Task 2.5 Pre-industrialisation of large area silicon detectors

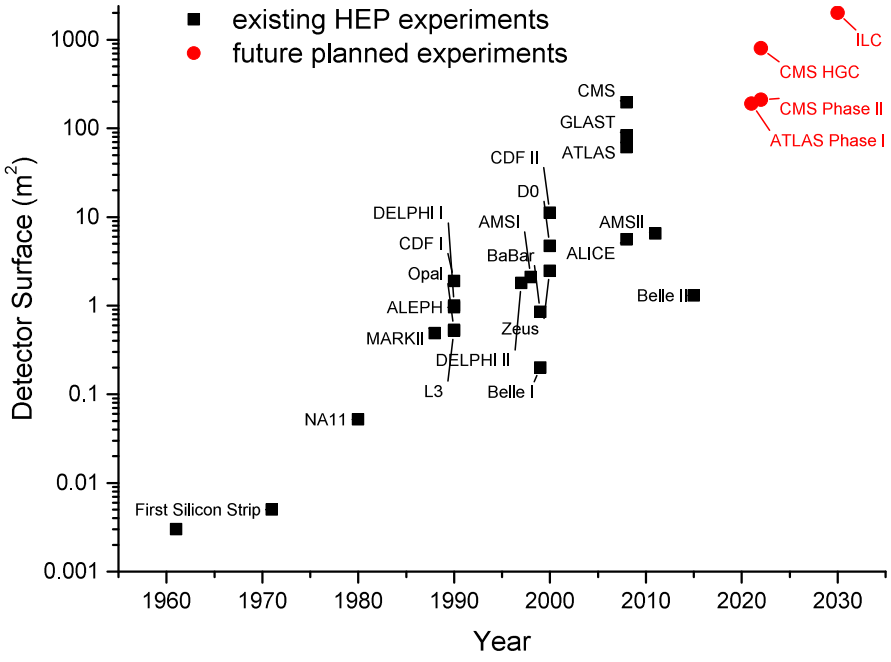
(OEAW, CNRS-LLR, KIT, UNILIV, UniFreiburg)

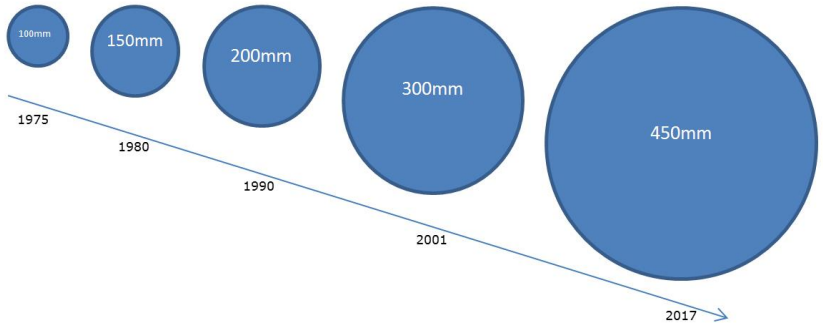
Thomas Bergauer

Demand on Sensors

- Silicon surface
  - Today: Up to 200 m^2 (CMS)
  - Similar size for the upgrades of CMS and ATLAS (~200 m^2 each)
  - Significant increase for CMS HGCal ~ 600 m^2
- Wafer Size
  - NA11 started with 2” and 3”
  - Today 6” (150 mm) is standard (used by LHC Experiments)

→ Introduced in the Industry in the 80ies!





Vendors known to the HEP community

- Small Scale Production (few 10-100 wafers per year)
  - Many institutes and companies
  - 6” available at many sites
  - Broad spectra of quality and price

SINTEF
VTT
MICRON SEMICONDUCTOR ltd
CANBERRA
MPG HLL Halbleiterlabor der Max-Planck-Gesellschaft
FONDAZIONE BRUNO KESSLER
CiS Forschungsinstitut für Mikrosensorik und Photovoltaik GmbH
CNM Centre Nacional de Microelectrònica IMB

- For large scale production (few 1.000 – 10.000 wafers per year)
  - Up to now only one producer
  - Japanese company

HAMAMATSU
PHOTON IS OUR BUSINESS

Dual Source Strategy

- To have (at least) a second option which can immediately take over in case of problems is in principle not a bad idea
  - Imagine: quality issues, bankruptcy, earthquakes,…

Common CMS/ATLAS Market survey for Tracker Sensors

Enabling factors:

- Strip sensors for ATLAS and CMS are very similar
- Different specifications are not so significant for the production

Advantages:

- Shows the combined demand of the largest projects of the coming years to interested companies
- We can share qualification work among the two collaborations
- BUT: A very large fraction of sensor production is not reflected in this MS: CMS High Granularity Calorimeter
  - Nevertheless, we are syncing these efforts between tracker and HGCal

CMS/ATLAS Market Survey Procedure

Each interested company has to successfully pass a three step qualification procedure to be eligible to receive the Invitation to Tender!

- **Step 1:** Companies need to return the *"Technical Questionnaire"* document where the responses need to fulfil the requirements set in the "*Qualification Criteria"* document **-> ADIA-2020 Milestone MS30 (2016)**

- **Step 2:** Companies need to provide samples free of charge of functional devices of e.g. previous project **-> reported here**
  - **ATLAS and CMS qualified samples developed by HEPHY-ÖAW as 8" proof-of-principle**

- **(Step 3:** CMS/ATLAS orders (and remunerates) a batch of prototype sensors according to CMS layout and specs)

Market Survey results

- ADIA-2020 Milestone MS30
- Eight companies replied to the market survey
  - **Some "usual suspects"**
  - **some jumped into business only recently**
- Existing collaborations with "new" companies:
  - Infineon (CMS, HEPHY)
  - Novati (CMS, US groups)
  - Lfoundry (CALICE)

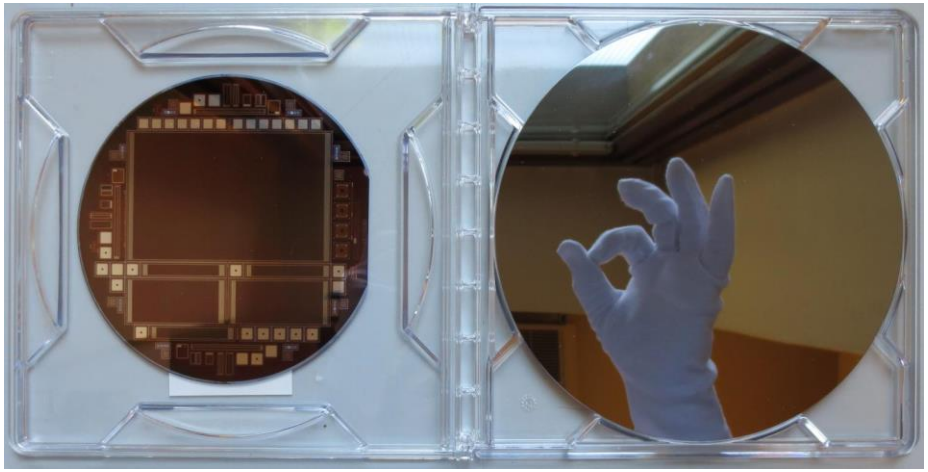
Company	Country	Wafer size	AC-Coupled strip sensors	DC-coupled PS-p sensors
Advacam (VTT)	Finland	6"/(8")		x
BEL	India	6"		x
CiS Erfurt	DE	4"	x	x
Hamamatsu	Japan	6"/(8")	x	x
Infineon	AT/DE	**8"**	x	x
Lfoundry	Italy	**8"**	x	x
Micron	UK	6"	x	x
Tezzaron/Novati	USA	**8"**	x	x

Demand according to Markey Survey:

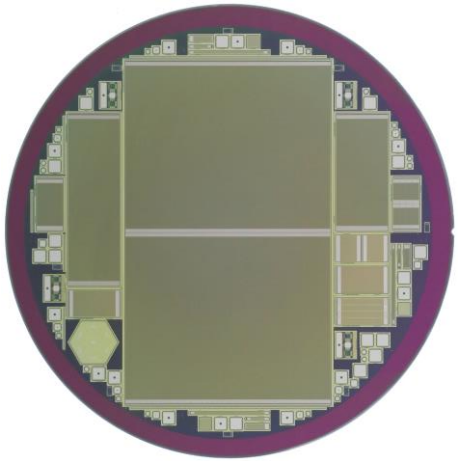
	AC-Coupled strip sensors	DC-coupled PS-p sensors
ATLAS	23'000 on 6"	
CMS	27'500 sensors ≈ 23'500 6" wafers	8'500 sensors ≈ 4'250 6" wafers

