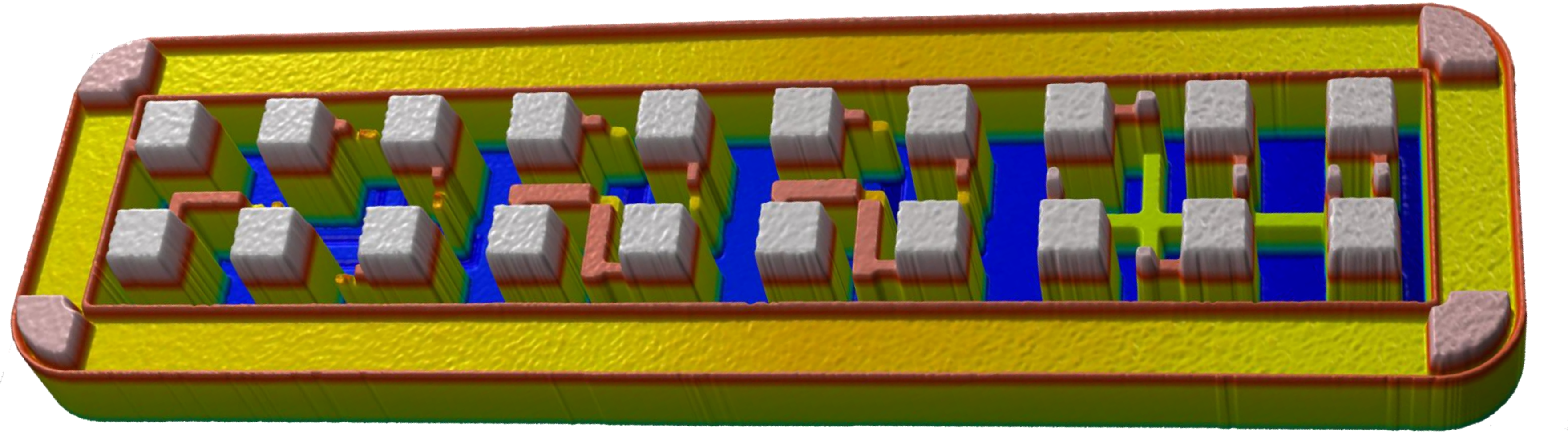
Process Quality Control Strategy for the Phase-2 Upgrade of the CMS Outer Tracker and High Granularity Calorimeter

Viktoria Hinger on behalf of the CMS collaboration

TREDI2020, Vienna, Austria



Process quality control test structures (confocal laser scanning microscopy image)

