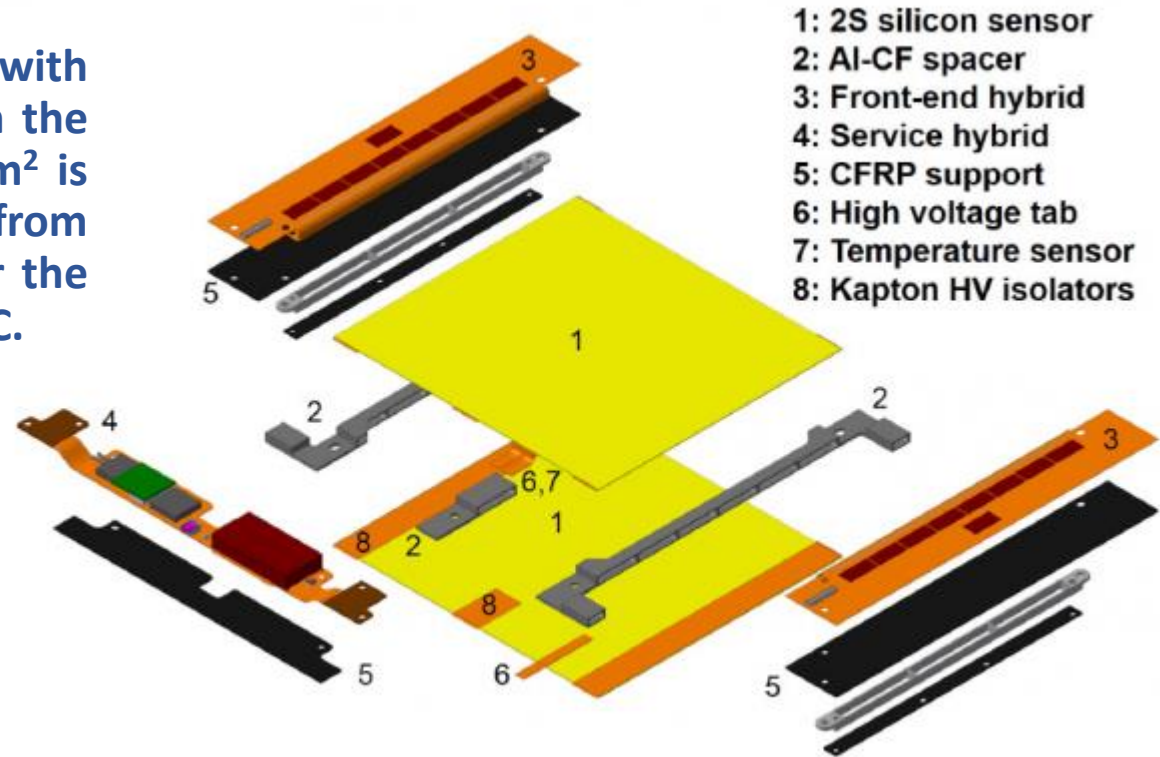
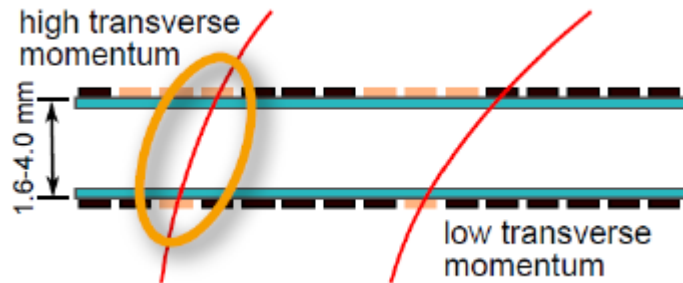




NCP is one of the Module Assembly and sensor qualification centre.

A dedicated lab for semiconductor detector technology has been developed

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 cm² 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 °C.



- 1: 2S silicon sensor
- 2: Al-CF spacer
- 3: Front-end hybrid
- 4: Service hybrid
- 5: CFRP support
- 6: High voltage tab
- 7: Temperature sensor
- 8: Kapton HV isolators

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

Module will have on board pT discrimination:

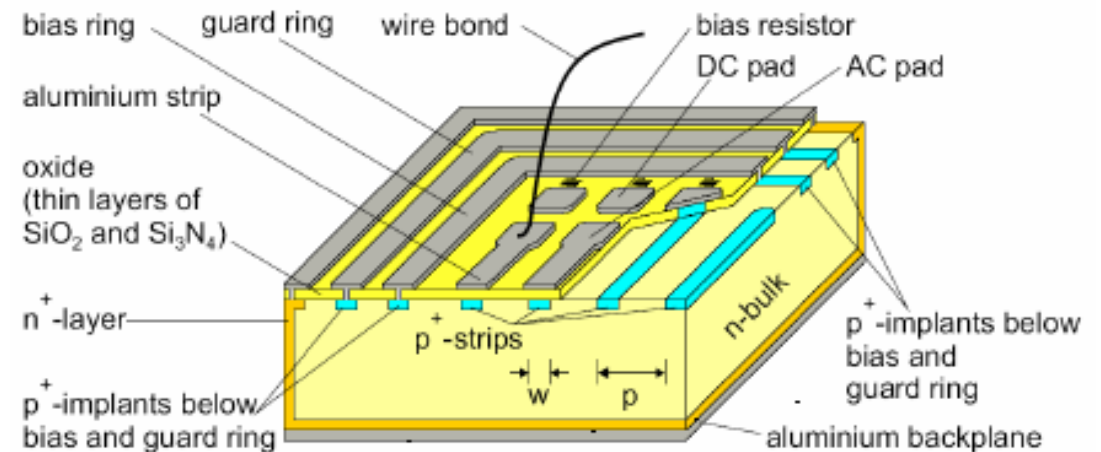
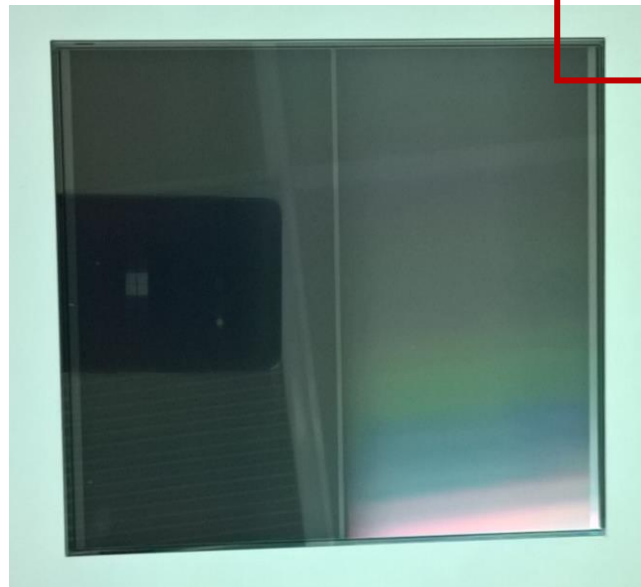
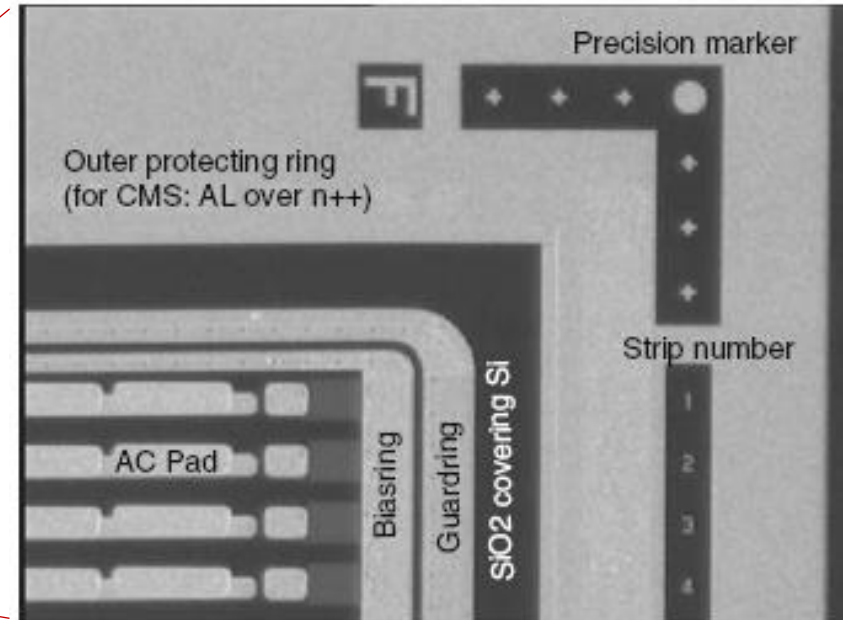
- Signals from two closely spaced sensors are correlated
- Exploit strong magnetic field for local pT measurement
- Local rejection of low pT tracks to minimize data volume