Focus on Infineon

- Although other companies also replied to market survey, we are concentrating to only one company here, since there is already a fruitful collaboration between them and HEPHY
- Infineon is an European Semiconductor company
  - Focus on power devices -> experience with fully depleted devices



6” p-on-n sensors (2012) → bare 8” wafer (2014)

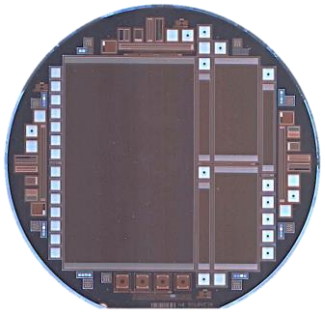


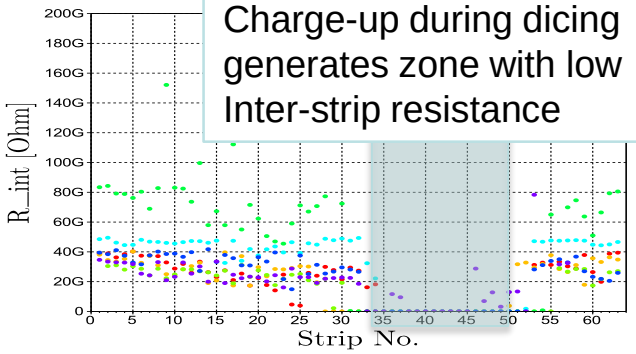
Fully processed
8” wafer (end 2015)

Collaboration HEPHY -- Infineon

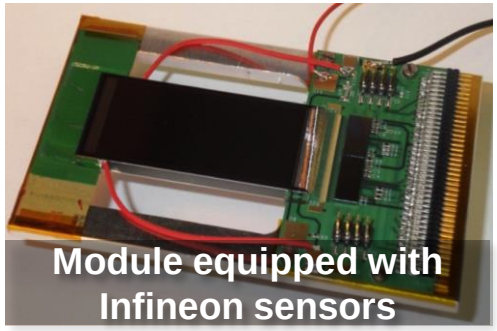
- **2009: Project started between HEPHY and IFX**
  by private contacts and a “semi-official” visit of HEPHY staff and students to Infineon Villach
- **2012: First production of 6” p-on-n sensors**
  - Goal: **re-produce the current CMS tracker sensors**
  - Several batches in 5 different runs with good quality, but some issues, eventually tracked down to charge-ups
- **Since 2014: Working on 8” n-in-p process for CMS tracker phase II upgrade**
  - First production finished in October 2015
  - Second batch currently under production with many improvements
- **Since 2015: Development of sensors for CMS High-granularity calorimeter**
  - ~15 wafers delivered with different thicknesses

6“ p-on-n Wafers:





Charge-up during dicing generates zone with low Inter-strip resistance



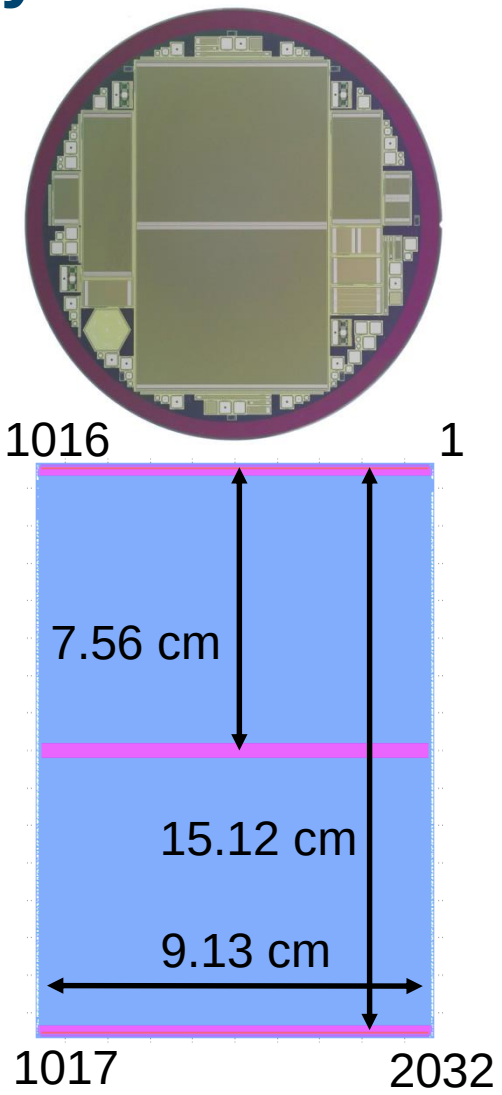
Module equipped with Infineon sensors

TRACKER SENSORS

”CMS” should read KIT and HEPHY-ÖAW
“ATLAS” should read “Freiburg” and “Uliverpool”

Specifications and Wafer Layout

- **Specifications**
  - High resistive float-zone p-type base material
  - Resistivity of 7 kΩ cm
  - 200 µm physical and active thickness
- **Wafer Layout**
  - Main sensor 2S long → elongated version of 2S for CMS
    - ≅ 10 cm x 15 cm, strip length ≅ 7.5 cm, w/p ≅ 0.25
    - 2032 strips segmented into two parts
  - 8 different baby sensors
    - Irradiations
    - P-stop geometry studies, etc.
  - Test structures
    - Diodes, MOS, GCD, dielectric breakdown, etc.
  - “HGC-shaped” test diode



Split Groups of 1st batch

- Infineon processed 25 wafers in total
- 23 delivered to HEPHY
- Four 2S long assembled to modules for beam tests
- One 2S long destroyed during handling

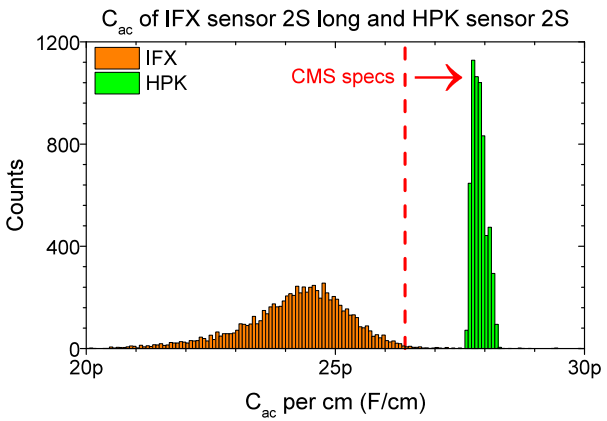
18 2S long sensors available for detailed testing

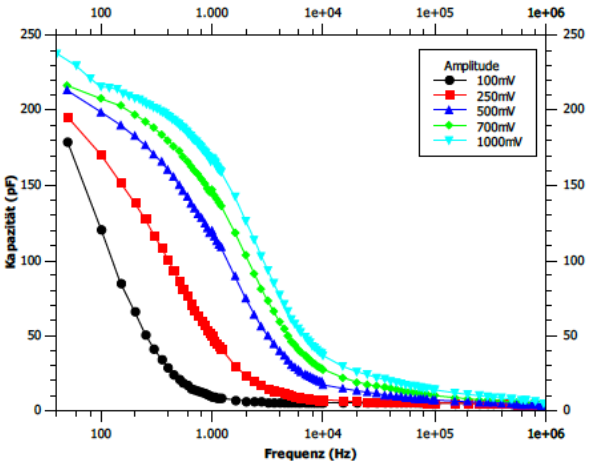
- **Split groups**
- 6 different realizations of Pstop
  - 3 different implantation doses
  - 2 different thermal budgets
- 2 different Pspray implantation doses
- 5 different R_{poly} implantations

PStop	01	02	03	04	05	06	07	08	09							16	17	18	19	20	21	22	23	24	25
PSpray										10	11	12	13	14	15										
PSpray A										10	11	12													
PSpray B													13	14	15										
Pstop early A	01	02	03																						
Pstop early B				04	05	06																			
Pstop early C							07	08	09																
Pstop late A																16	17	18							
Pstop late B																			19	20	21	22			
Pstop late C																							23	24	25
Rpoly A	01	02	03	04	05																				
Rpoly B						06	07	08	09																
Rpoly C										10	11	12	13	14	15										
Rpoly D																16	17	18	19	20					
Rpoly E																					21	22	23	24	25

