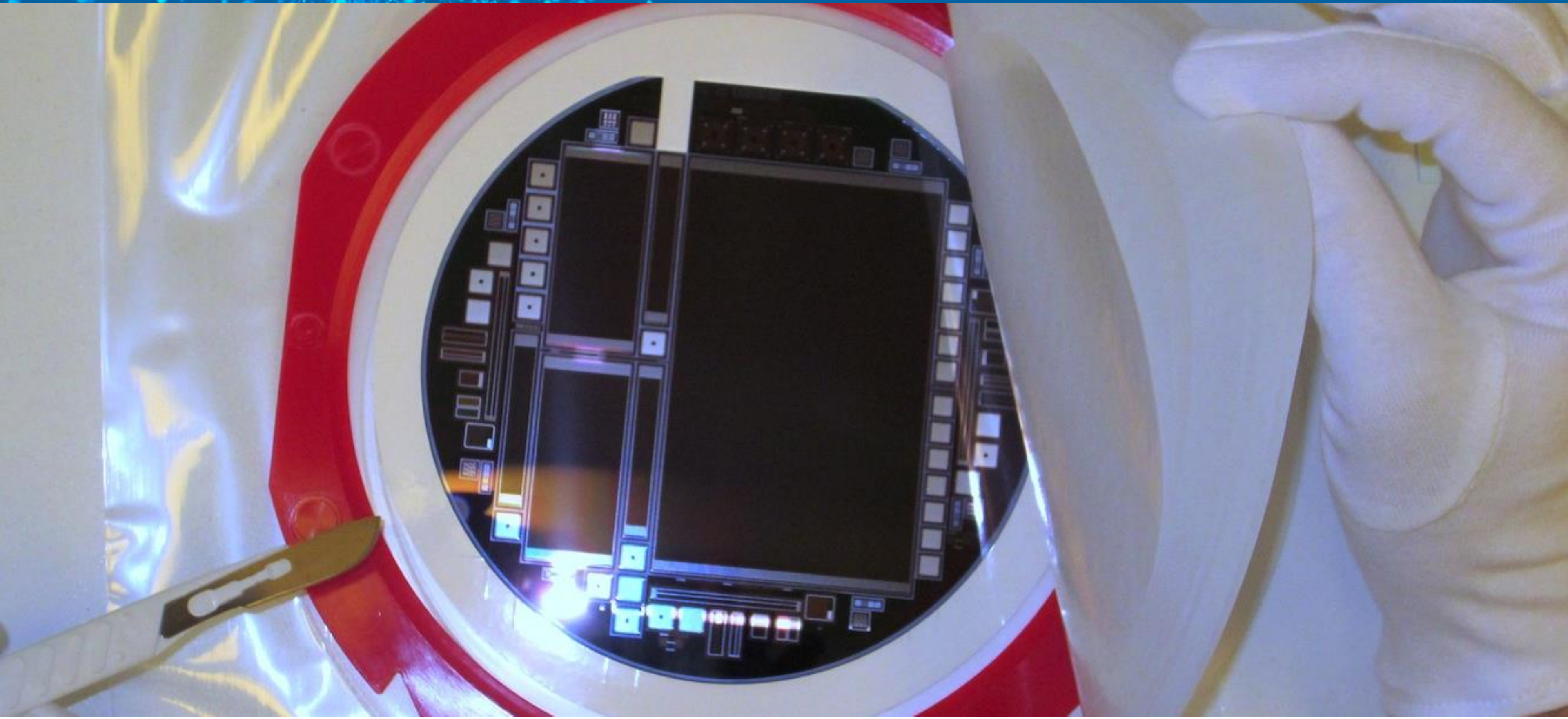


Industrial production of silicon strip sensors with Infineon

Thomas Bergauer (HEPHY Vienna)

TREDI2015

17 February 2015

Outline

- Motivation
- Overview about the project
- **Results from the Electrical Characterization with new results**
- **Beam Test results**
- Outlook
- Summary

Motivation

- Silicon detectors are an impressive success in HEP experiments

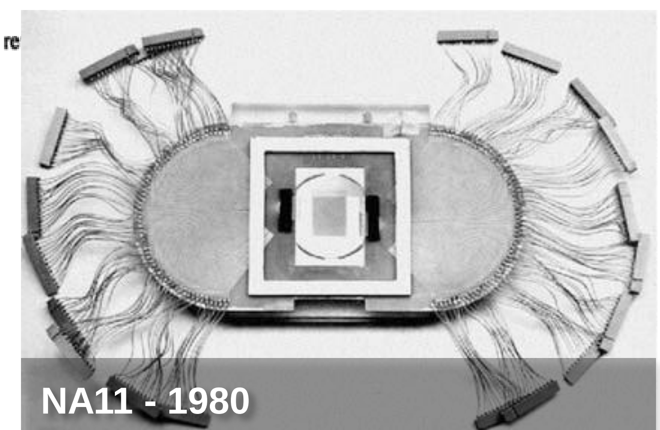
NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 499-502,

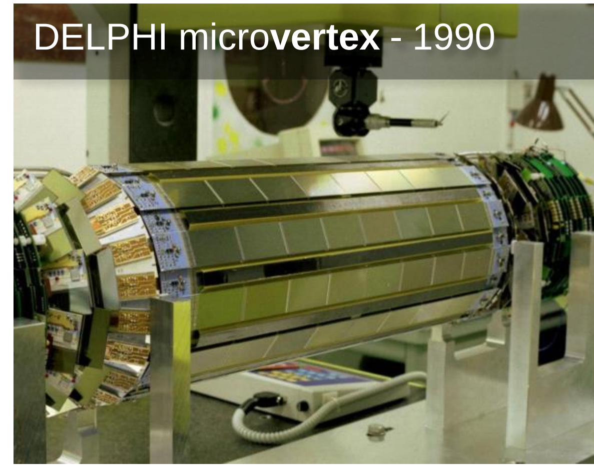
FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

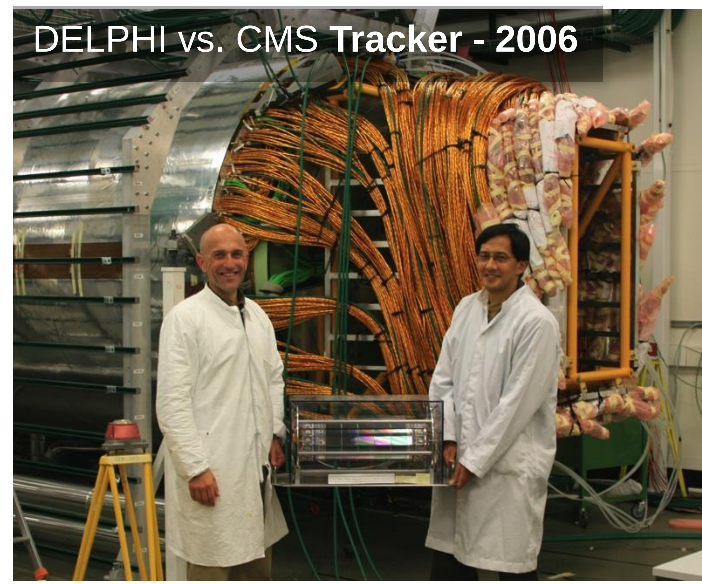
J KEMMER

Fachbereich Physik der Technischen Universitat Munchen, 8046 Garching, Germany

Received 30 July 1979 and in re

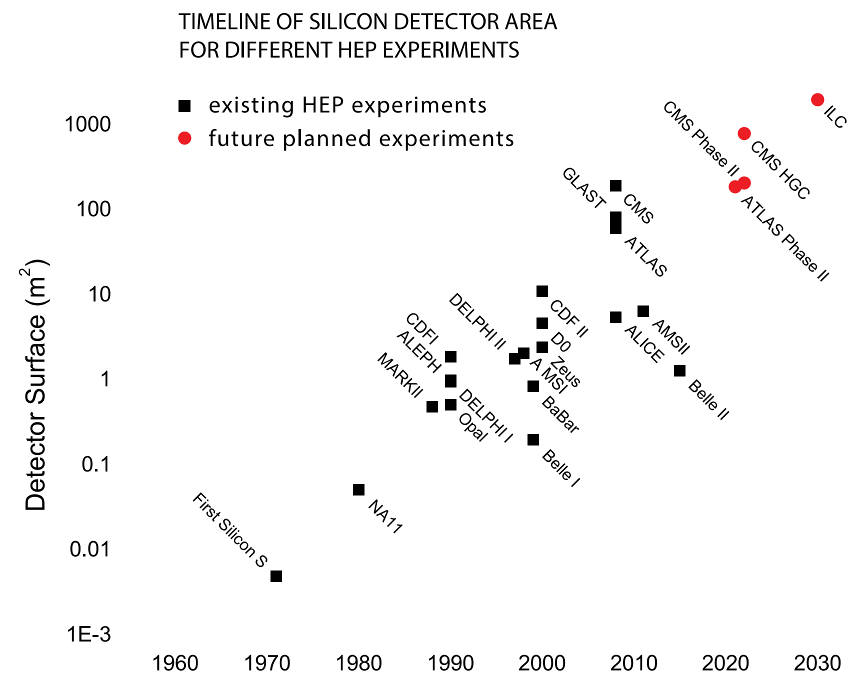

NA11 - 1980


DELPHI micro**vertex** - 1990

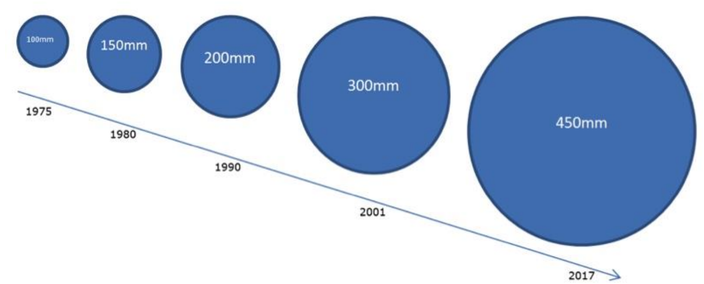

DELPHI vs. CMS **Tracker - 2006**

What has changed since the 80ies

- Silicon surface
  - Today: Up to 200 m² (CMS)
  - Similar size for the phase II upgrades of CMS and ATLAS
  - almost 800 m² for CMS high granularity calorimeter
  - CALICE Si-W-Calo: 2000 m²



- Wafer Size
  - NA11 started with 2" and 3"
  - Today 6" (150 mm) is standard
  - → **Introduced in the Industry in the 80ies!**

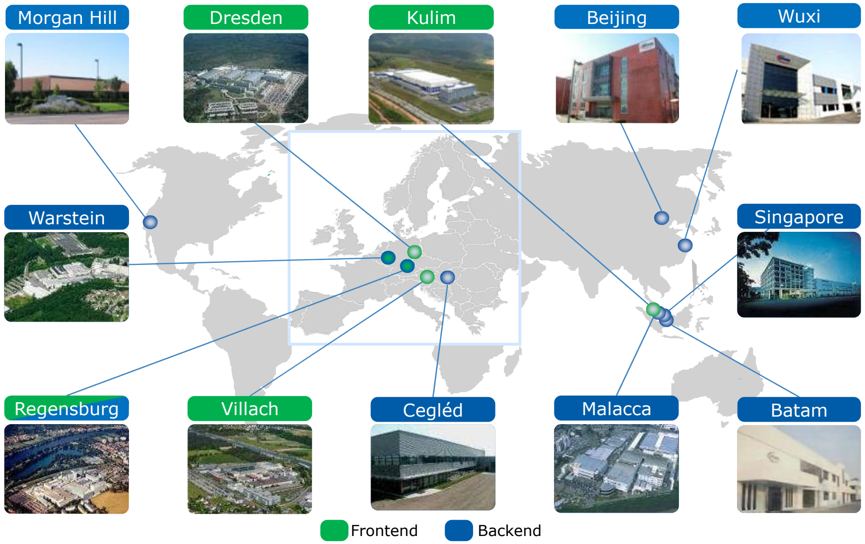


Silicon Producers worldwide

- Small Scale Production (few 10-100 wafers per year)
  - Many institutes and companies
  - 6” available at many sites
  - Broad spectra of quality and price
- For large scale production (few 1.000 – 10.000 wafers per year)
  - Currently only one (high quality) producer
  - Dual or multi-source strategy would be preferable
- Possible new producer: Infineon
  - Wafer Output (Villach): 50.000 per week
  - Production up to 12” wafers could be possible