2S Module Silicon Sensor



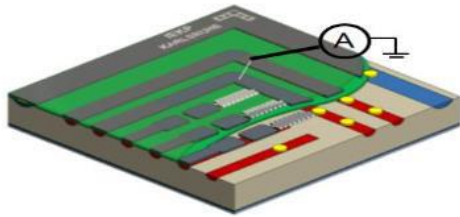
- Dimension of Sensor **102.7 x 94.183 mm**
- Thickness of Sensor **320 μm**
- Number of Strips **2032 (2 x 1016)**
- Length of Single Strip **5cm**
- Strip Pitch **90 μm**
- Standard Wafer Material **Float Zone (FZ)**



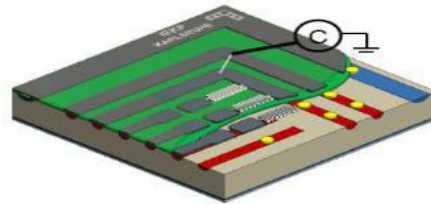
N in P sensor for phase-2 HL-LHC i.e., bulk material is p-type with n-implants

Electrical Characterization of Silicon Sensors

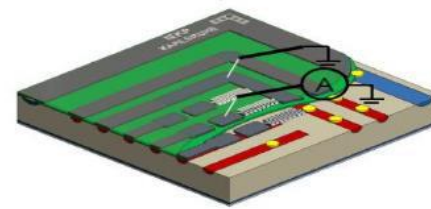
1. IV
Sensor current vs
Bias



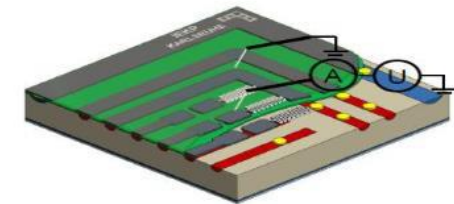
2. CV
Sensor capacitance vs