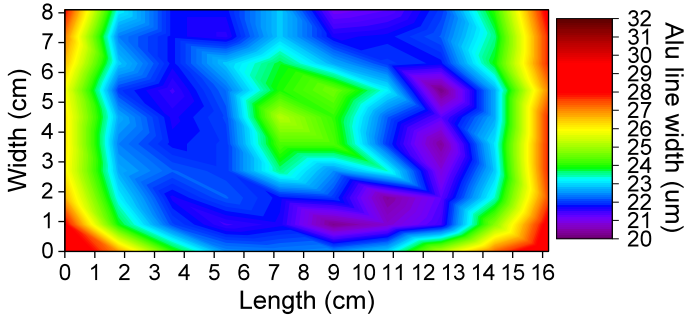
Coupling Capacitance Issues

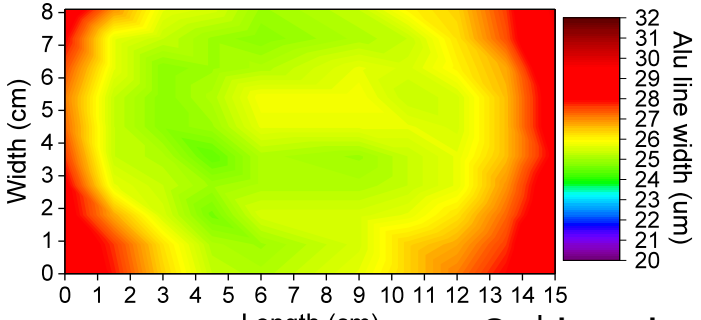
- The coupling capacitance of 2S long sensor shows a dependency on the **measuring frequency and amplitude** and **strip number**
- Tracked to Schottky contact (**too low strip implantation**) and **differences in metallization** in 1st batch





1st batch

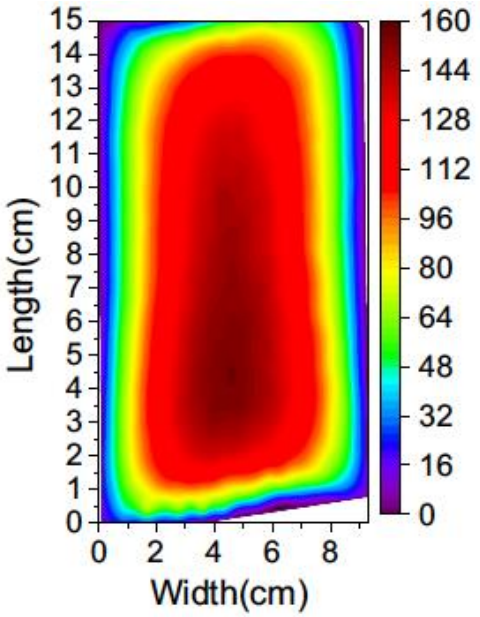


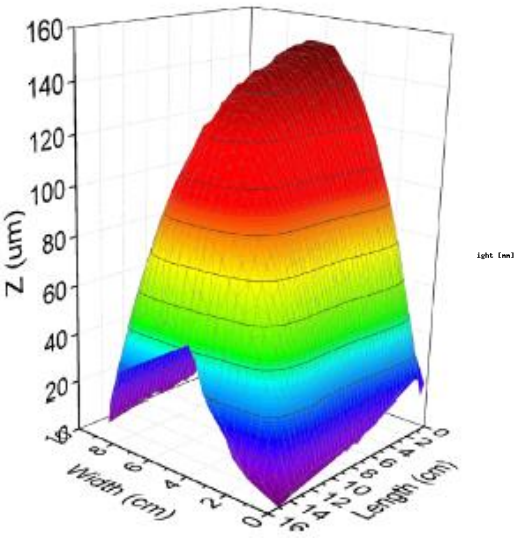


2nd batch

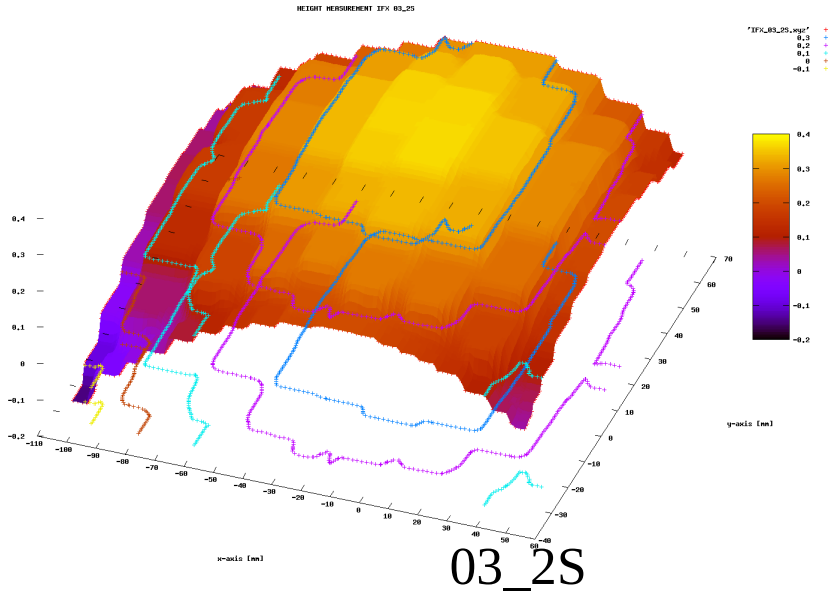
- Implantation significantly improved on 2nd batch
- Metal line thickness improved a bit

Sensor Bow





CMS 2S Sensors



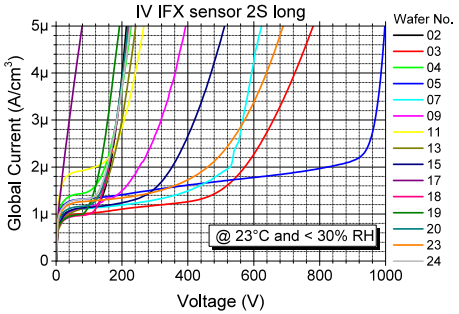
03_2S

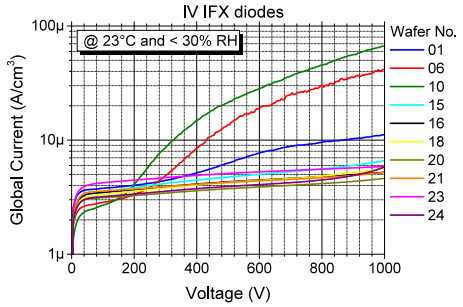
- Application of vacuum visibly flattens 2S sensor on the chuck
- CMS reports sensor bows of 160um and 80um
- ATLAS 03_2S seems to have bow about 400um…

HV Stability

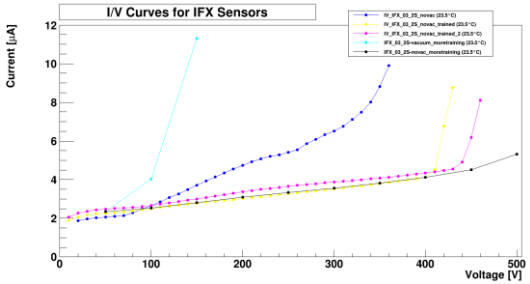
- CMS found more stable IV for smaller sensors rather the large 2S ones (15x10cm^2)
- ATLAS also saw vacuum dependence of current
  - "Training" allowed to achieve higher breakthrough voltages
- Both saw humidity dependence of breakthrough
- With feedback provided to IFX they are working on improvements

CMS 2S vs. Diodes

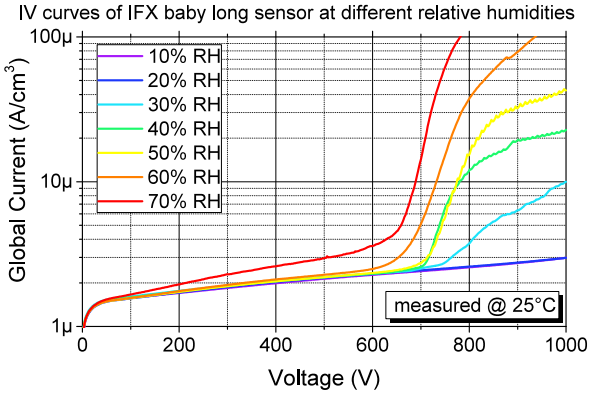




ATLAS "training"