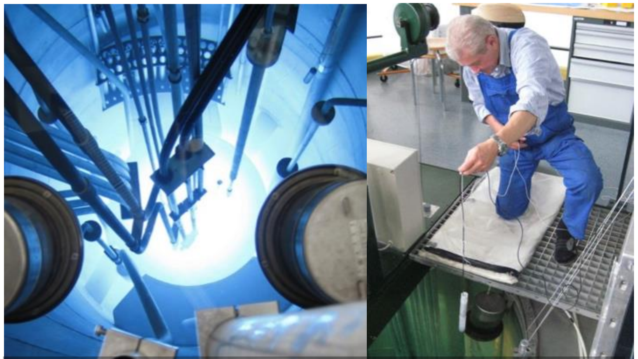
Company profile Infineon

- Infineon is one of the major players in the semiconductor business
  - 29,000 employees worldwide
- Main target markets
  - Automotive, Power, Chip Card
- Villach (Austria): R&D and "frontend" production
  - 3,300 employees (1200 in R&D)
  - Production in clean room of class 1 with 10,000 m^2 area



Timeline of the project

- April 2009: delegation from HEPHY visited Infineon Villach and discussed joint development
- October 2011-February 2012: **First batch** production
- October 2012: Beam tests and Irradiation
  - Beam tests at SPS, Gamma Irradiation at SCK-CEN Mol, Belgium
- Nov 2012-Feb 2013: Production of a **second batch**
  - July 2013: Neutron irrad at ATI Vienna and proton irrad at KIT
- August 2013-January 2014: **batch 3**
  - Jan 2014: beam test at DESY
- April 2014-Oct. 2014: **batch 4**
  - Nov 2014: beam test at SPS
- In parallel since 2013: Discussion about 8” Production



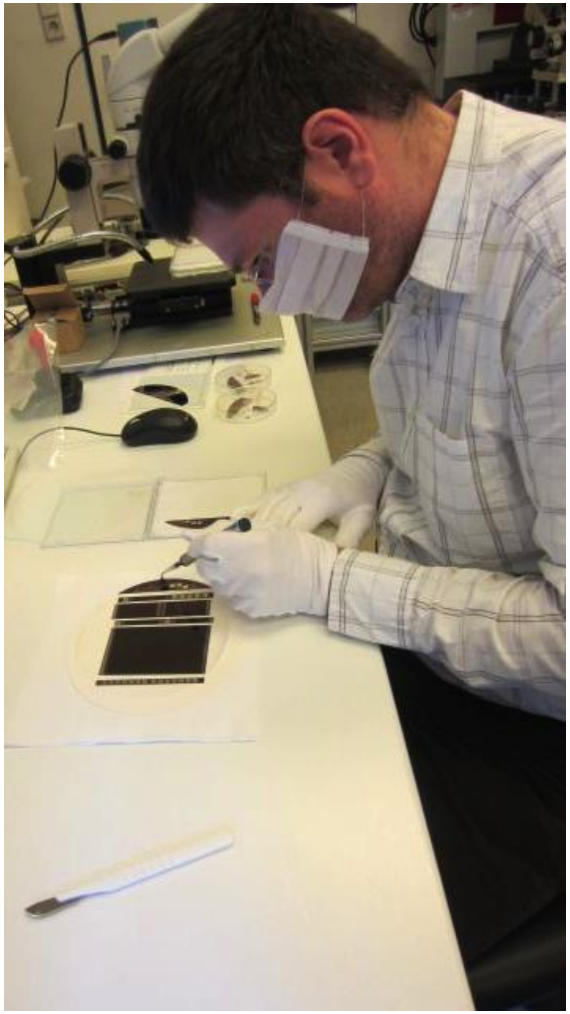
TRIGA Mark II @ ATI Vienna

Beam Test @ DESY Jan 2014

Comments on the Collaboration

- Since the beginning of 2010 we held **weekly video meetings**
- We are discussing all technical details **directly with the engineers** in an bottom-up approach
- Attribution of resources to the project was (and is still) low, but **steadily increasing** *(at HEPHY and Infineon)*
- The design of the masks was entirely **made by us**
- The production was **accompanied by two diploma students**
- We received **every wafer from the production** batch **→ no hidden losses**

Baseline for the production up to now



Goal: re-produce the same sensors CMS tracker is using now

Wafer Material

- 6 inch diameter, 300 micron thickness
- Float-zone n-type substrate,
  ~1.2 kOhm cm resistivity

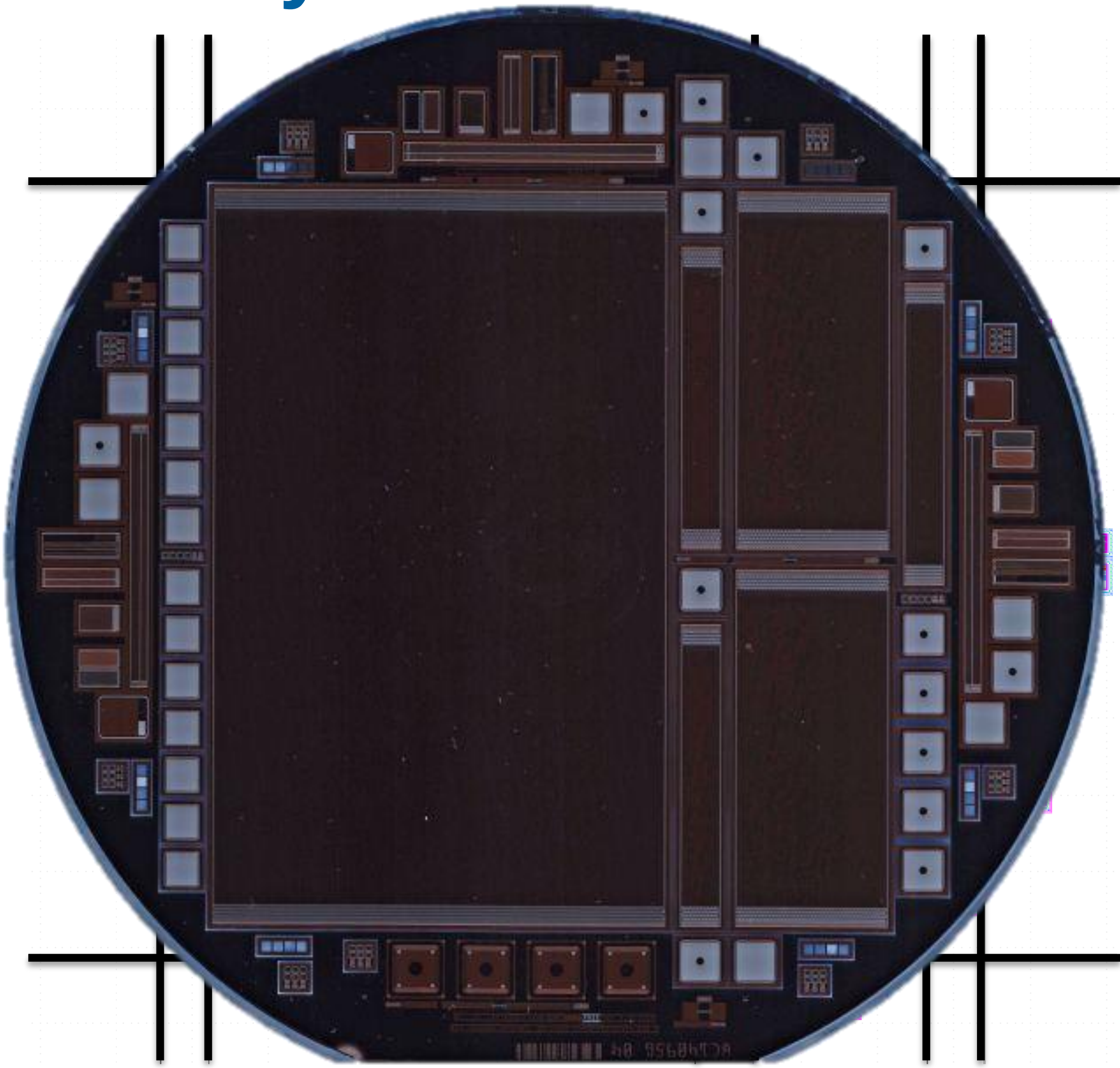
Process Specifications

- AC coupled p-in-n strips
- SiO_2/Si_3N_4 sandwich coupling dielectric
- PolySi resistor biasing

→ 8 photomasks

Wafer Layout

- Large Sensor: STL
- Small Sensor: STS
- Strixel Sensor: SX2
- Irradiation Sensor: STI
- CMS halfmoons (Test structures)
- Large number of diodes and MOS
- SIMS fields



Main Device Properties

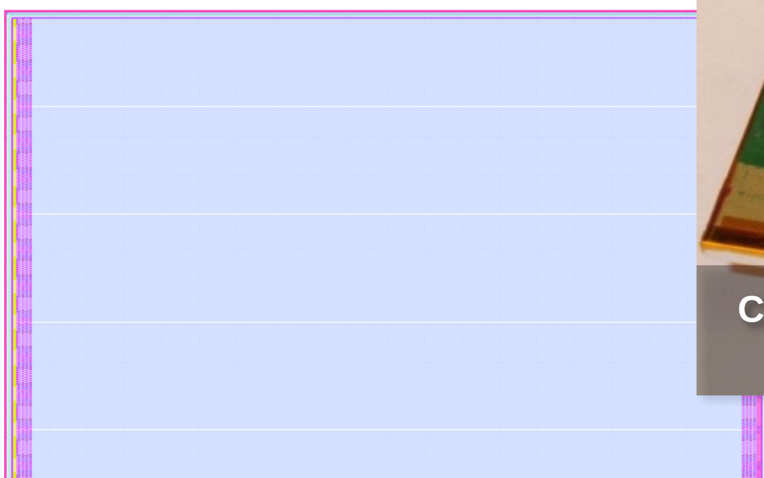
Sensor STL

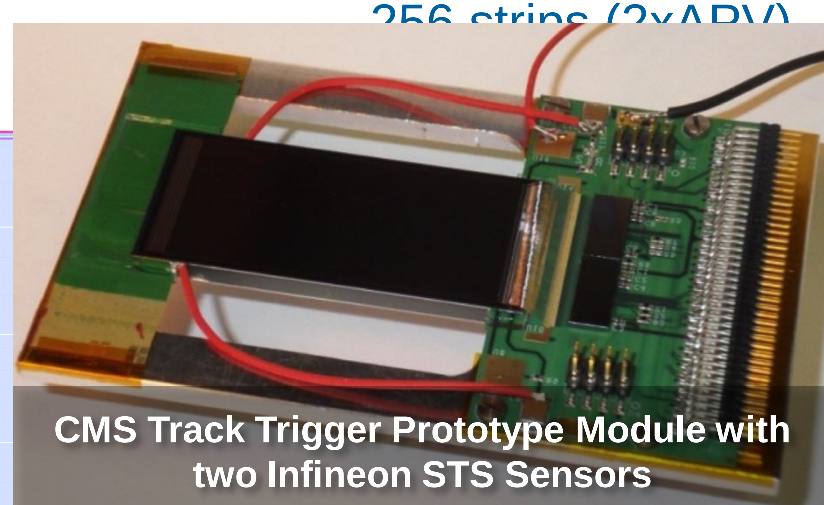
- 120 µm pitch
- 20 µm strip implant width
- Size: 64 x 102 mm
- 512 strips (4xAPV)