Bias



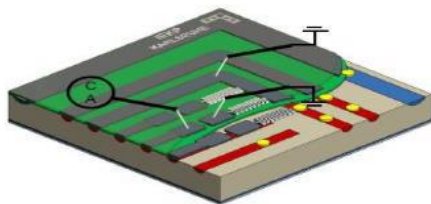
3. I_{leak}
Strip leakage
current



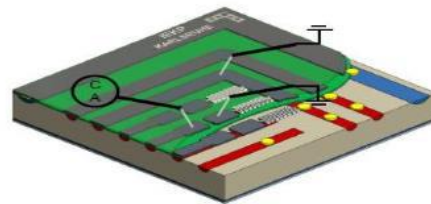
4. R_{bias}
Strip bias resistor



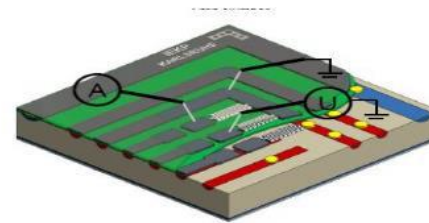
5. C_{Coup}
Coupling capacitance



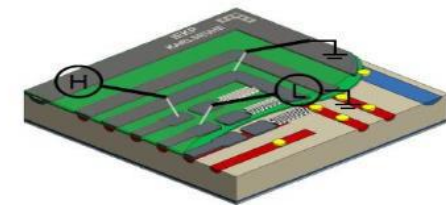
6. I_{diel}
Dielectric current



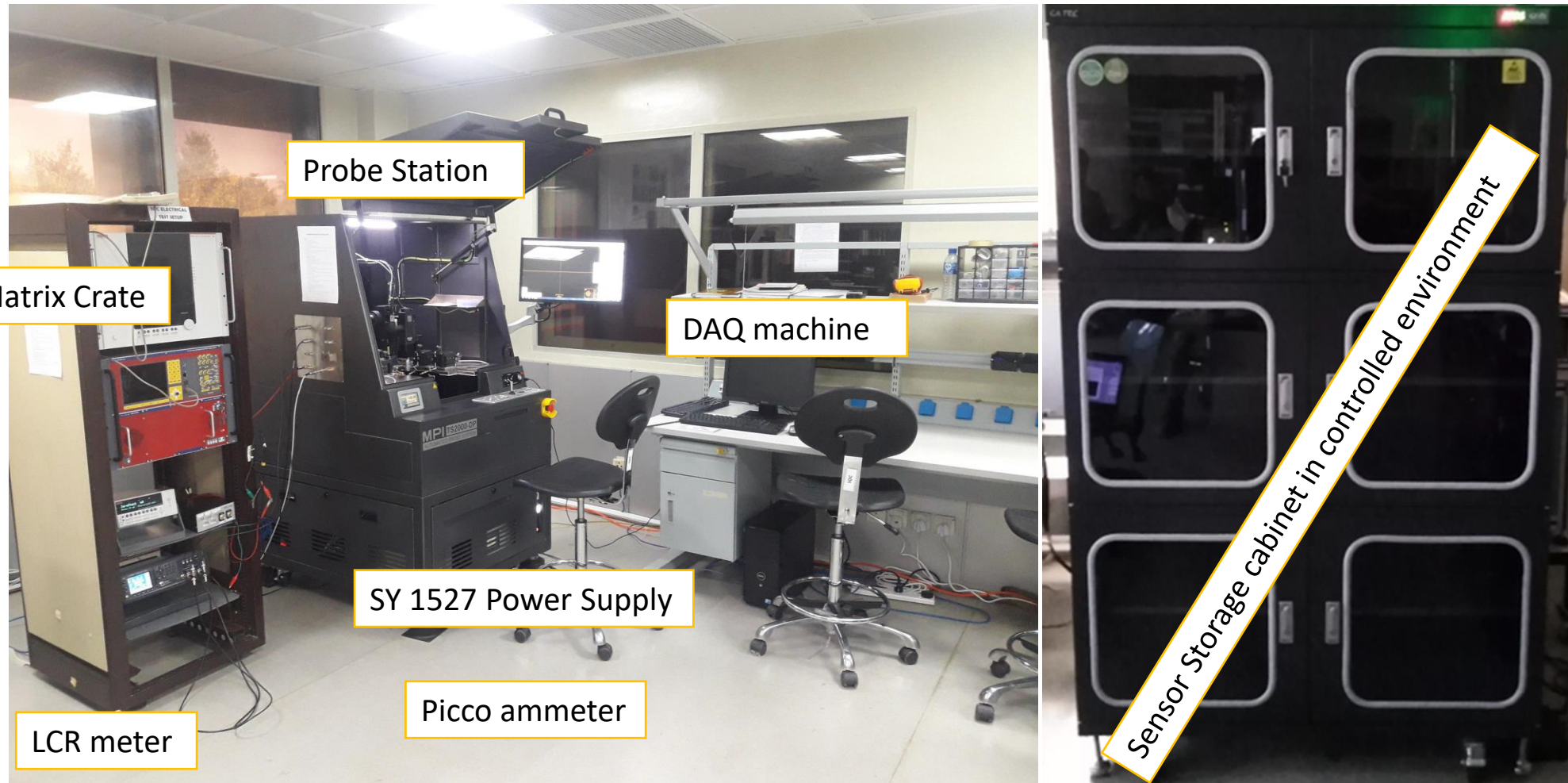
7. R_{int}
Interstrip resistance



8. C_{int}
Interstrip capacitance



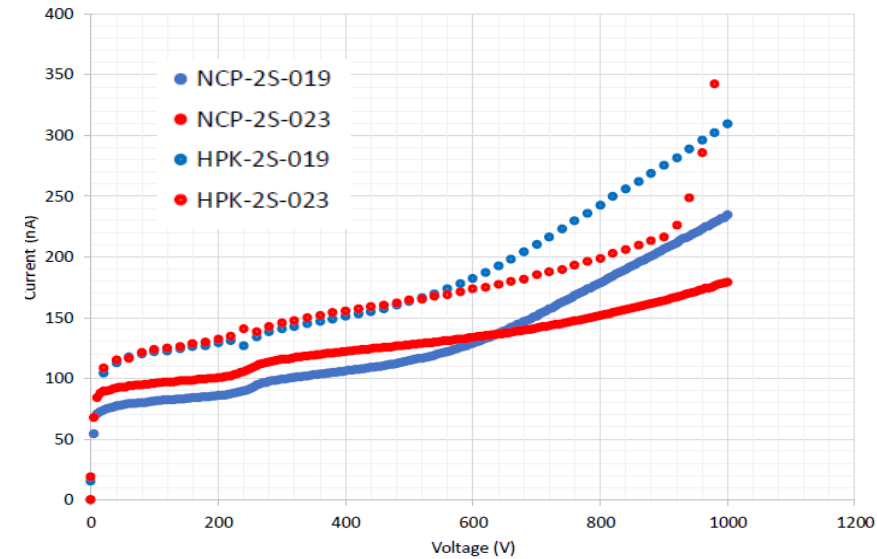
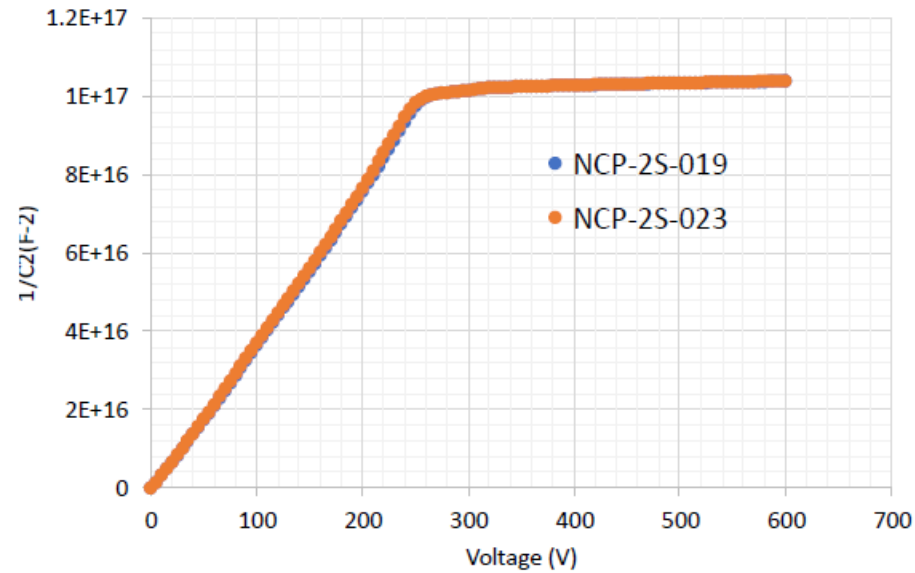
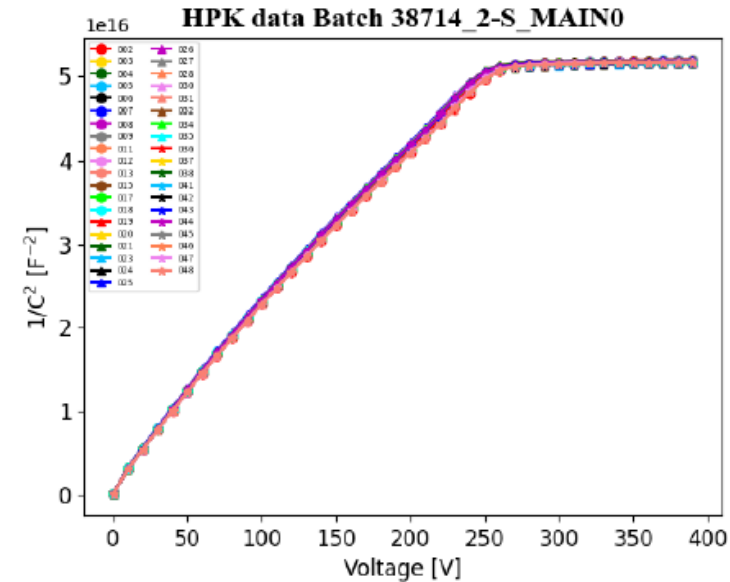
Sensor Qualification Setup at NCP