Outline

~ 800 m^2 silicon for the CMS Phase-2 Upgrade

- Tracker: ~ 200 m^2
- Calorimeter endcap: ~ 600 m^2

Process quality control: The concept

- Efficiency
- Comparability
- Sensitivity

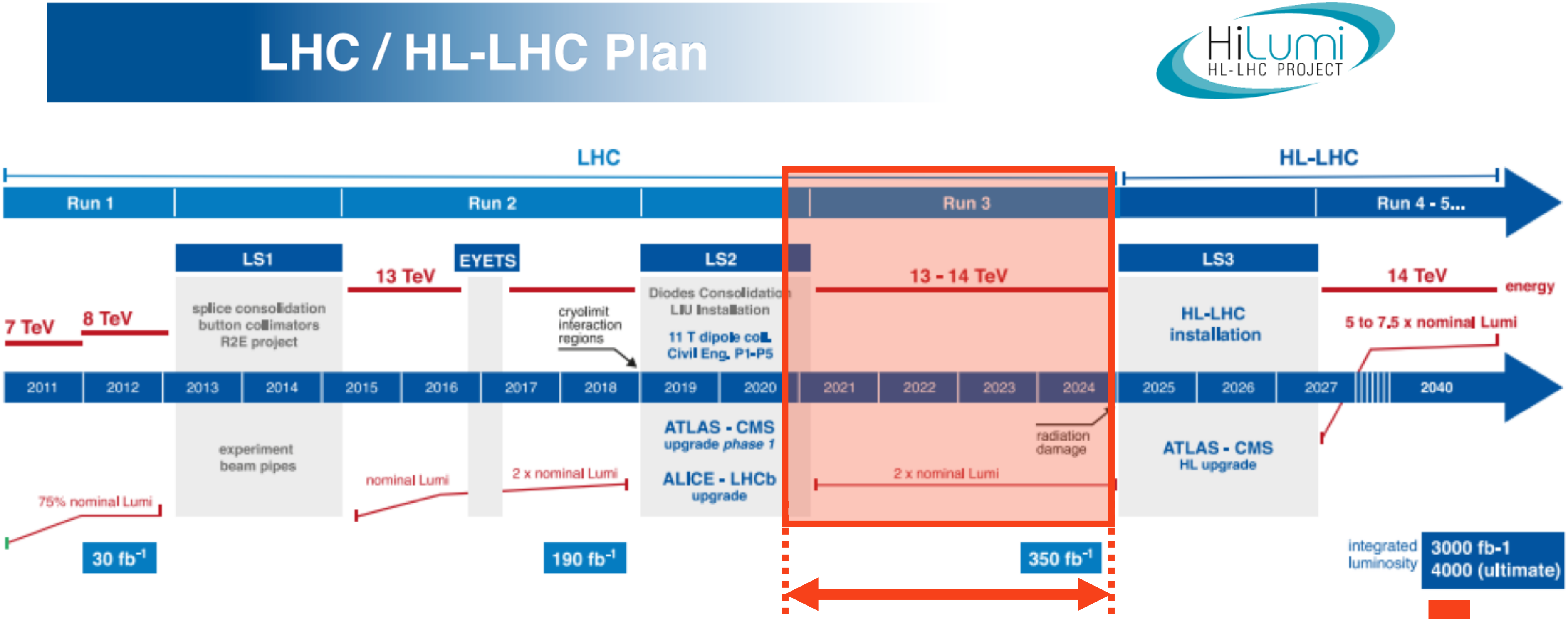
Universal set of test structures

- The “flute” concept

Process parameters and performance examples

Summary and outlook