Sensor STS, SX2 and STI

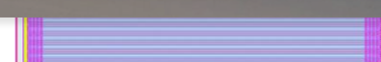
- 80 µm pitch
- 20 µm strip implant width
- STS and SX2:
  - Size: 23 x 50 mm
  - 256 strips (2xAPV)

7 mm

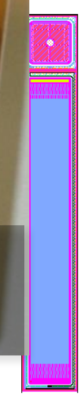




CMS Track Trigger Prototype Module with two Infineon STS Sensors



SX2: Strixel



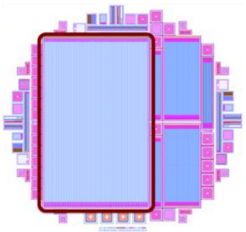
STI

RESULTS FROM THE ELECTRICAL CHARACTERIZATION

Global Parameters of first batch

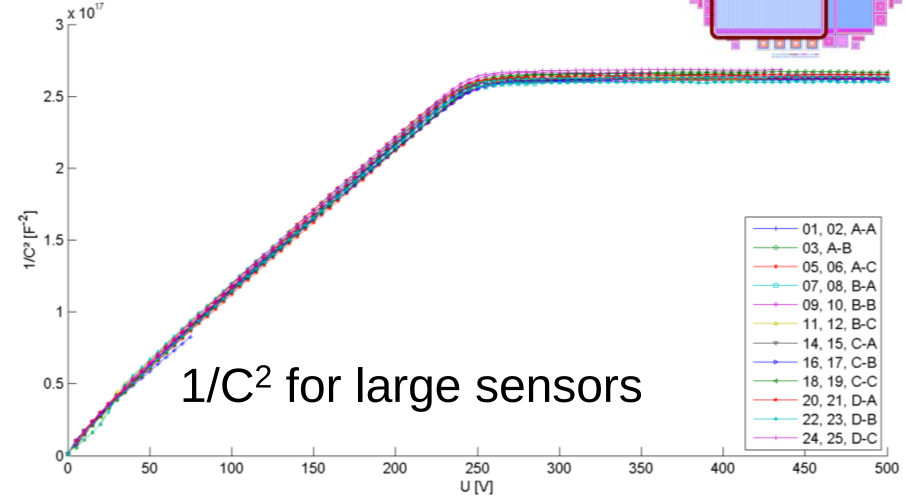
Large Sensor

- Size: 64 x 102 mm
- Active Size 61.5 x 99.6 mm
- 512 strips (4xAPV)
- 120 µm pitch
- 20 µm strip implant width



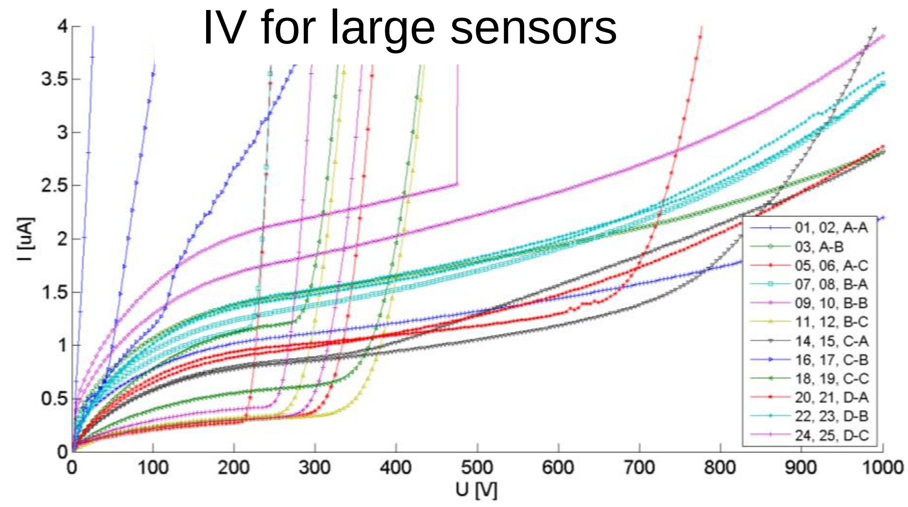
CV-Curves

- Uniform for all sensors on all wafers
- Depletion voltage well defined ≈ 240 V
  - Corresponds to 1.2 kΩcm and matches specs of bulk material



IV-Curves

- Many sensors are stable up to 1000 V
- Some sensors with very low leakage current but early breakdown
  - Different treatment of the backside n+ implant

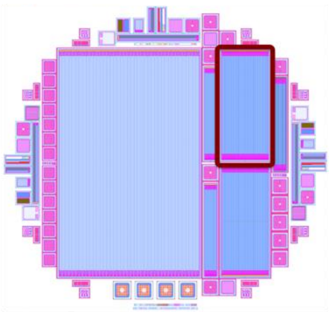


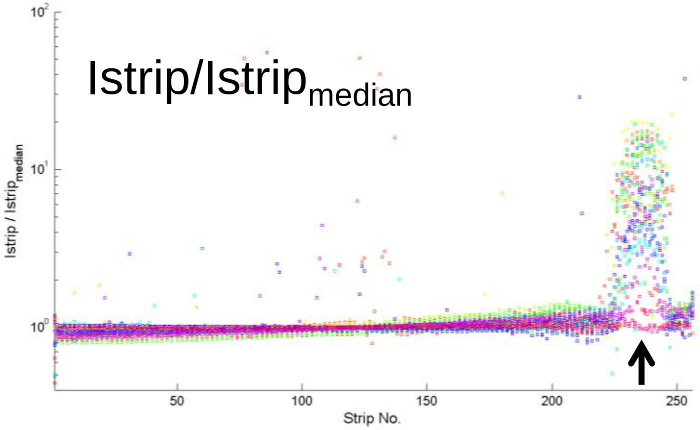
„Bad Strip“ Area

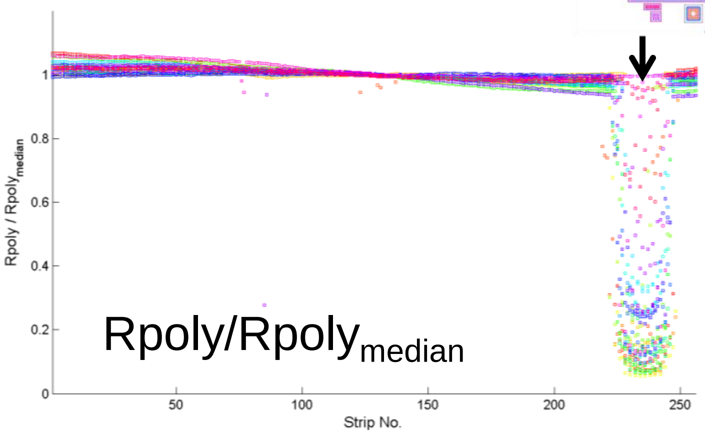
- Accumulation of anomalous strips around strip no. *222-248*

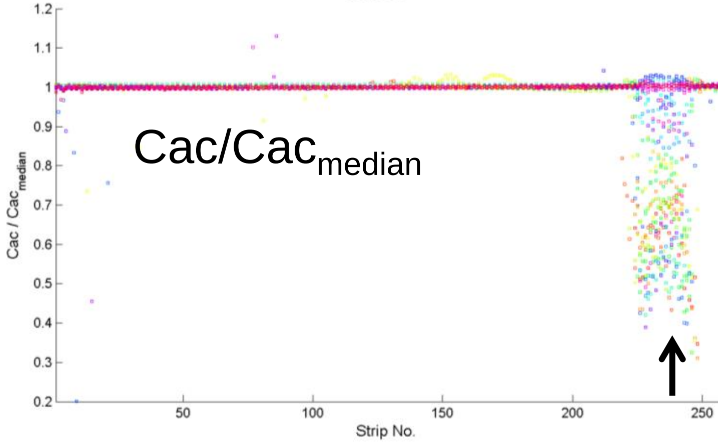
Baby Sensor

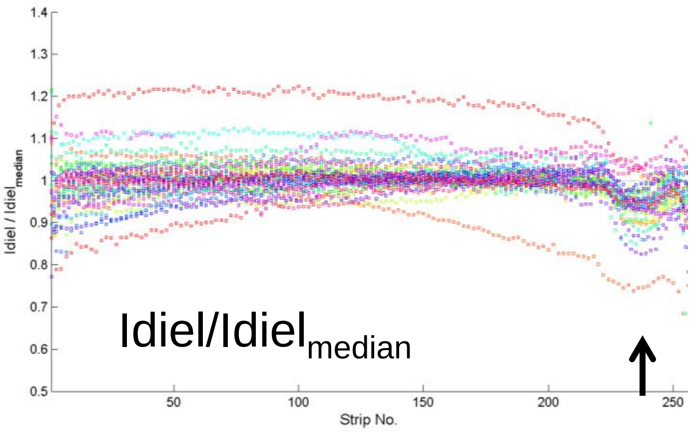
- Size: 23 x 50 mm
- Active Size 20.6 x 48.3 mm
- 256 strips (2xAPV)
- 80 µm pitch
- 20 µm strip implant width







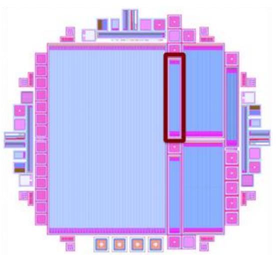




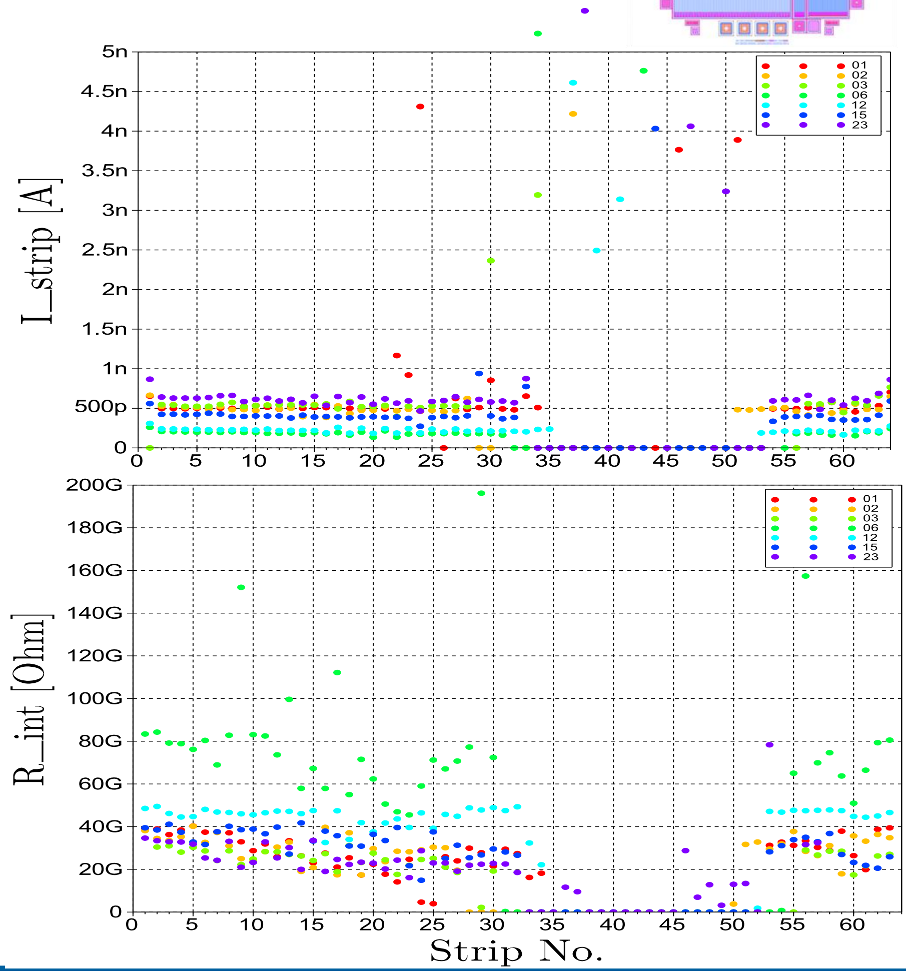
Low R_{int}: "bad strips" are shorts

Narrow Sensor

- Size: 7 x 42.5 mm
- Active Size 5.3 x 40.7 mm
- 64 strips (0.5xAPV)
- 80 micron pitch
- 20 strip implant width