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.



$$C_{bulk} = \begin{cases} A \sqrt{\frac{\epsilon_{Si}}{2q\mu V_{bias}}} \\ A \frac{\epsilon_{Si}}{D_{depletion}} = const. \end{cases}$$

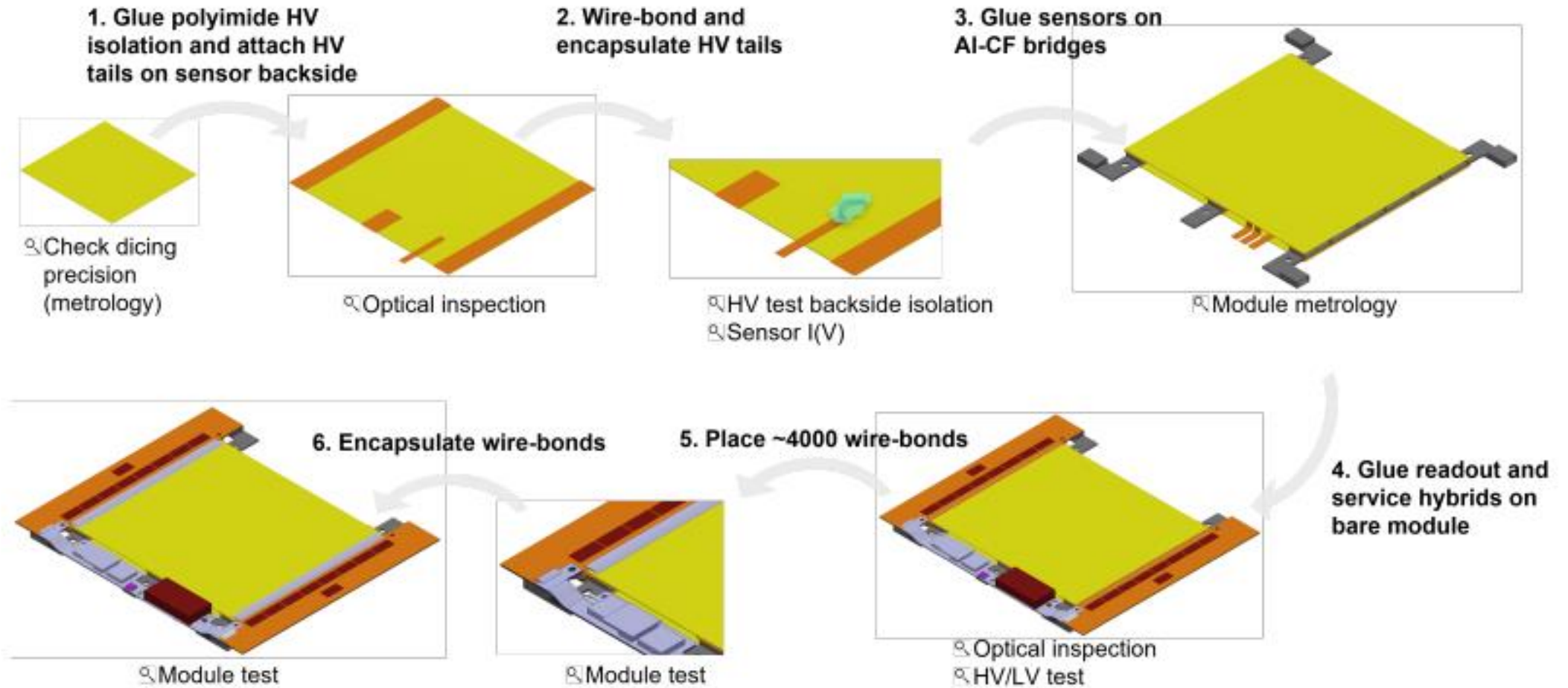
$$V_{bias} \leq V_{FD}$$

$$V_{bias} > V_{FD}$$

HPK: Temp = 25 C, RH = 40%

NCP: Temp = 20 C, RH = 10%

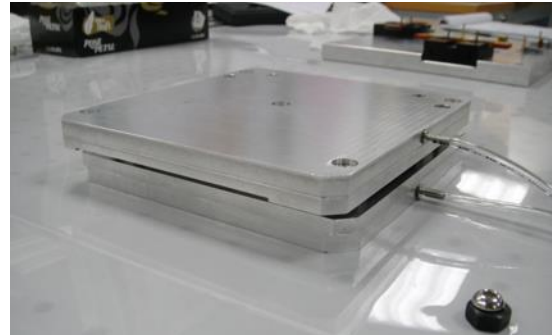
2S Tracker Module Assembly Steps



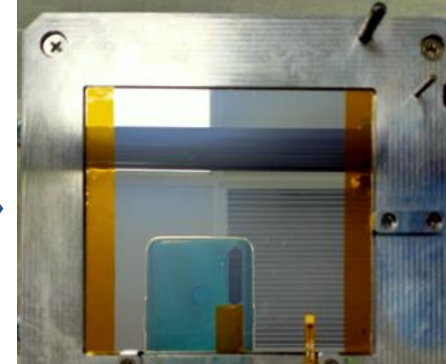
Dedicated Fixtures for Each Assembly Step