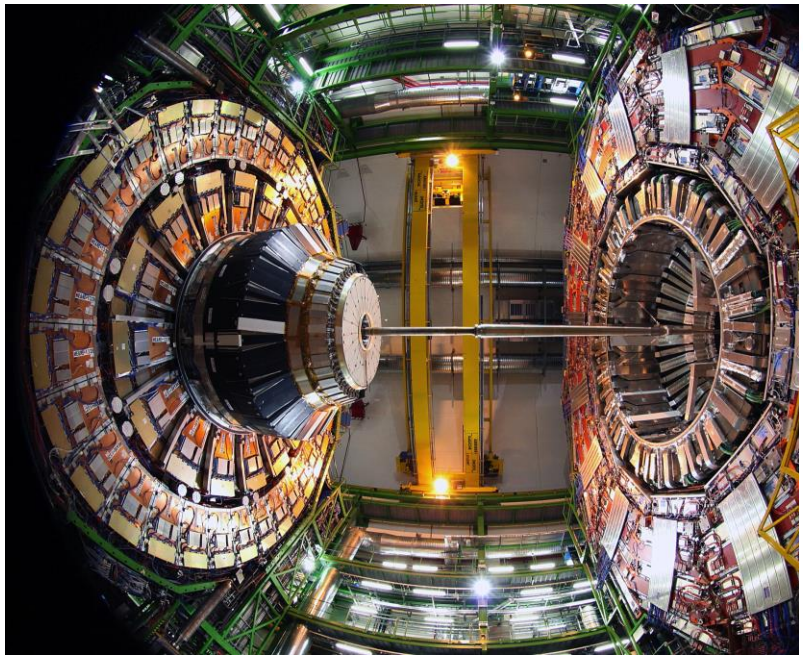


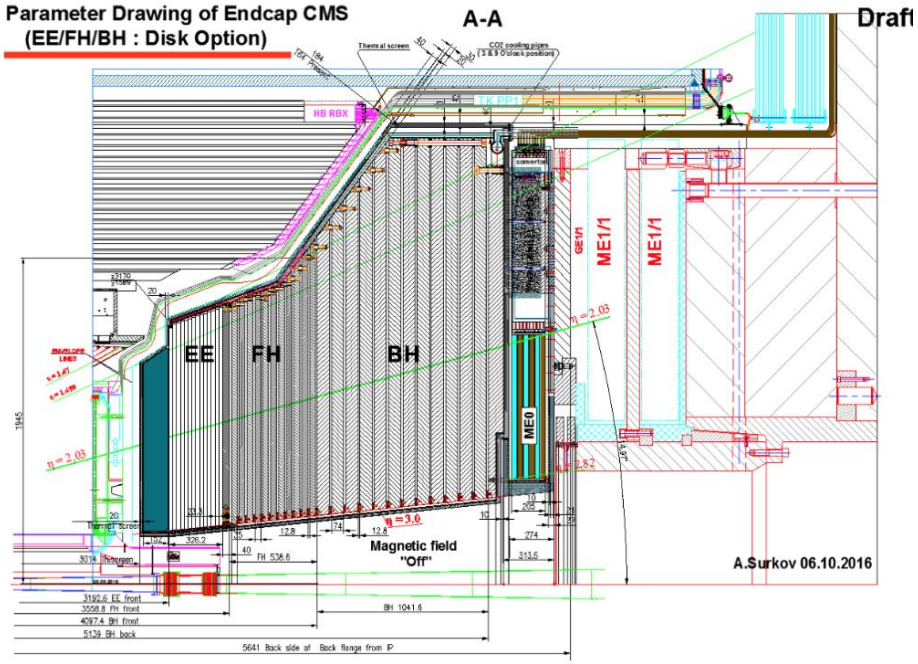
Humidity dependence



HGC SENSORS

CMS Phase II Endcap Calorimeter





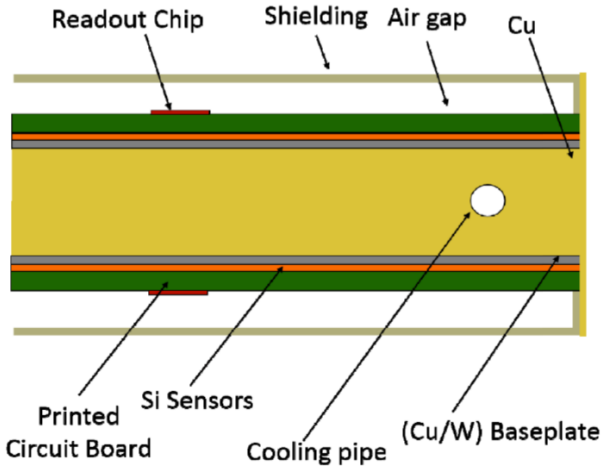
- Planned upgrade project to be installed during LS3 (2023-2025)

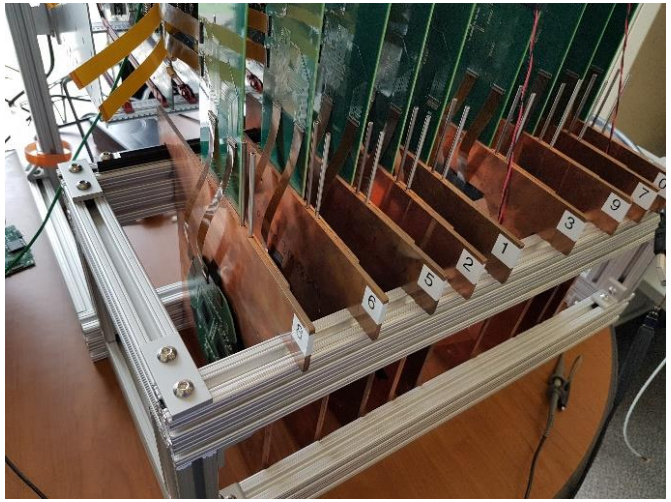
	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

Test Beam Setup

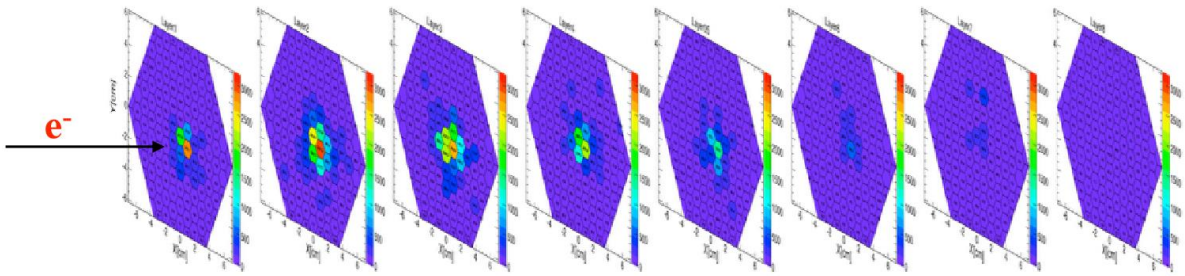
- Modules built using 6“ sensor from HPK and SKIROC readout chip
- Modules mounted on absorber plates
- used for Testbeam at FNAL (July 2016)