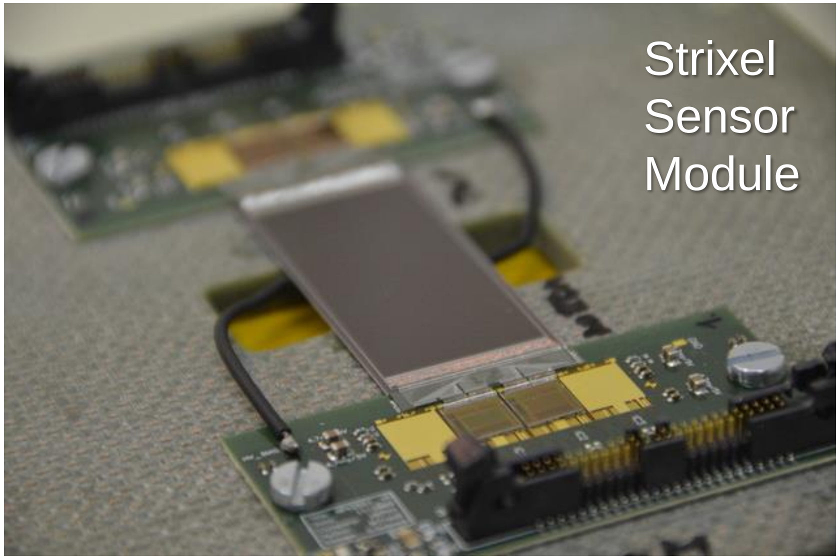


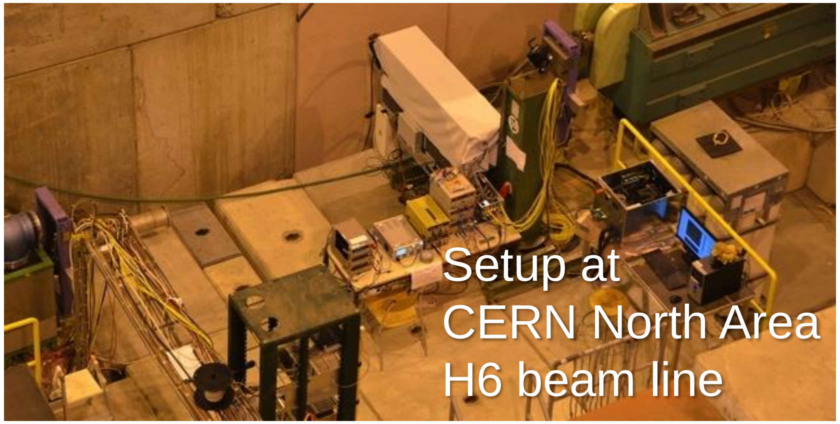
- **Low Inter-strip Resistance**
  - Measurement shown for narrow sensor with only 64 strips
  - Good outside of "Bad Strip Area" (> 10 GΩ)
  - "Bad Strip Area" from strip 30 – 50 shows very low strip isolation (< 1MΩ), i.e. shorted strips
- **Seen on all sensors**



Beam test at CERN's SPS

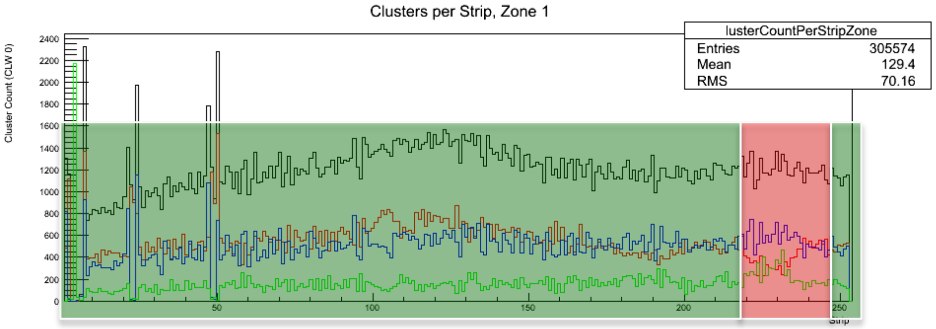
- Two detector modules built with baby sensors
- Two detector modules built with strixel sensors
- Readout chips (APV25) same as in the CMS Tracker
- Readout system is a prototype for the Belle II Experiment
- Detector modules were
  - Tested at CERN
  - Gamma irradiated in Mol, Belgium (because of available irradiation slot)
  - Tested again at CERN

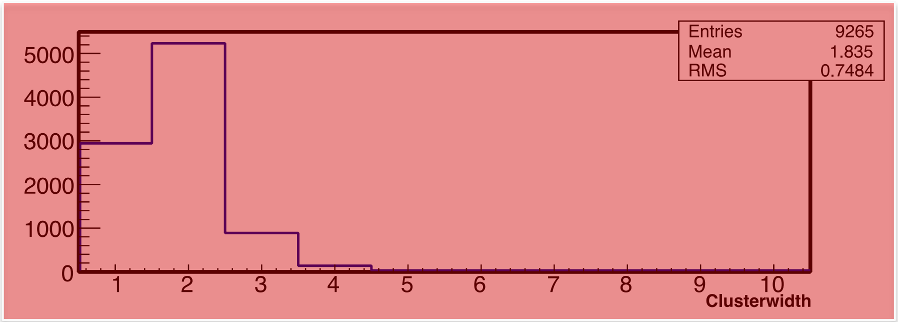


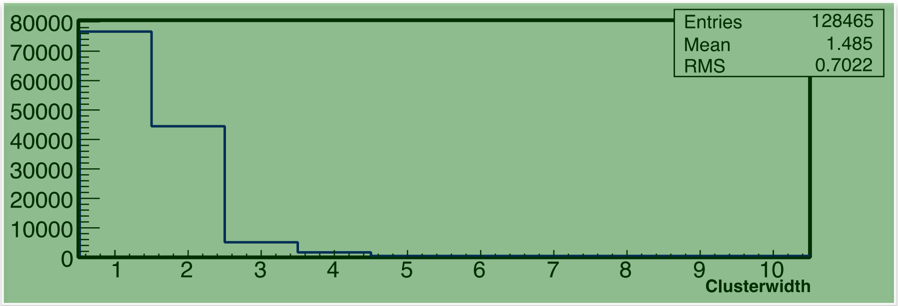


Selected results: Cluster Widths

- *"Bad Strip Area"* does not stand out clearly in beam profile
  - Area seems to be fully efficient
- But clusters are wider in "bad strip area"
  - Would be expected for bad strip isolation

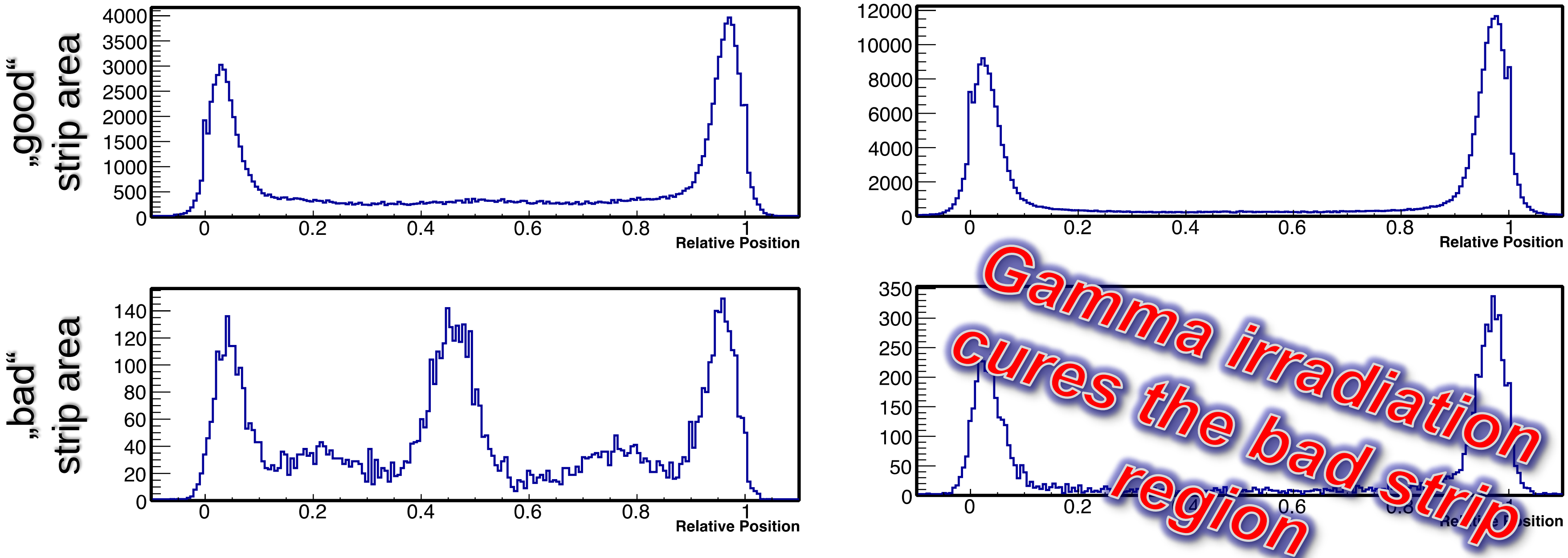




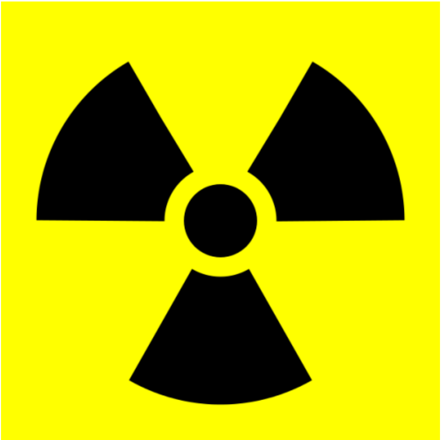


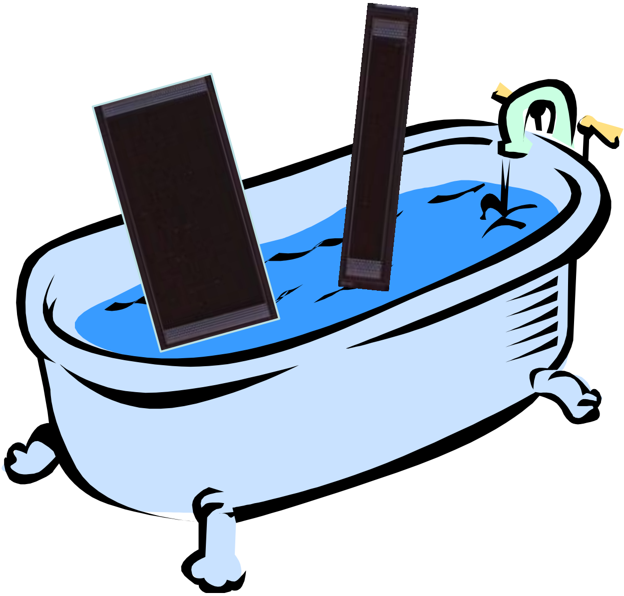
Selected results: η distribution

η distribution before irradiation → 100 kGy of γ → η distribution After irradiation