High-Luminosity LHC requires full upgrade of tracker and calorimeter endcap

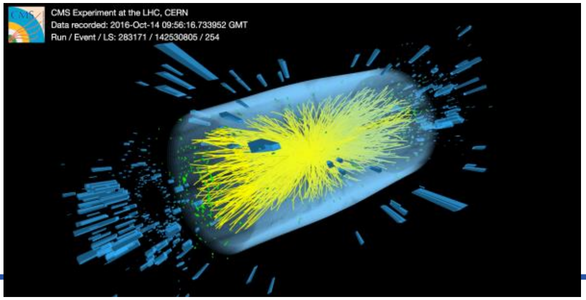


Production of > 50,000 new silicon sensors

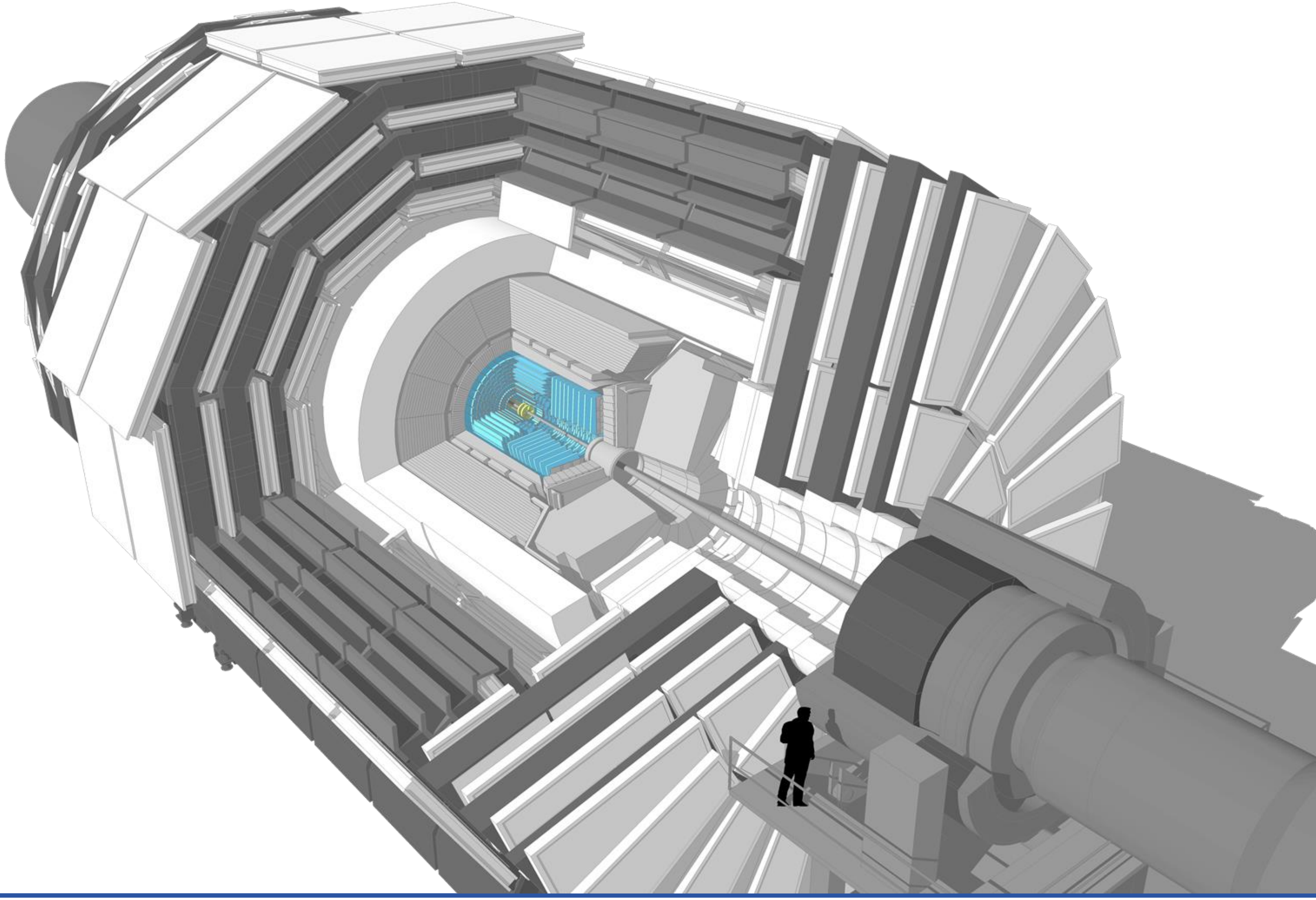
Collision rate increases by a factor 5

Instantaneous luminosity: $7.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

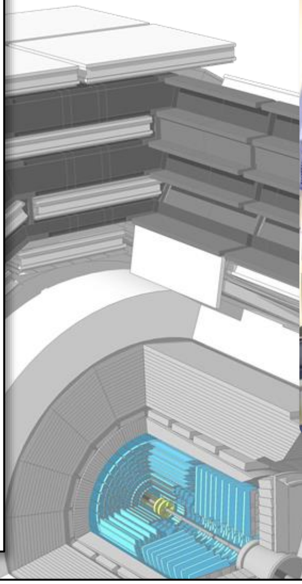
Integrated luminosity: $3000\ \mathrm{fb}^{-1}$ by 2037