- HGC EE prototype up to 16 layers was successfully constructed and operated

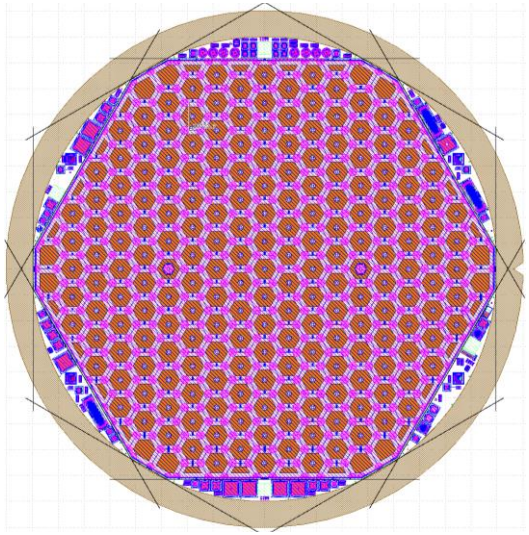


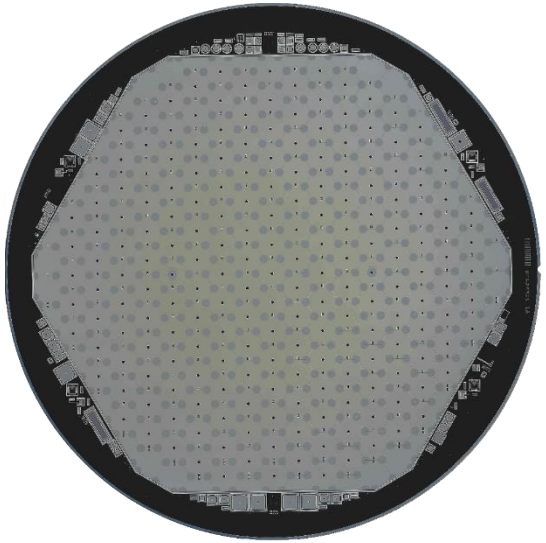


250 GeV Electron passing through the 8 layers

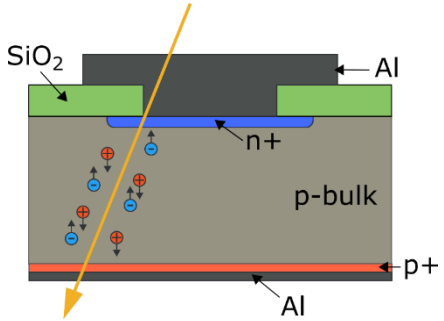


8-inch Infineon Prototype Wafer





Each cell: n-on-p **Diode**



- 8-inch n-on-p Wafer designed
- Wafer **production:**
- First 5 wafers of order **arrived** in November 2016
- Next 16 wafers of order arrived in February 2017

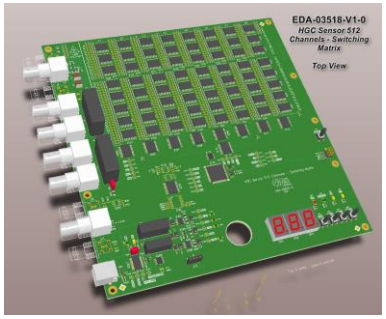
- Wafer Thickness: **200 µm**
- **235** cells (diodes)
- **~1 cm²** pad size
- **Hexagonal** structure to use the space on wafer more efficiently

- Large size of sensor (≈ 18 cm x 16,5 cm) no standard size, therefore new measurement setups need to be developed
- Size leads to additional difficulties in irradiations of full 8“ sensor

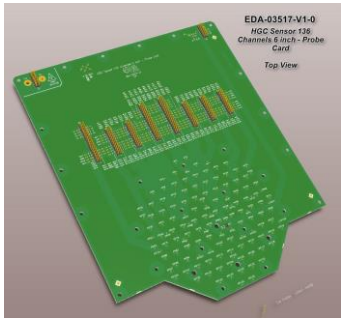
Measurement Challenges

- >200 individual diodes without any bias rail
- IV/CV curves not fully significant due to lateral extension of depletion zone

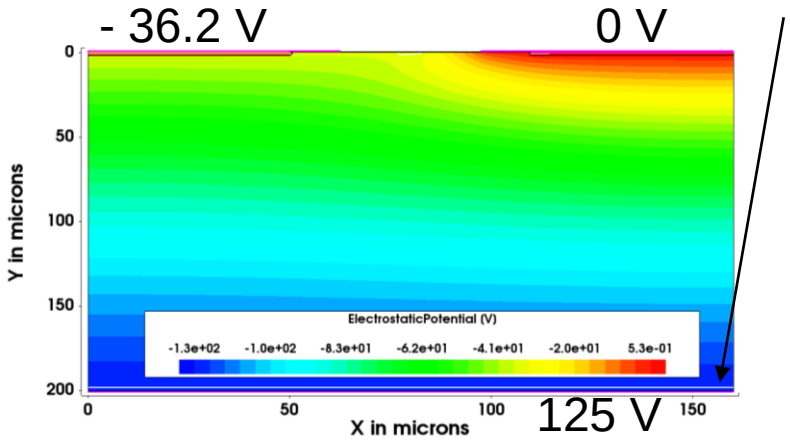
- Ways for characterization:
  - Single Needle (by motorized XYZ-table; preferred by Infineon)
  - 7-Needle-Probecard (HPK)
  - Full probe card (switching card developed by CERN)

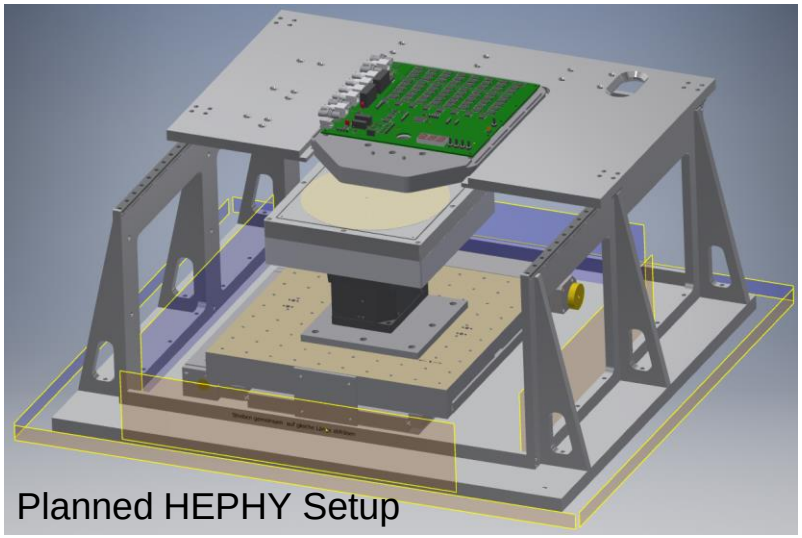


CERN switching card

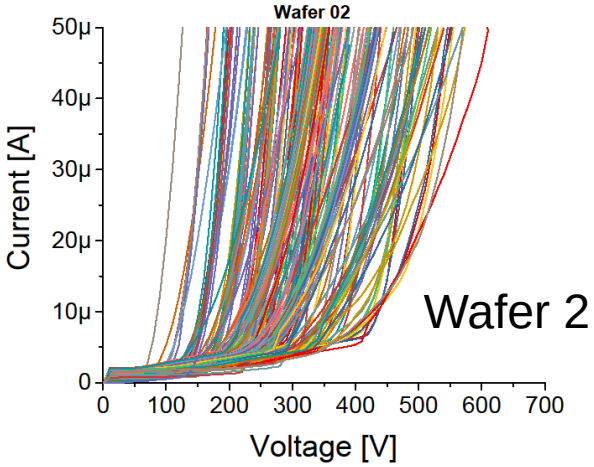


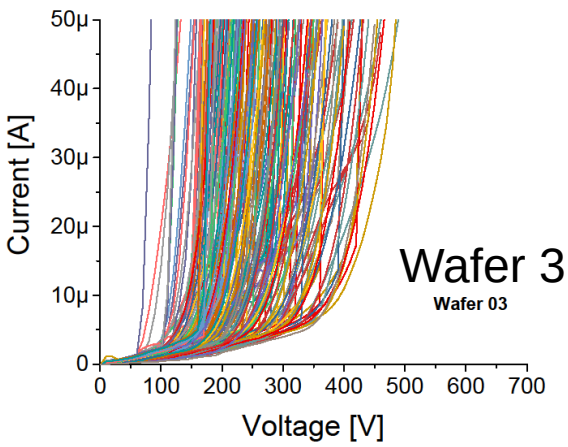
CERN 6” probe card

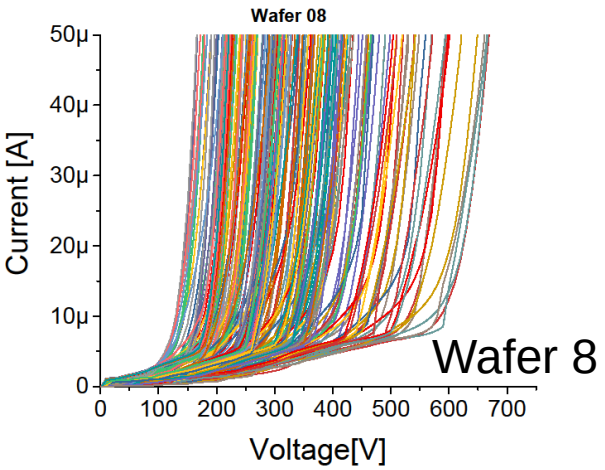



Planned HEPHY Setup

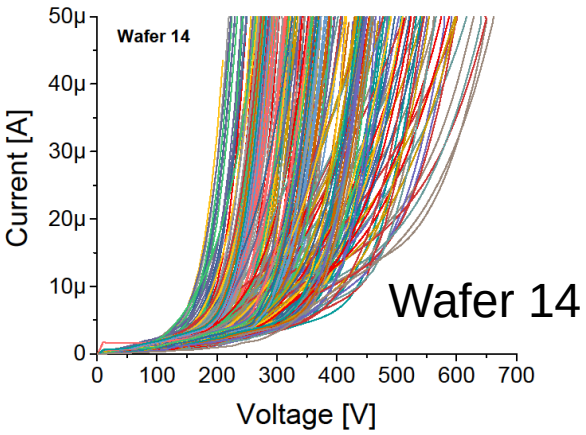
IV Curves of 200 µm thick IFX HGC Sensors