- *“Bad Strip Area”* shows a distorted η distribution
  - Outside bad area it looks fine
- After γ irradiation η distribution looks fine for all strips





Other ways of curing the bad strips

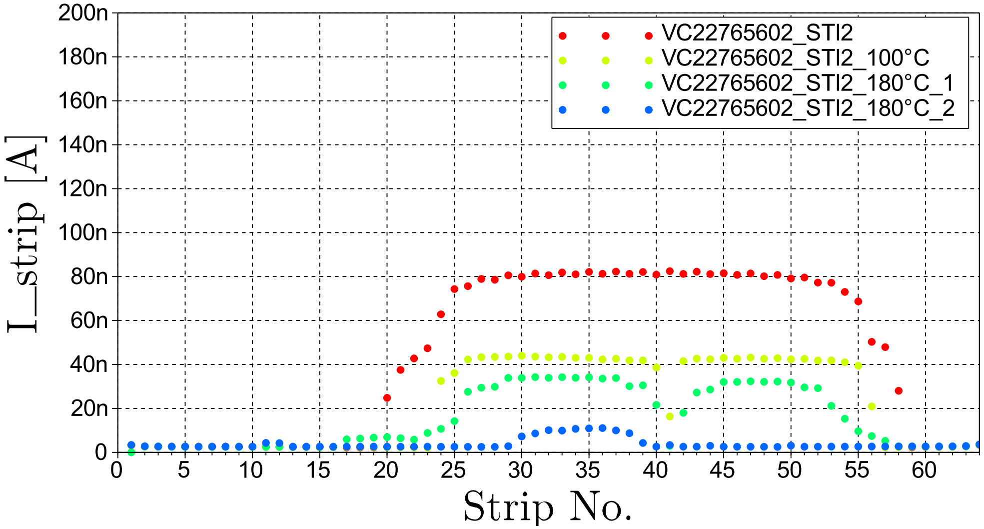
Temperature tests

- Manipulate the area of bad strips in an positive way → heat up sensors

- Therefore the climate chamber at HEPHY was used (max temp. 180 ° C)

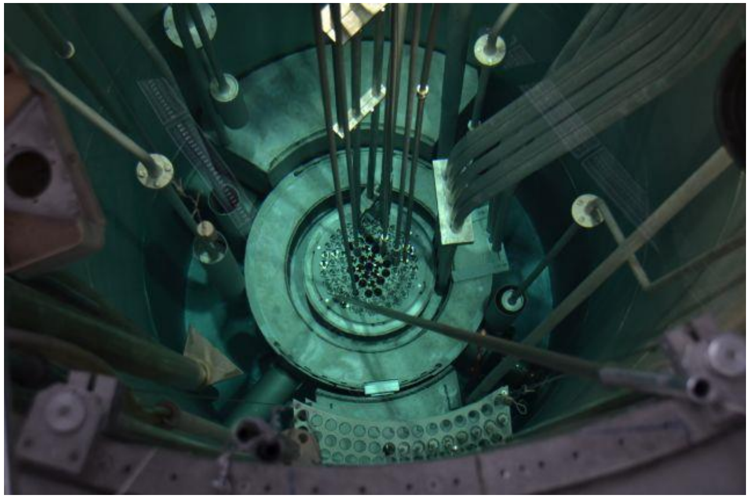
- Heating procedure:
  - 100 ° C for 6 h
  - 180 ° C for 17 h
  - 180 ° C for 90 h

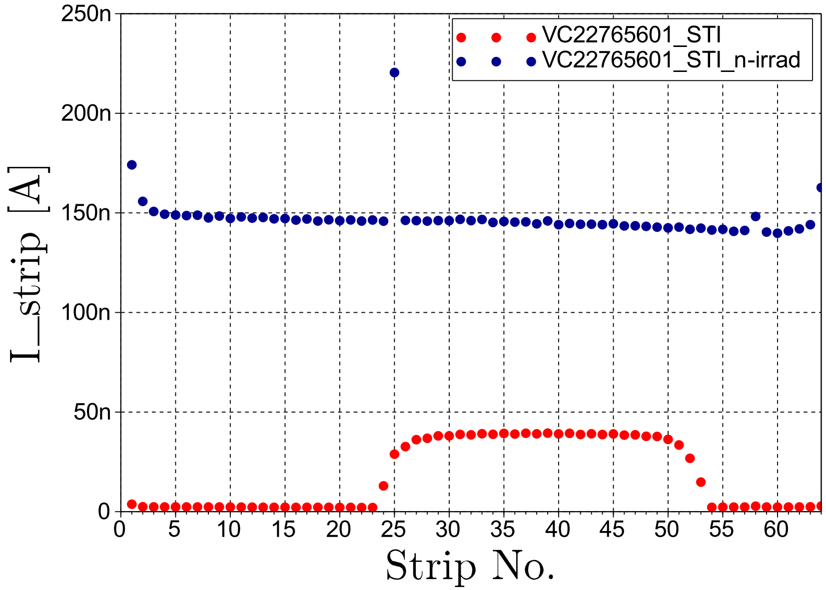
→ Strip parameters continuosly getting better

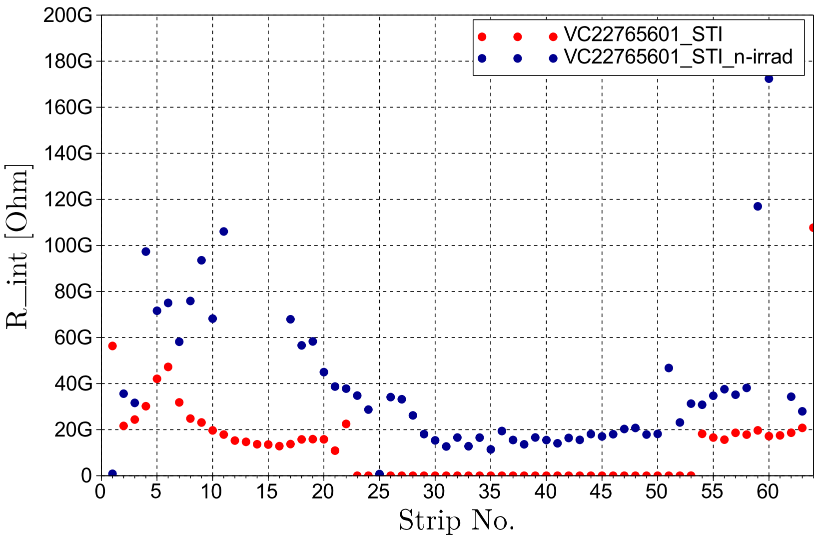


Neutron irradiation

- STI sensors were irradiated to a fluence of about 1E11 n_{eq} cm^{-2} using our Triga Mark II nuclear reactor
- Region of bad strips vanished after irradiation







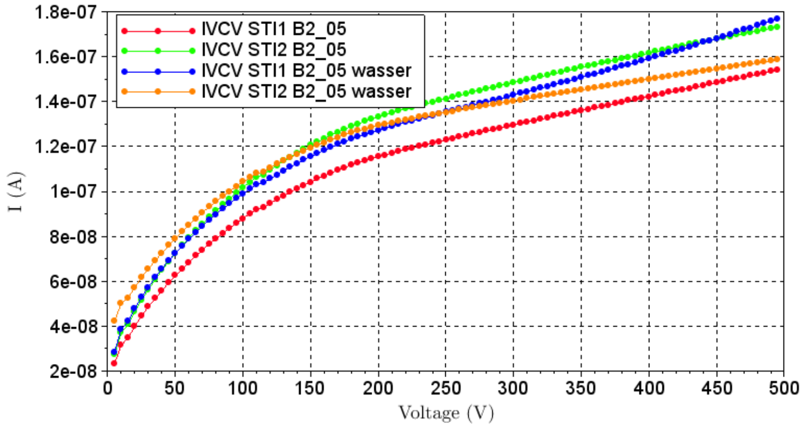
Bathing in deionized water

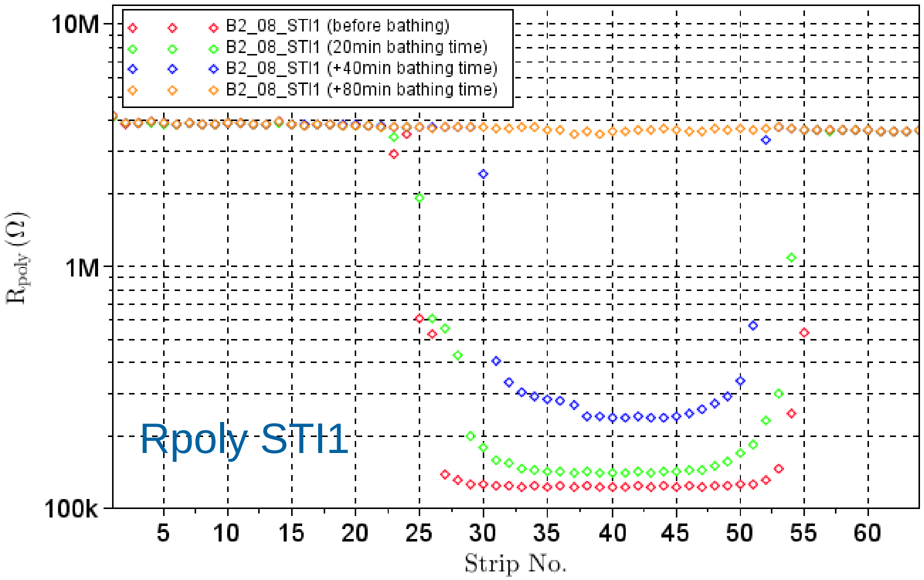
- Sensor STI1 of batch 2 wafer 08 was bathed for different time periods in deionised water

- Parameters continuously restore (same for Istrip, Cac etc.)

→ Bathing restores sensors

Before bathing
20min bathing
+40 min bathing
+80 min bathing



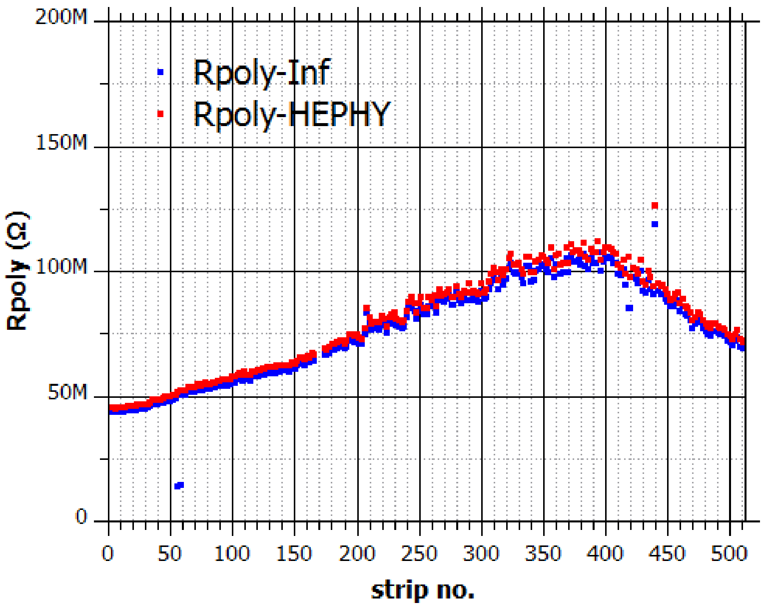


IN THE MEANTIME AT INFINEON

Test Setup at Infineon

- Infineon **was setting up test equipment** to mimic our electrical characterization
- They use standardized **Automated Test Equipment** (ATE)
  - tests undiced wafers only!
- Today, they are able to measure the same **per strip parameters** as HEPHY (except for inter-strip parameters!)
- Very **good agreement of measured parameters** (HEPHY also measured the STL sensor on the undiced wafer)

→ **No Area of bad strips** for undiced wafers!