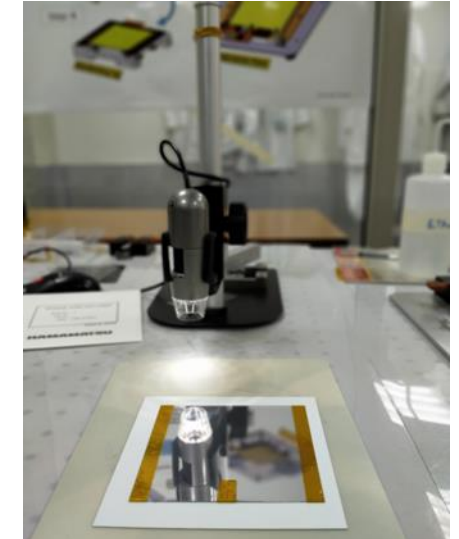
Kapton Strips Positioning



Kapton Strips pasting



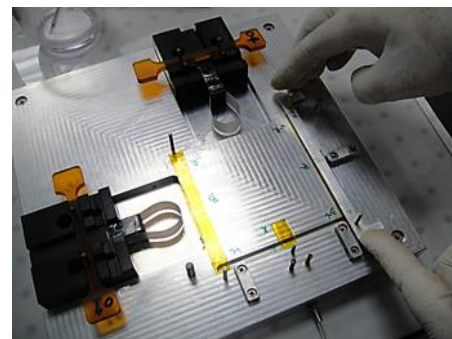
Kapton Strips Gluing



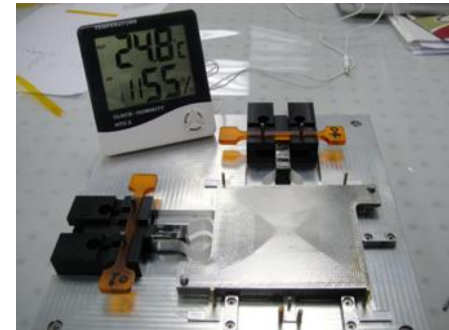
Metrology Setup



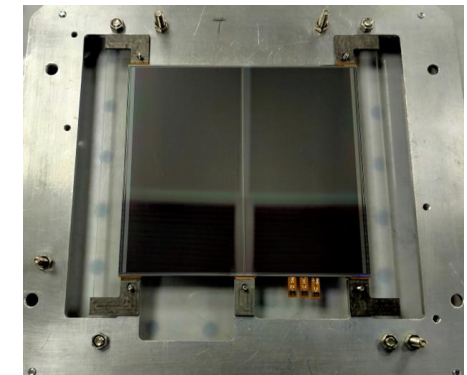
Glue Transfer Plate



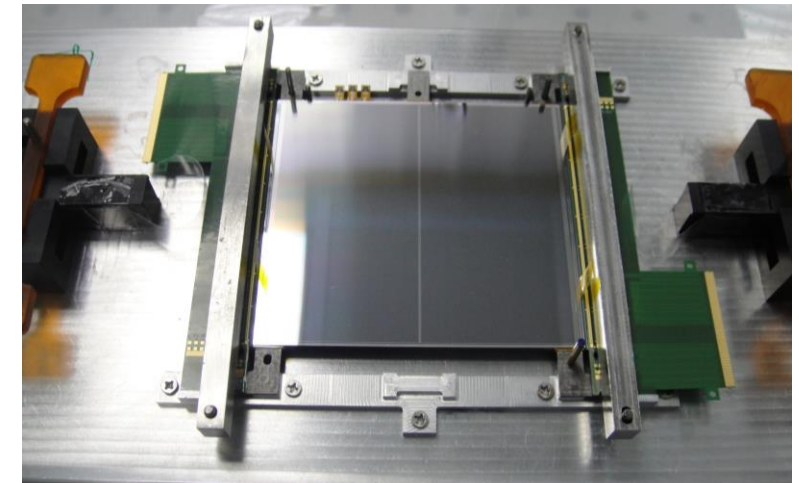
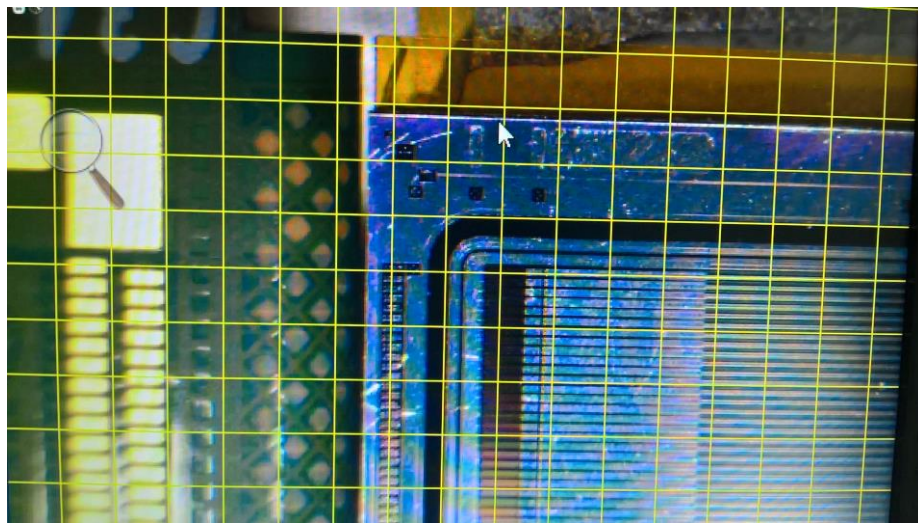
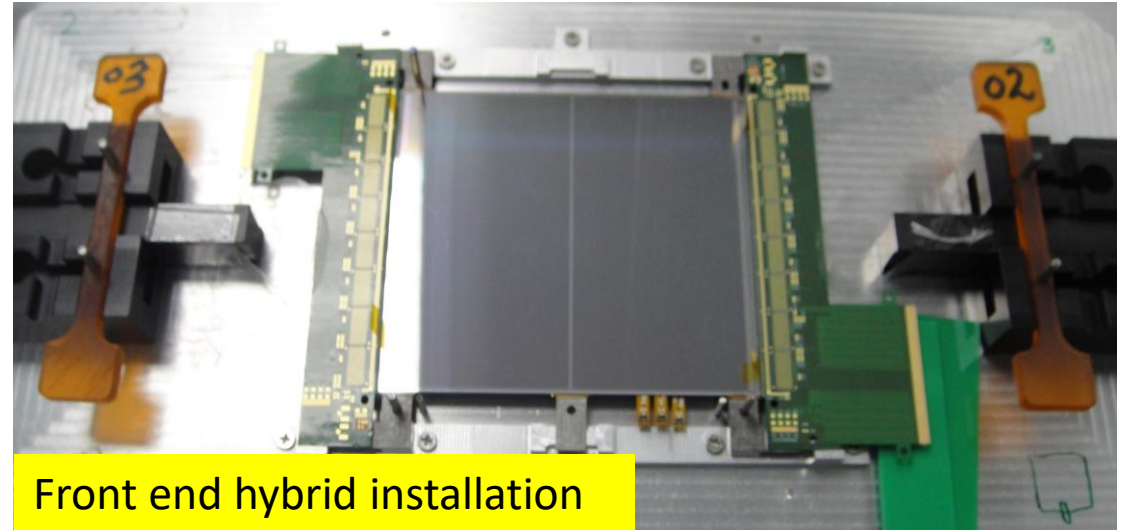
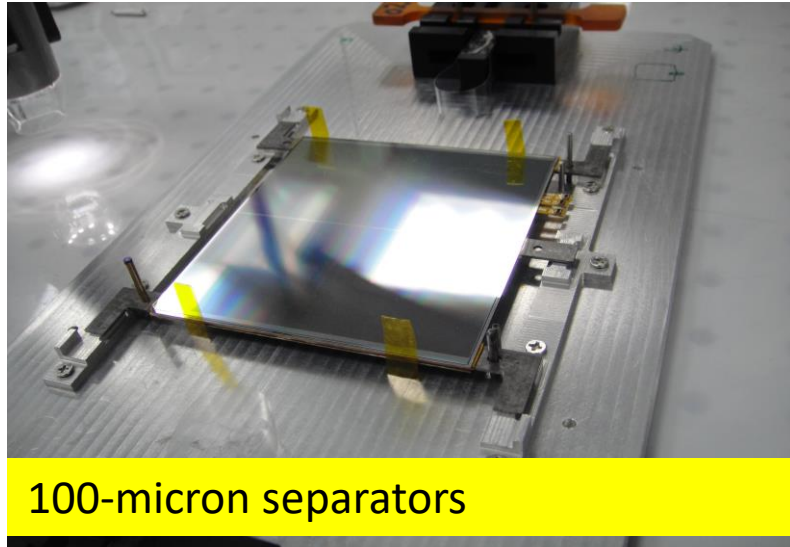
Sensors Sandwich Assembly