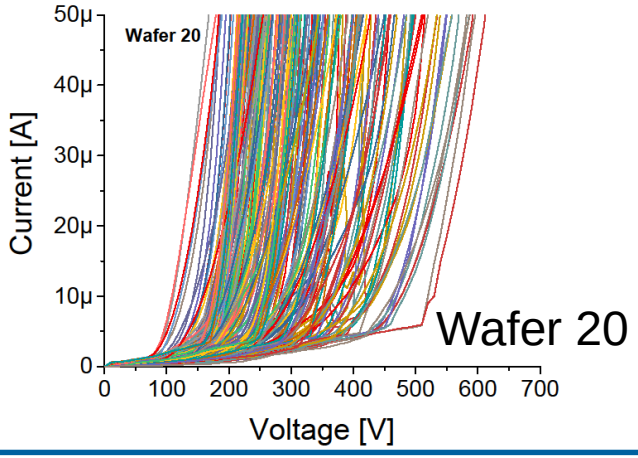




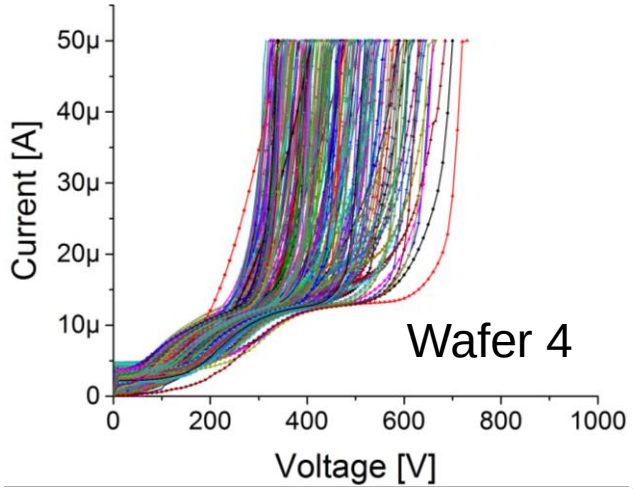


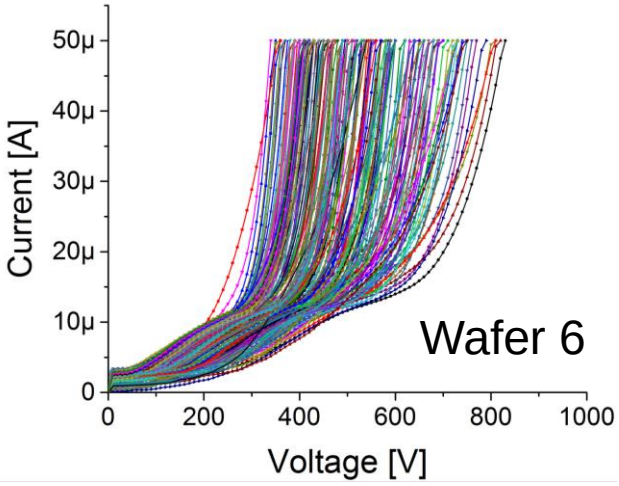
- Single Needle IV-Curves with HV on Needle
- Backplane on GND
- Temperature 22 +/-1 C
- Humidity 45-50%
- All IV-curves measured by hand at the moment
  - ~8 hours per wafer

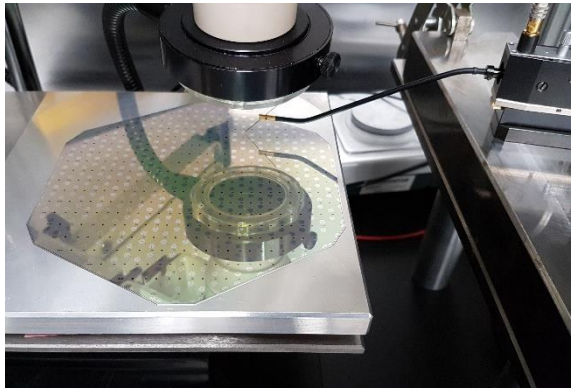




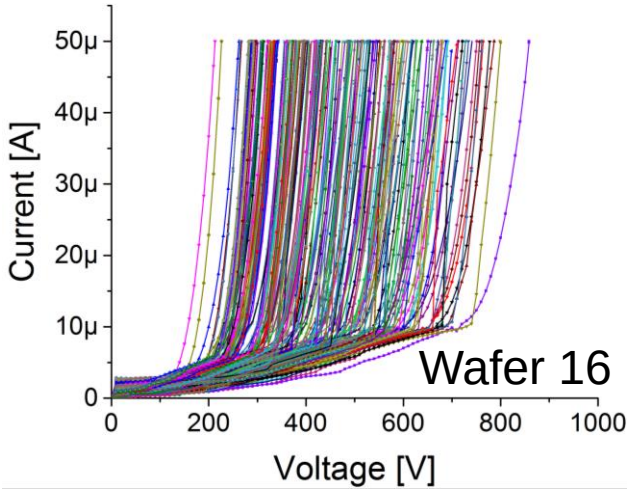
IV Curves of 300 (350) µm thick IFX HGC Sensors