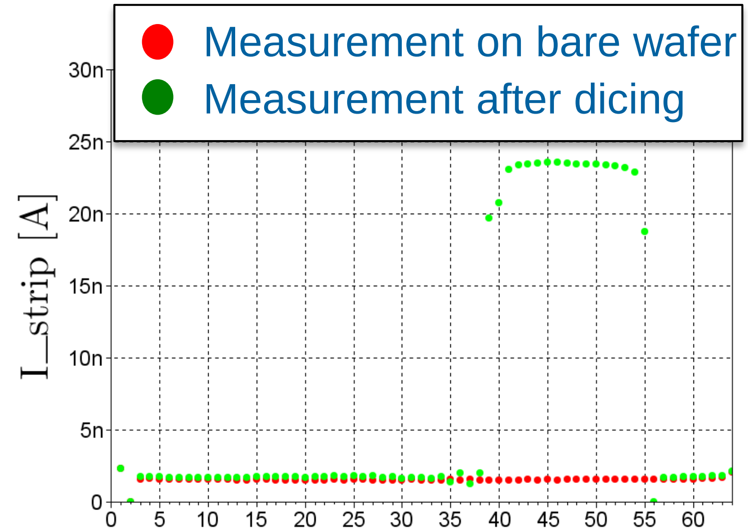


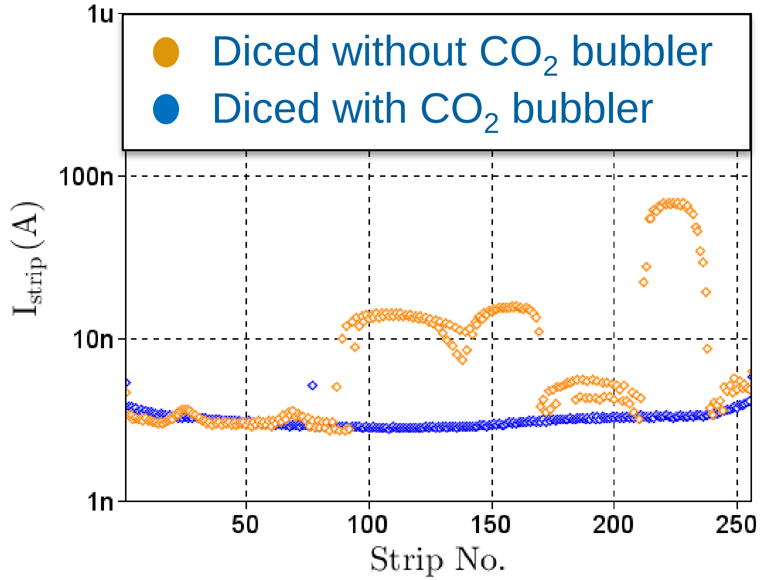
Dicing tests

- Initially not much thought was put into dicing
  - Seemed trivial to us – but nothing is
- Electrostatic charges generated during the dicing process can influence strip isolation
  - → **ESD topic** well known at Infineon and other vendors
  - → Several ESD protection methods are available

- Possible way to reduce electrostatic charges → **CO_2-bubbler**
  - CO_2 added to the dicing water in order to carbonize it
  - Resistivity of the dicing water:

    17 MOhm cm → 0.5 MOhm cm
- Infineon diced some wafer with and without CO_2-bubbler

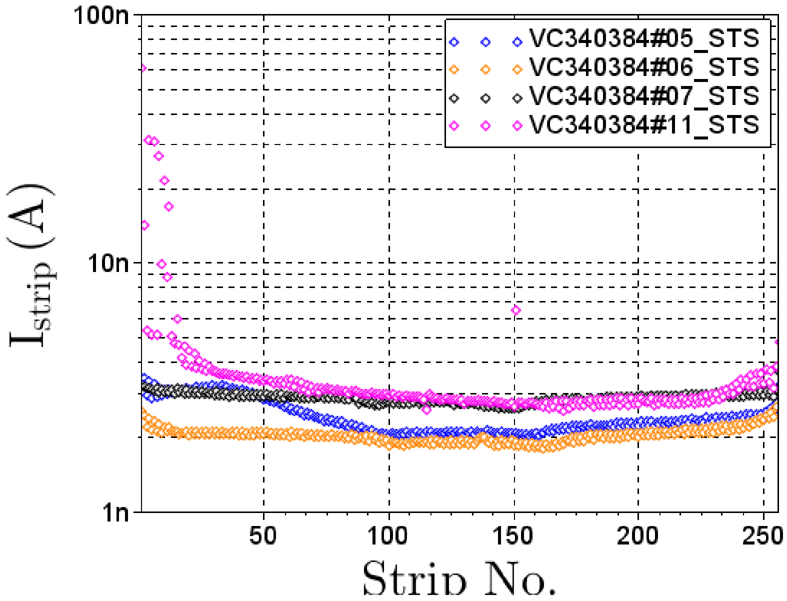




Batch 3/4: different passivation layer thicknesses/materials

- One assumption was that the passivation layer is more sensitive to static charges
- Comparison of 4 sensors with the same specifications expect for the passivation layer
- No significant changes among the different sensors can be observed
- Defective area for sensor 11 is untypical (no low R_{int} observed)

Sawed with CO_2 bubbler, new masks



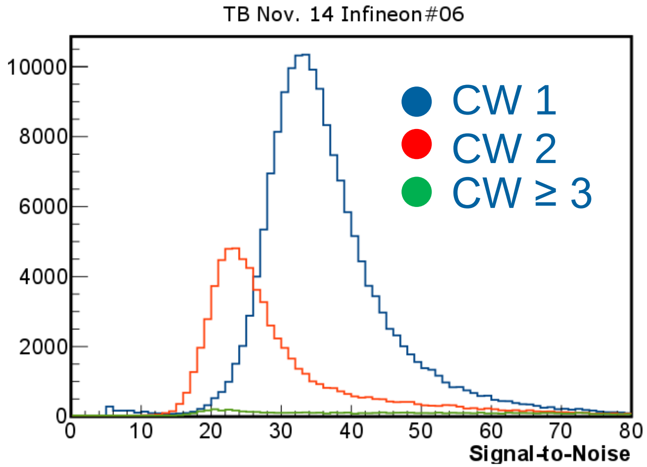
- Passivation 1
- Passivation 2
- Passivation 3
- Passivation 4

Beam Test at SPS in Nov 2014

- After electrical measurements, STS sensors of wafers 5, 6, 7 and 11 were assembled in modules for beam tests at the SPS (North Area H6B)
- Sensors were read out with APV25 Chips
- Only the STS sensor of wafer 11 shows a narrow defective area on the far left (reminder)
- DUT's were placed into the EUDET Telescope Setup:
  - Primary use: Trigger information
  - Secondary use: Tracking (to be prepared)

$$SNR_n = \frac{S_{\text{cluster}}}{N_{\text{cluster}}} = \frac{\Sigma_{i=1}^{n} S_i}{\sqrt{\Sigma_{i=1}^{n} N_i^2}}$$

Infineon DUT's – 4 modules parallel to telescope planes

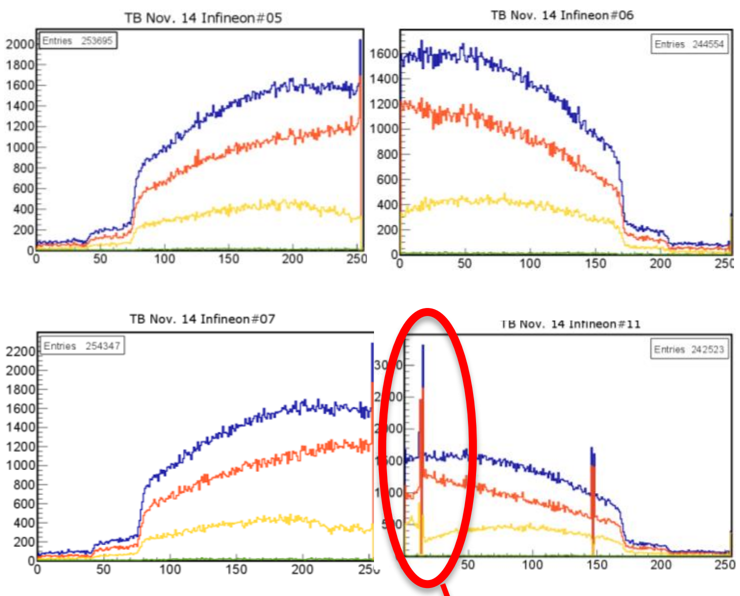


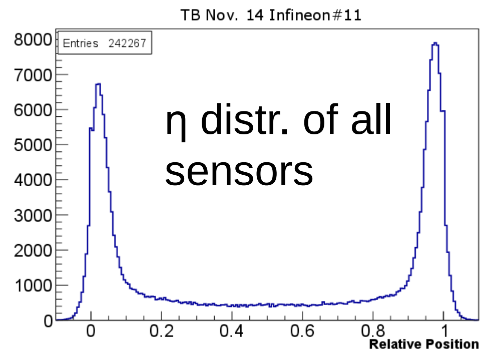
Beam Test at SPS in Nov 2014 (cntd.)

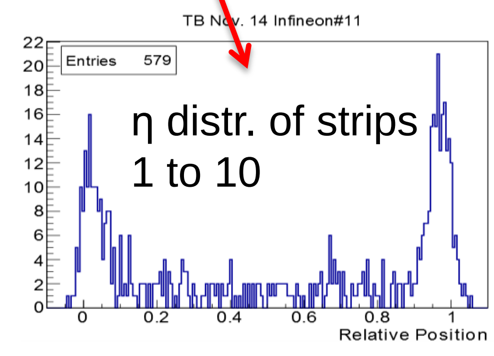
- Beam spot is fairly small due to small overlap of trigger PM's
- Beam profiles look reasonable
- Sensor 11 shows small irregularities for strip numbers 0-10 (more events with CW2 and less for CW1) → correlated to electrical characterization