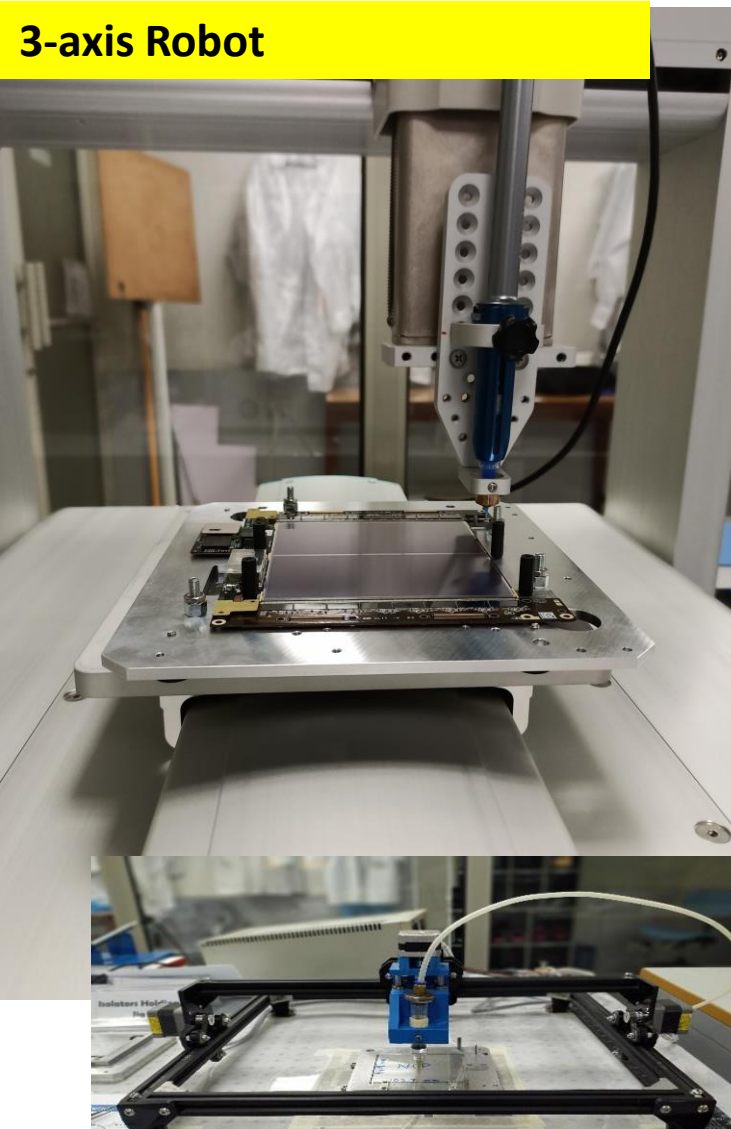
Glue curing for 24 hours



Dedicated Fixtures for Each Assembly Step



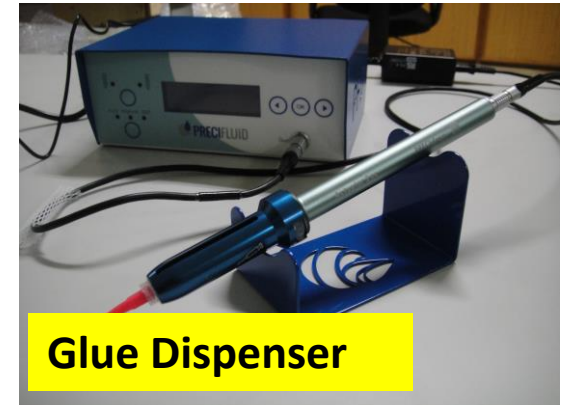
- Glue is mixed in vacuum with controlled speed (SmartMix X2)
- The glue dispenser can be programmed for speed and quantity for controlled dispensing of glues (Precifluid)
- 3-axis robot can be programmed to dispense the glue at desired location on the modules
- The glue is passed through an independent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



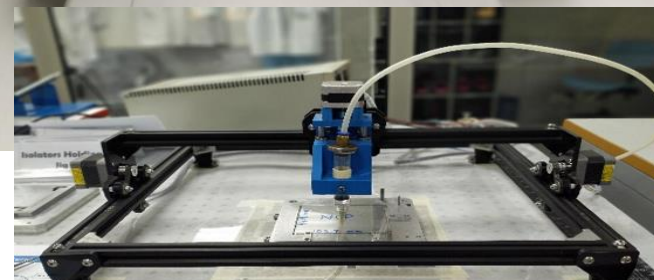
3-axis Robot



Glue Mixer



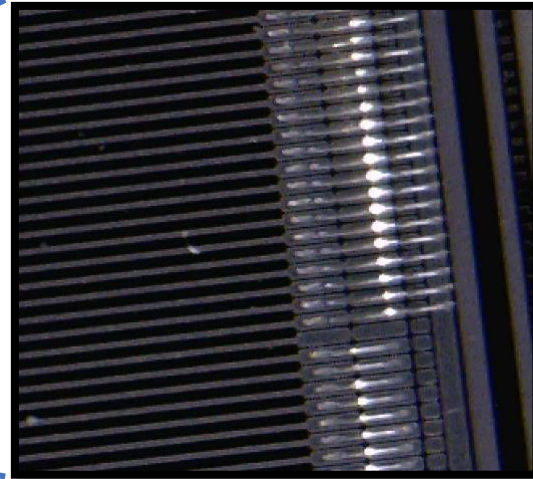
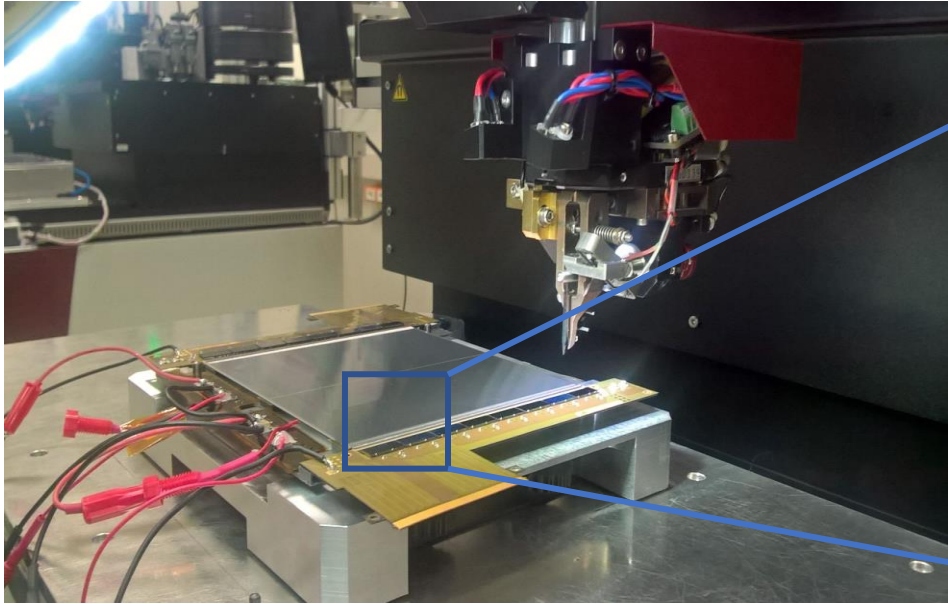
Glue Dispenser