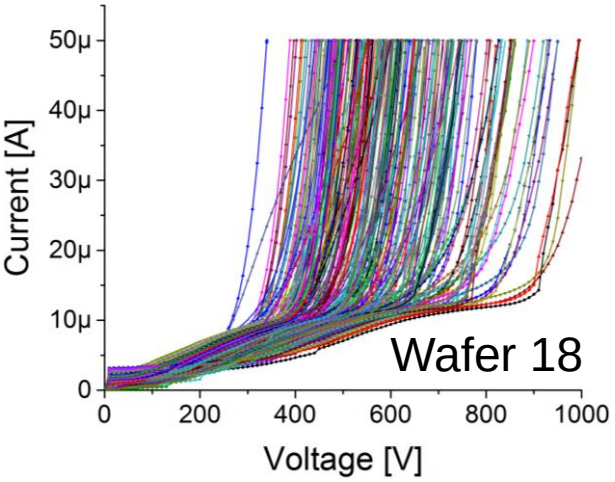


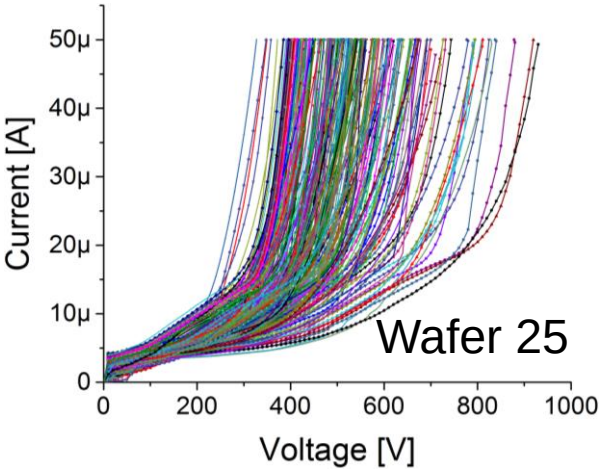




T= (23 ± 2)° H: 45-50%

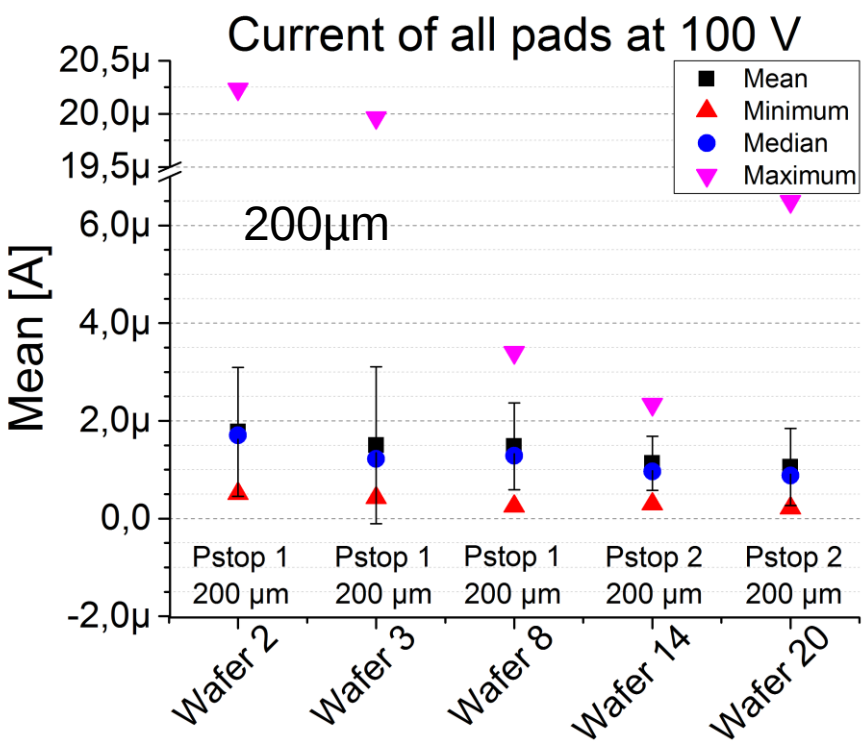


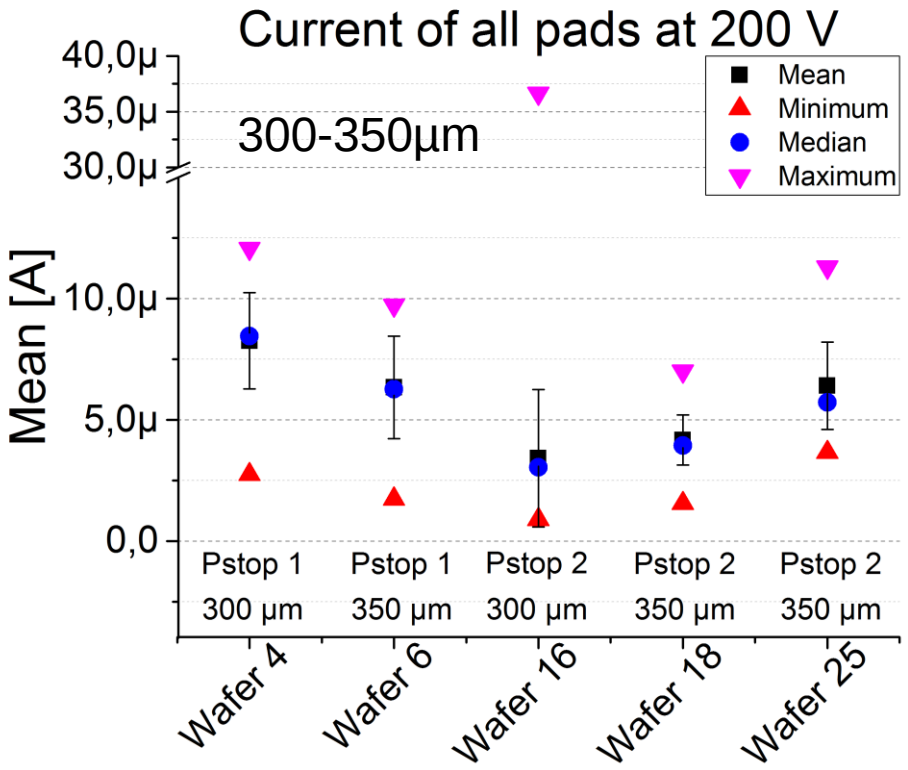




Current Statistics for Single Needle Measurements

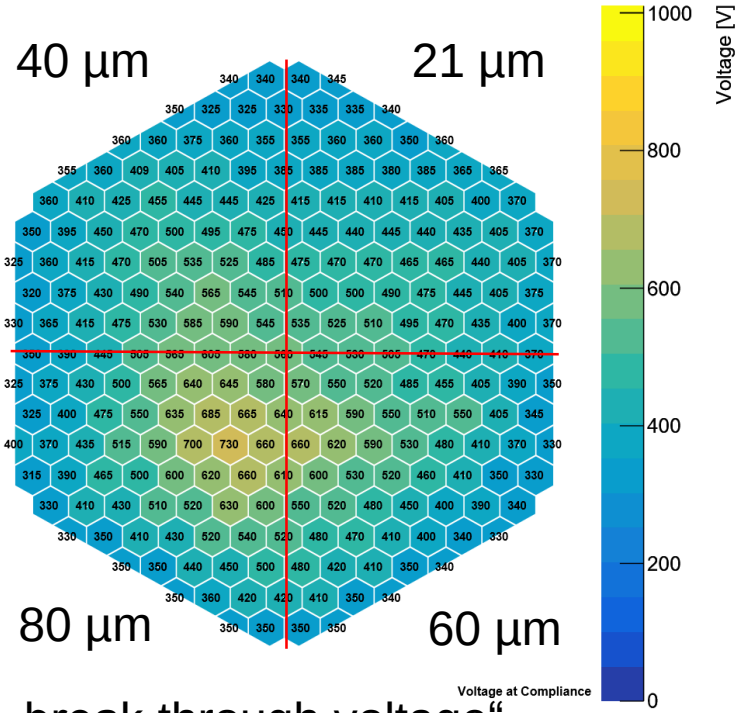
- Plots show the presence of a defect cell on a wafer (high maximum)
- Mean/Median shows that implantation dose “p-stop 2” gives lower currents





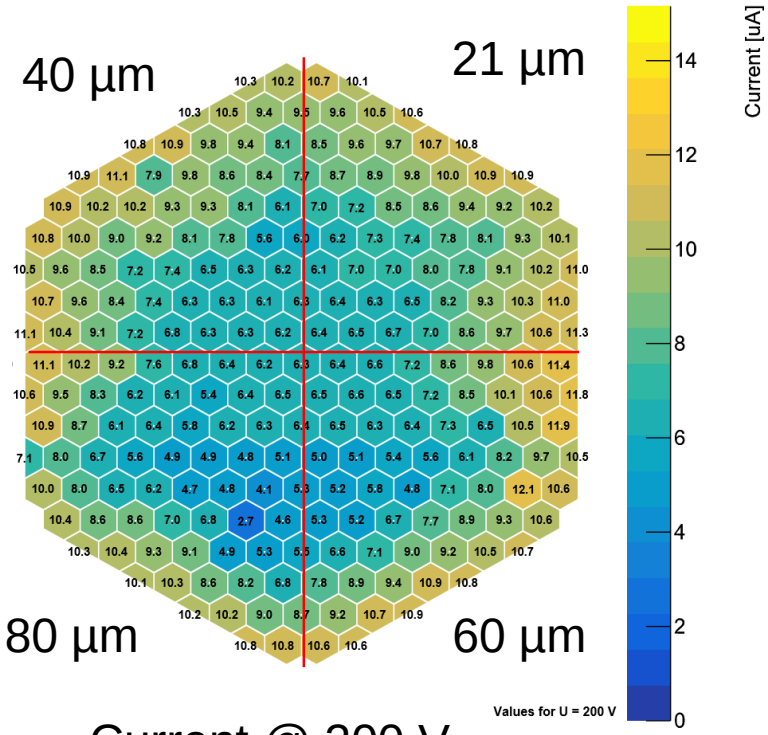
Single Needle IV mapped to geometry

- IV curves mapped to 8“ 256 pad HGC sensor geometry
- 4 Quadrants with different pad spacing can be seen in voltage and current behavior



„break through voltage“
(50 µA compliance)