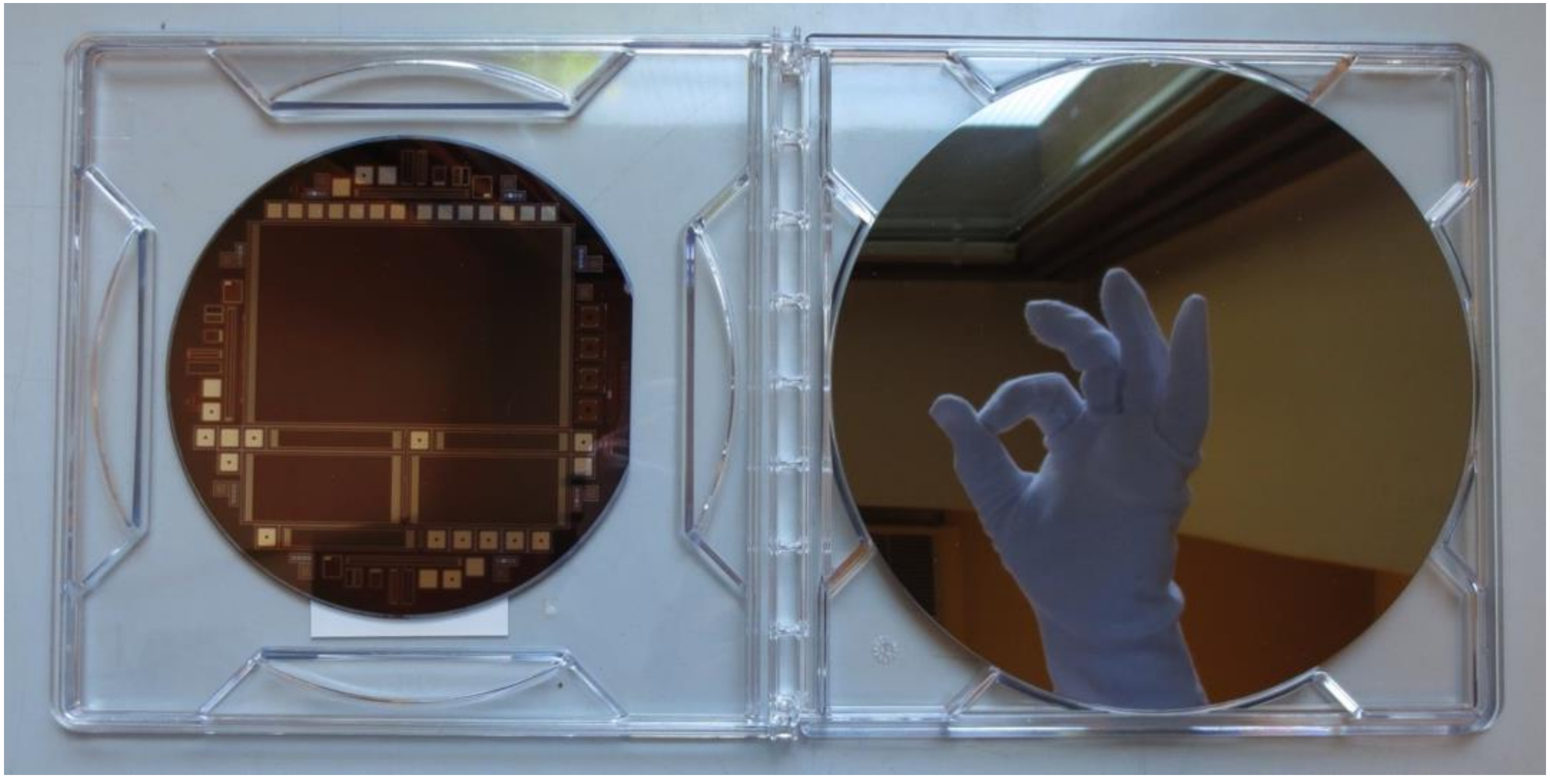
- Detailed look to eta distribution does not show charge-up
- Not even in small region of strip 1-10

● CW 1
● CW 2
● All CW

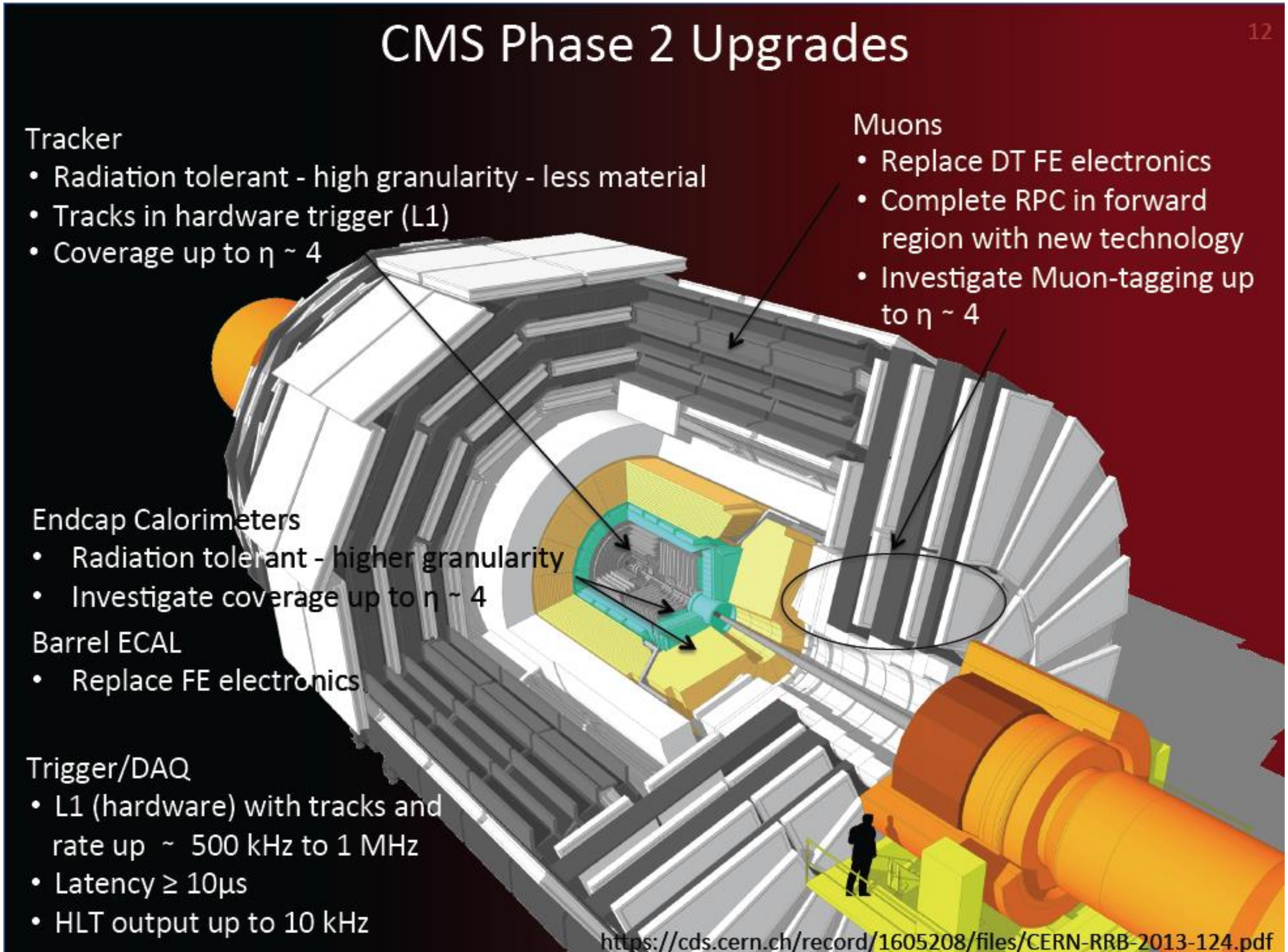








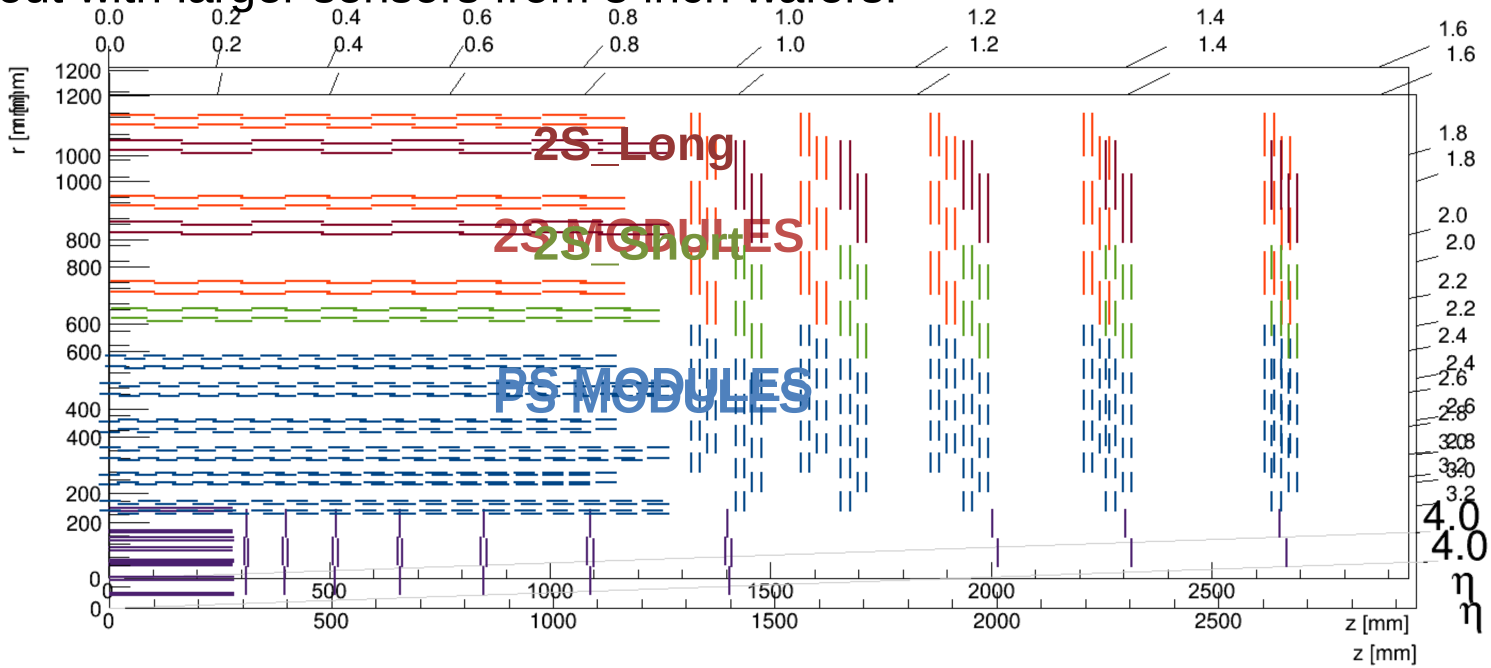
OUTLOOK


CMS Phase 2 Upgrades
12
Tracker
• Radiation tolerant - high granularity - less material
• Tracks in hardware trigger (L1)
• Coverage up to η ~ 4
Muons
• Replace DT FE electronics
• Complete RPC in forward region with new technology
• Investigate Muon-tagging up to η ~ 4
Endcap Calorimeters
• Radiation tolerant - higher granularity
• Investigate coverage up to η ~ 4
Barrel ECAL
• Replace FE electronics
Trigger/DAQ
• L1 (hardware) with tracks and rate up ~ 500 kHz to 1 MHz
• Latency ≥ 10µs
• HLT output up to 10 kHz
https://cds.cern.ch/record/1605208/files/CERN-RRB-2013-124.pdf