Locally developed 3-axis Robot



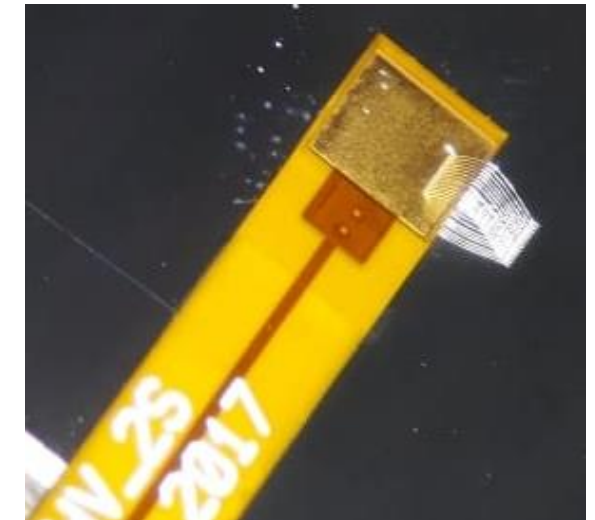
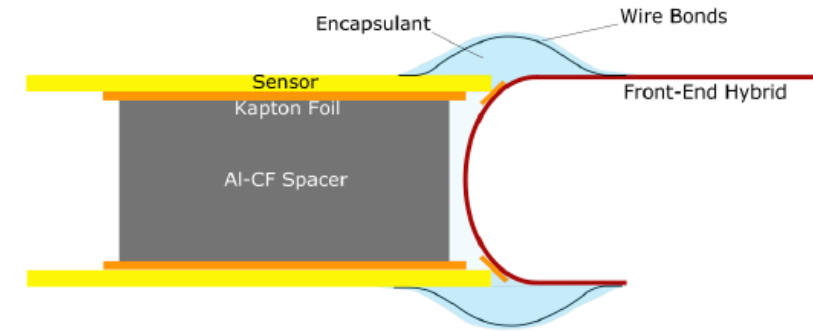
Vacuum chamber



Wire bonds on Silicon Sensor

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

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



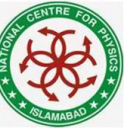
Wire bonds with height of **< 500 μm** is made between HV tail bond pad and sensor backside for biasing of the sensor



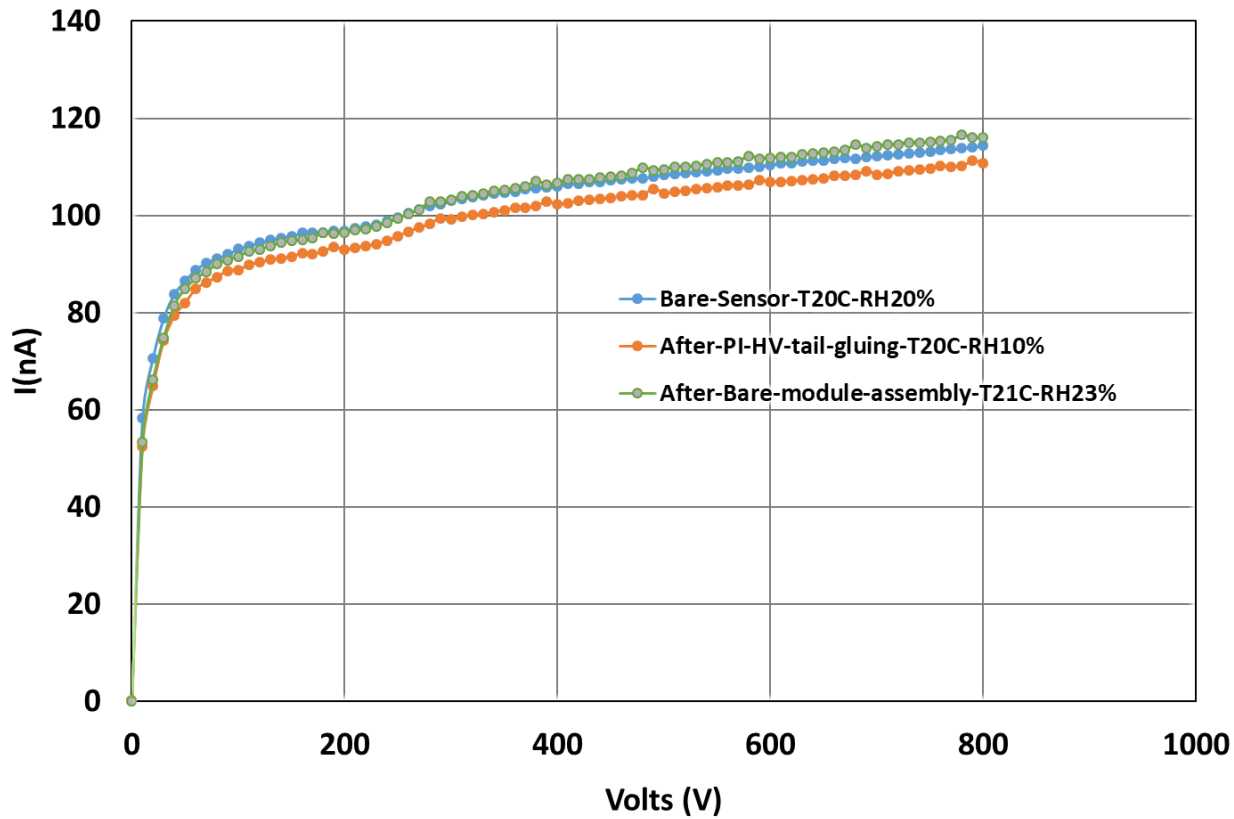
Sylgard 186 silicon elastomer is used to protect the wires