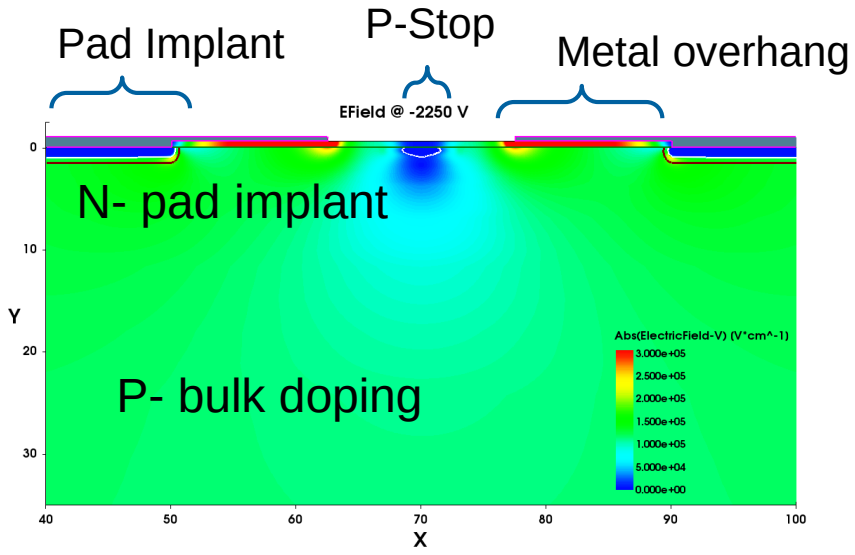
Pads on outside draw ~ 2 times the current

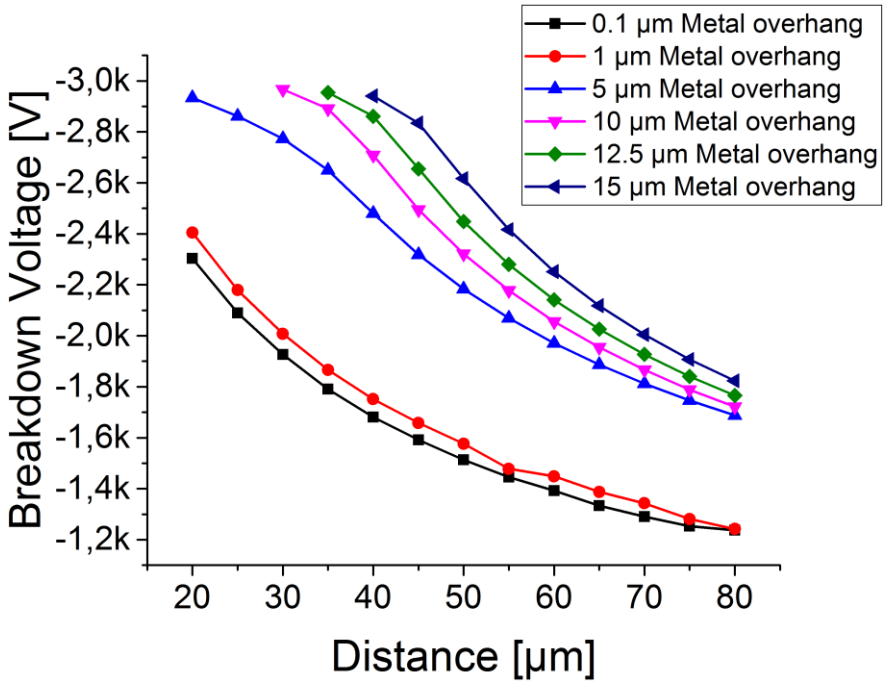


Current @ 200 V

2D Breakdown Simulation

- **TCAD Sentaurus Synopsys**: Finite element semiconductor simulation package (1D,2D,3D)
- 2 Pad Geometry (2D)
- Mesh: ~ $1.8 * 10^5$ elements
- Both Pads grounded





- Larger pad to pad distance leads to lower breakdown voltage
- In contradiction to single needle measurements

Metal Overhang at 21µm pad distance

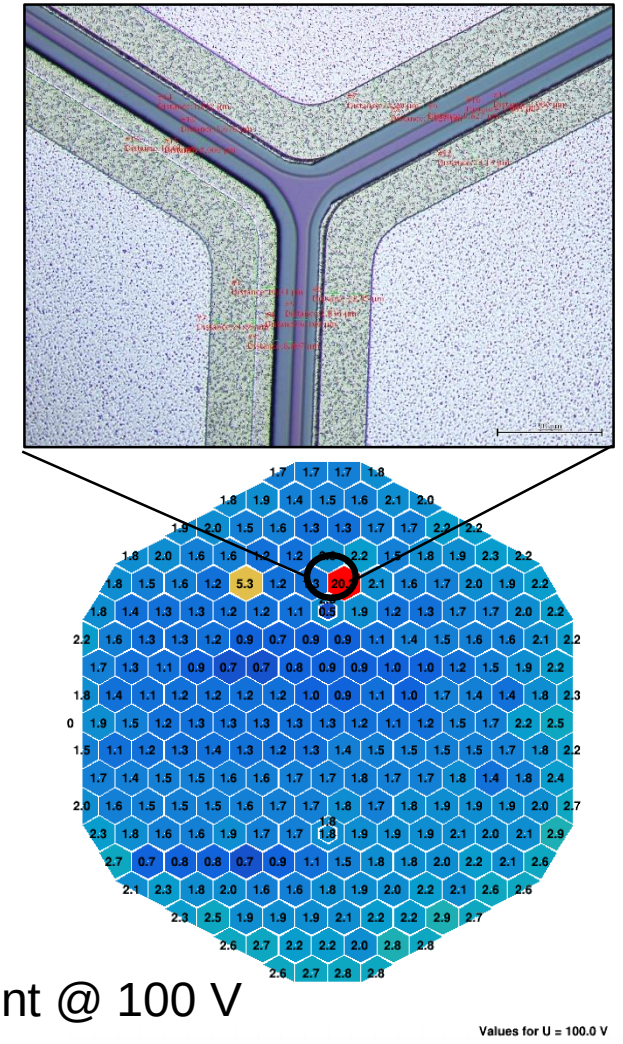
- Sensor design contains four regions with different pad distances 21/40/60/80µm

Region with 21µm pad distance:

- Metal overhang design value 5 µm
- Metal overhang here < 1µm
- High current of cell

Issue caused by process:

- Metal deposition after backside thinning, thus small sag during photolithography and metal etching causing inhomogeneous metal etching
- -> Infineon is working on improvement



Current @ 100 V

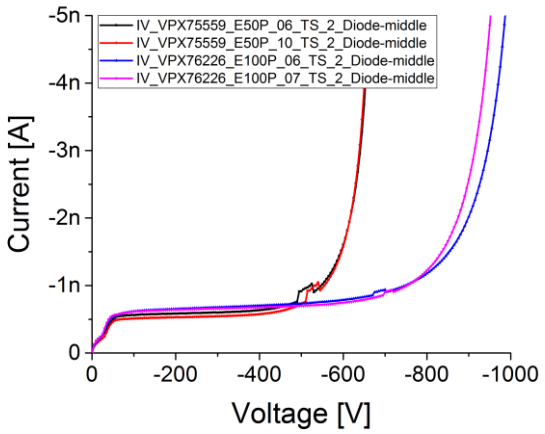
100-140µm thick sensors

- Infineon produced 8” sensors with both, physical and active thickness of 140µm
  - Unclear if mechanical stability of such thin sensors is feasible
  - No decision if IFX will offer 140µm for the series production
- We are working on two alternative approaches with Infineon:
  - Epitaxial sensors (currently only n-type bulk available)
  - New process with alternative backside processing (improves quality on all thicknesses, especially on metal overhang)

Old epitaxial HPK sensors for comparison:

Planar diodes with Epi thickness of

- 50 µm
- 70 µm
- 100 µm



Summary

- Monopoly situation in planar large-area silicon detectors exists
- CMS and ATLAS performed a market survey to find interested companies for providing sensors for the trackers of both experiments (~200m^2 each)
  - CMS HGCal adds another 600m^2
  - All with the same timescale (Phase II Upgrade 2023-2025)
- European vendor Infineon interested in large-volume productions, e.g.:
  - Prototype sensors for CMS tracker and HGCal produced
  - ATLAS evaluated sensors as Step 2 of market survey
  - Constant improvement visible from batch to batch
- Challenges Academia – Industry
  - Project started on technical side without involvement of business/legal departments
  - This changed now as project became more mature
  - Now also administrative / legal / IP discussion for prototype orders via CERN