CMS Plan for Phase II upgrade

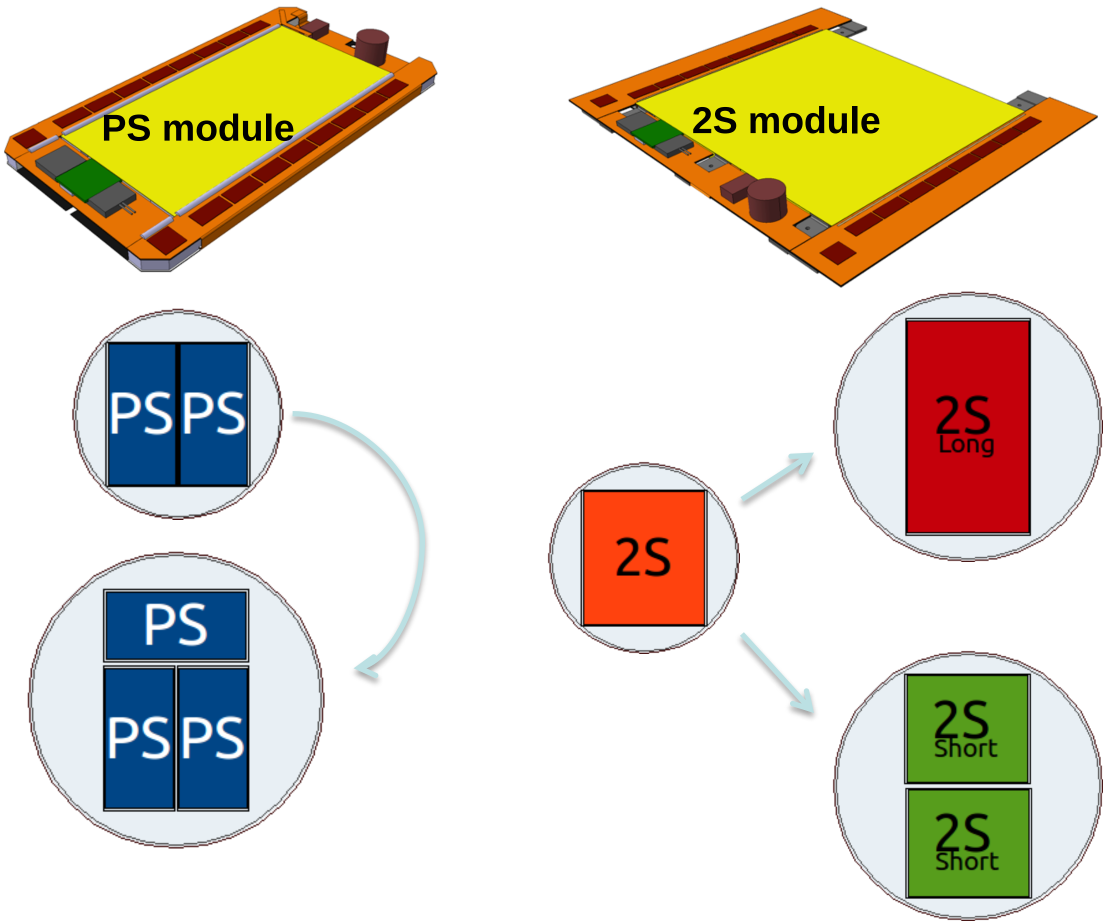
- During LHC long shutdown 3 (2022-2024): CMS will install a completely new silicon tracker
- The current layout is based on 6" sensors only comprising of two module types:

Layout with larger sensors from 8 inch wafers:



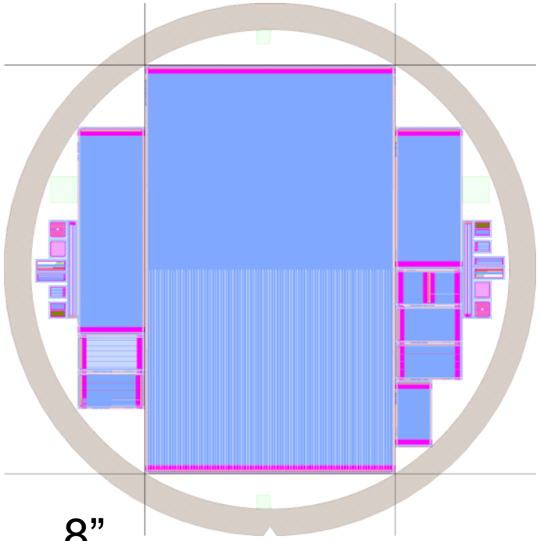
Wafer layout when CMS is going to 8”

- PS Module:
  - Module size stays the same
  - three sensors instead of two on one wafer
- 2S Module:
  - Fork single 2S concept into two: $2S_{long}$ and $2S_{short}$
- Could be a significant cost saving

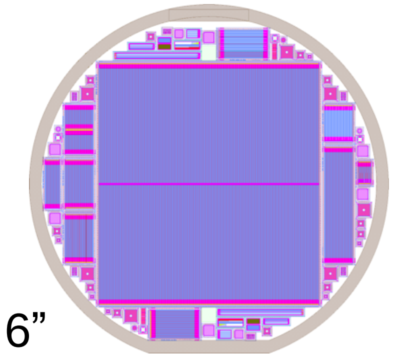


Outlook for 2015

- Infineon **developed a process** for thin (200-300µm) 6" and 8" wafers in 2014 after we started already some discussions in 2013
- Both ATLAS and CMS will go for p-type substrate because of radiation hardness reasons

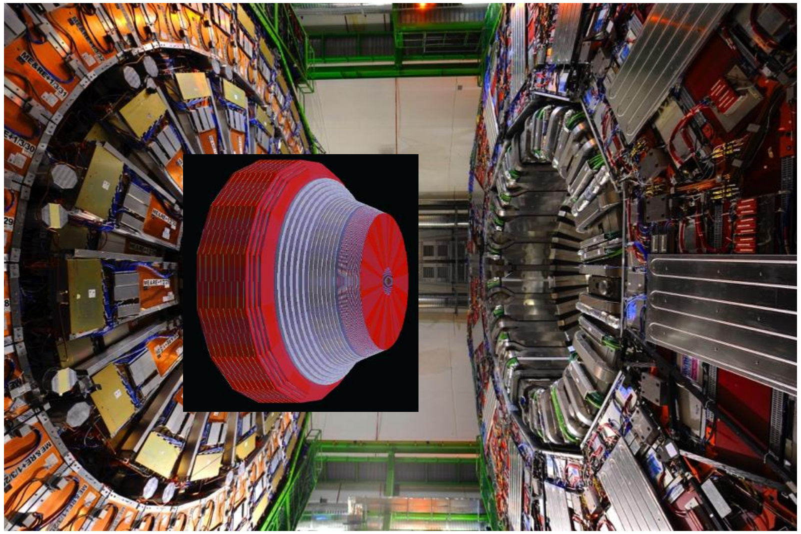


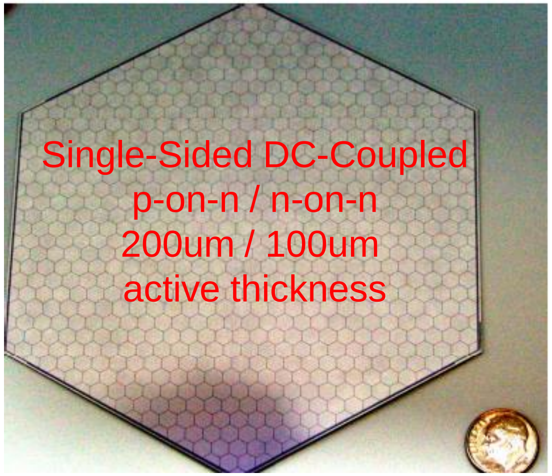
- CMS will have a **test production** on both wafer diameters in 2015
  - We are currently finishing the layout, tape-out in two weeks from now
  - Wafer to be ready in summer 2015



CMS High Granularity Calorimeter

- Both the endcap crystal calorimeter and the plastic scintillator calorimeters will need to be replace after LHC operations due to radiation damage.
- CMS is investigating in detail the possibility of using a high granularity calorimeter with ~2.5M channels of silicon pads.
- Total silicon area: 780 m^2





	Sensor Surface cm^2	
	Square	Hexagonal
6” wafers	~ 100	~ 130
8” wafers	~ 180	~ 230

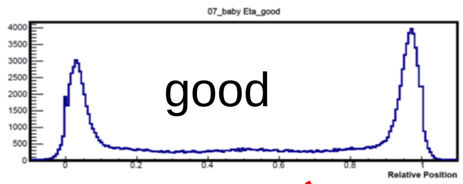
Summary

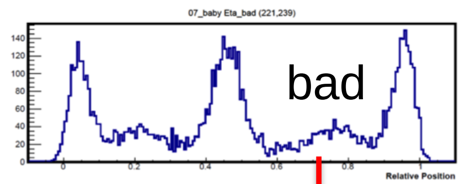
- Collaboration with Infineon started already five years ago with bottom-up approach
- Several batches in p-on-n technology produced
  - Baby sensors used by CMS for lab and beam tests with new CBC readout chip
  - "bad strip" area identified as charge-up problem and solved
  - Open question: Are Infineon sensors more sensitive to charge-up (to be investigated) and how to mitigate this behavior
- Process flow for n-on-p technology with 200/300 µm thickness developed
  - Will be used for both 8" and 6" test submission by CMS in 2015

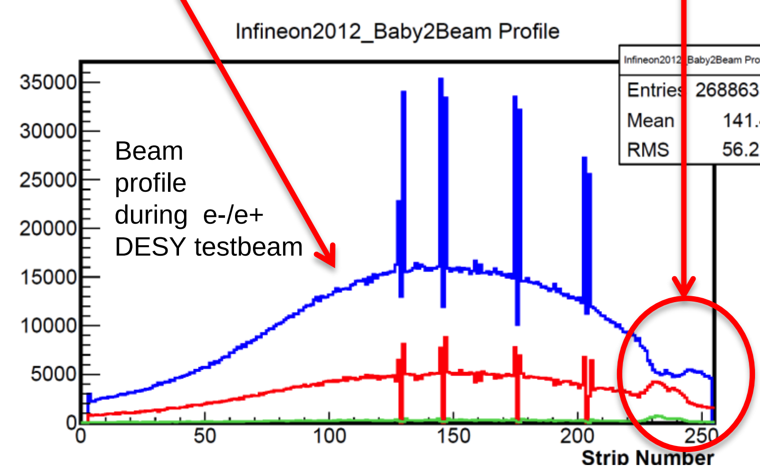
THE END

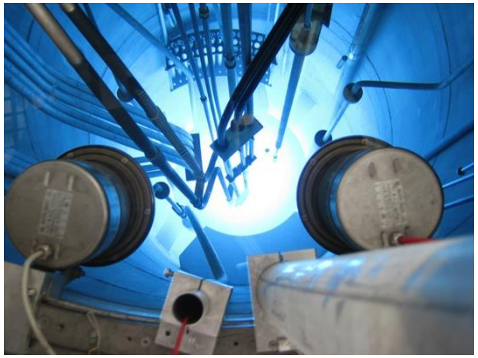
Beam Tests and Irradiations with Infineon Sensors

- Performance has been tested in several beam tests at CERN and DESY
  - Confirms region of bad strip isolation previously seen in electrical characterization
- Several irradiations, e.g. with Neutrons at Atominstitut of TU Vienna
  - Test radiation hardness
  - Qualify reactor as irradiation center (determine neutron spectrum)

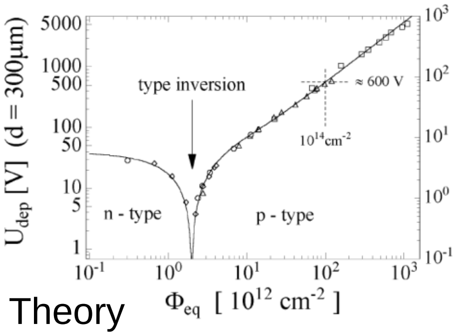




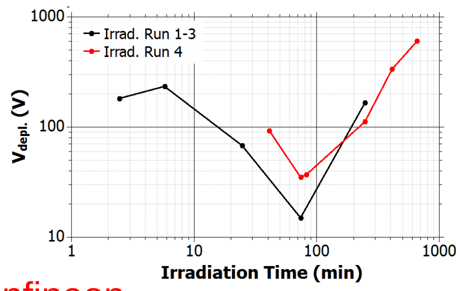




Triga Mark II Reactor ATI



Theory



Infineon

Batch overview

Batch	Date	masks	dicing	split groups	features
1	2012	original		Strip dielectric, backside implant	photoresist left
2	Q1 2013	original		R_poly variation, backside implant	
3	Q4 2013	original	partly CO_2	backside implant, passivation	
3.5	Q1 2014	original	CO_2	passivation	
4	Q3 2014	3 new layers	partly CO_2	passivation	