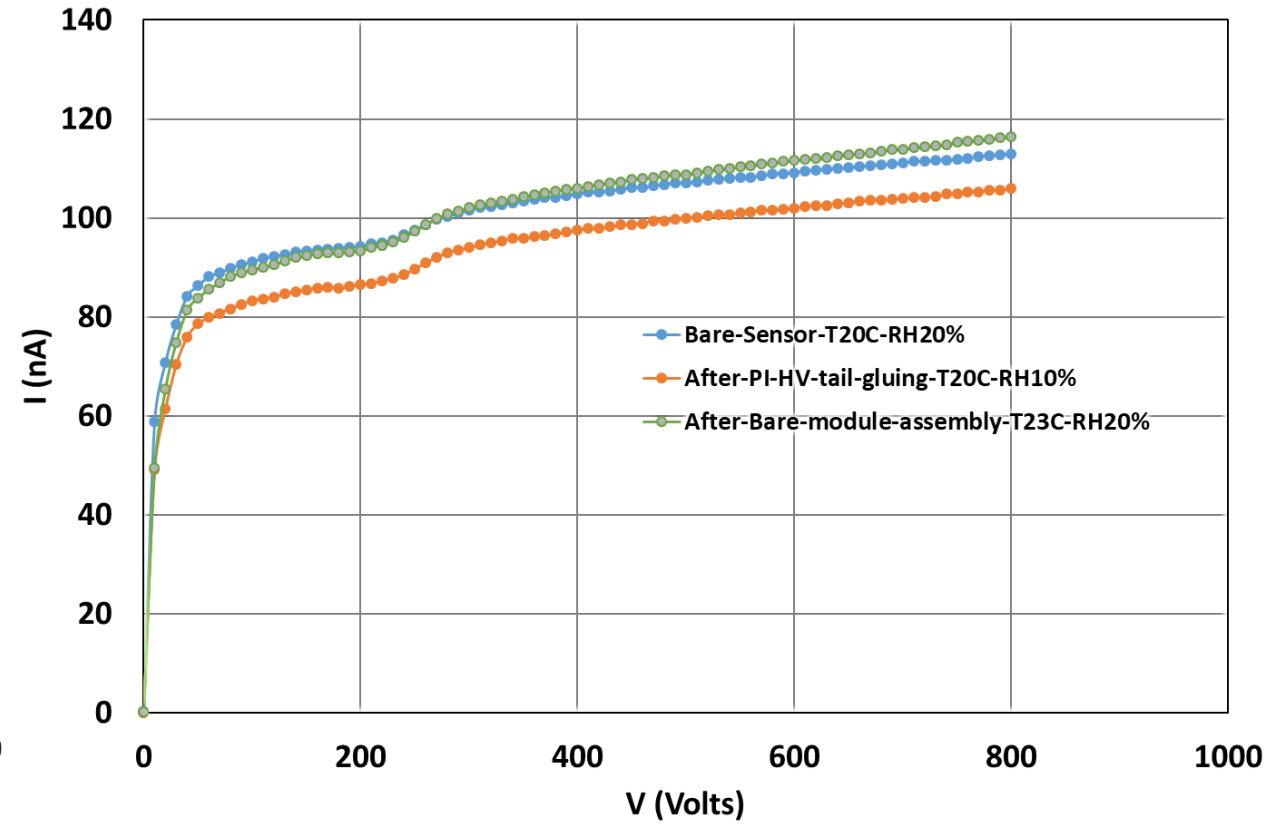
2S Module with 8CBC3 Assembly – IV Measurements



Bottom Sensor

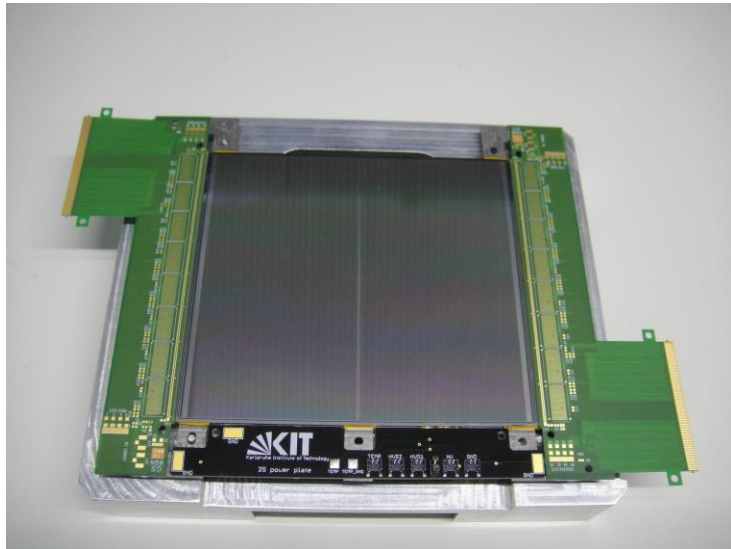


Top Sensor

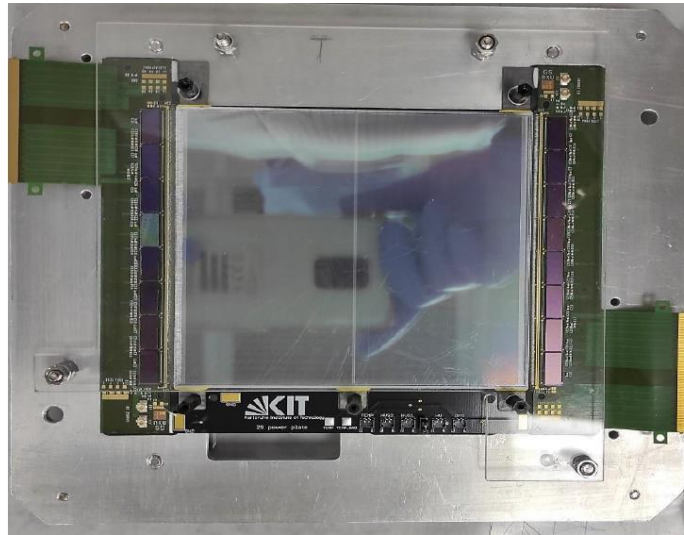




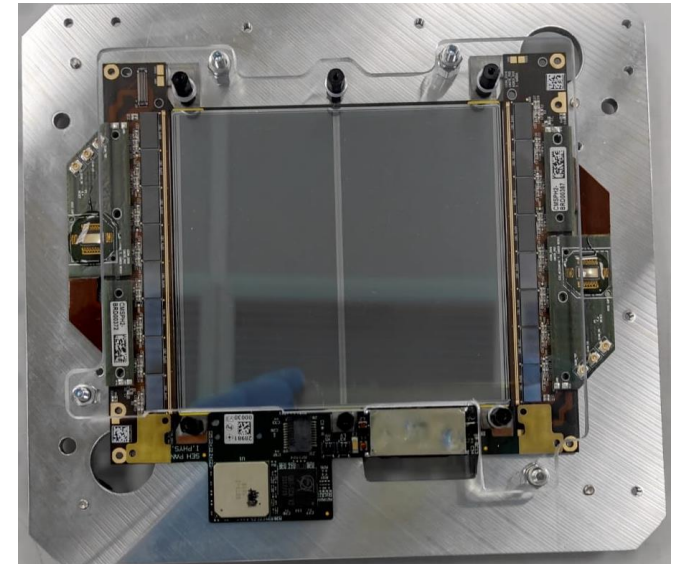
Tracker 2S Outer Tracker Module Assembled at NCP



**1st Silicon Dummy Module
Without CBC chips**



**2nd Silicon Functional Module
8CBC2 Front End Hybrids**



**3rd Silicon Functional Module
8CBC3 Front End Hybrids**

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

Thank You !