~ 200 m^2 silicon in the upgraded outer tracker



~ 200 m^2 silicon in the upgraded outer tracker

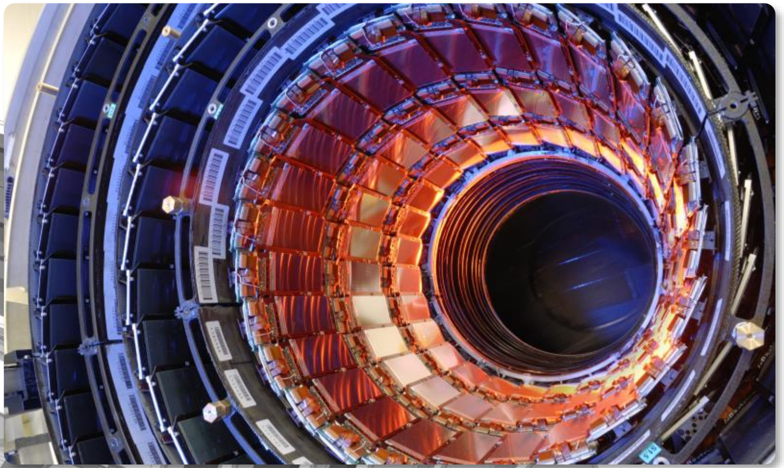


Sandwich of 2 sensors per module for module-level p_T discrimination

13,300 modules

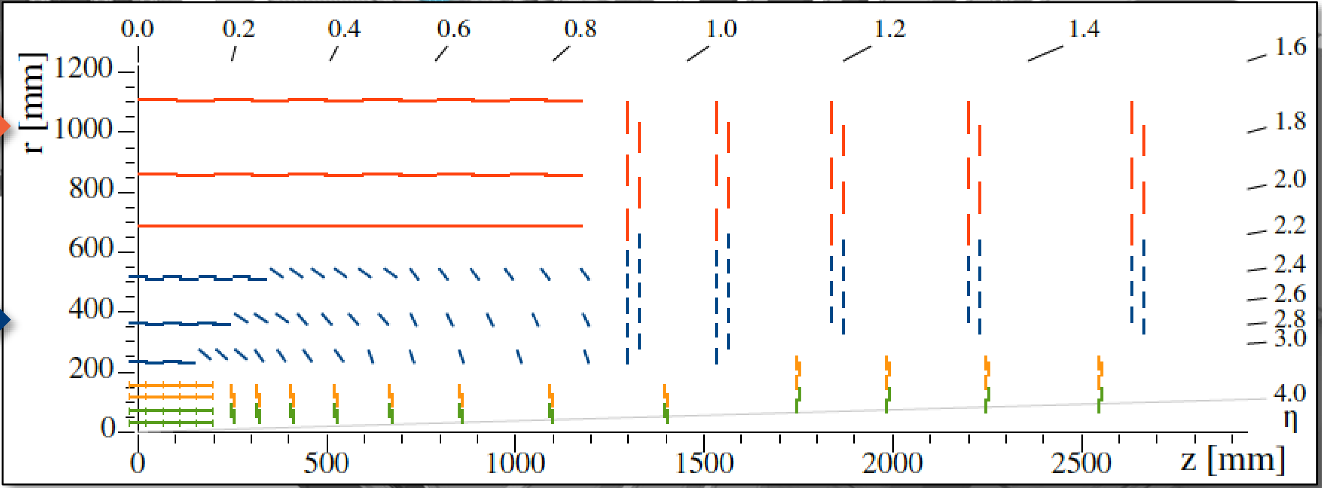
26,000 sensors

~ 24,000 wafers



2S modules
(**2 S**trip sensors)
~ 7700

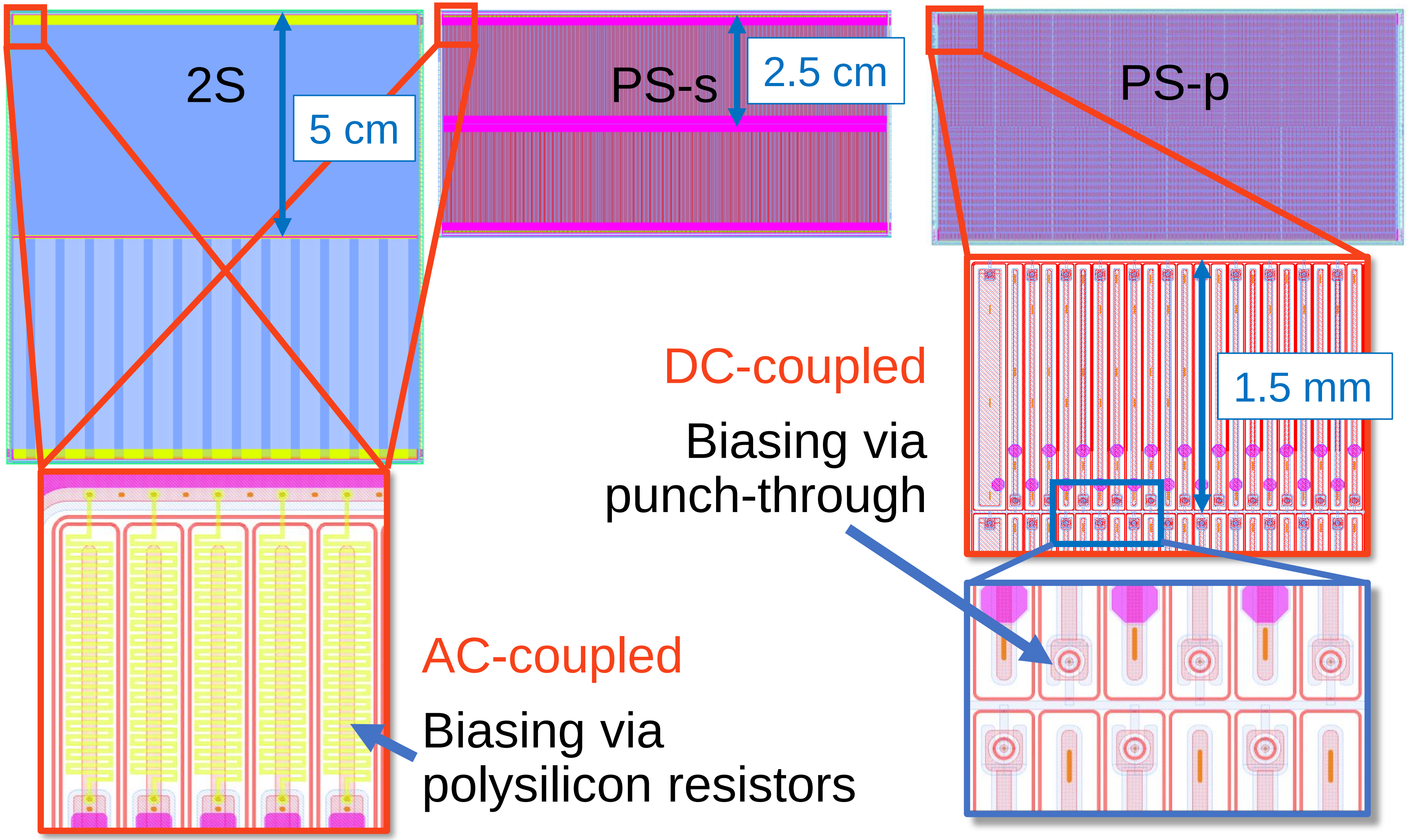
PS modules
(**P**ixel and **S**trip sensor)
~ 5600



Outer tracker silicon sensors

Strip sensors

Macropixel sensor



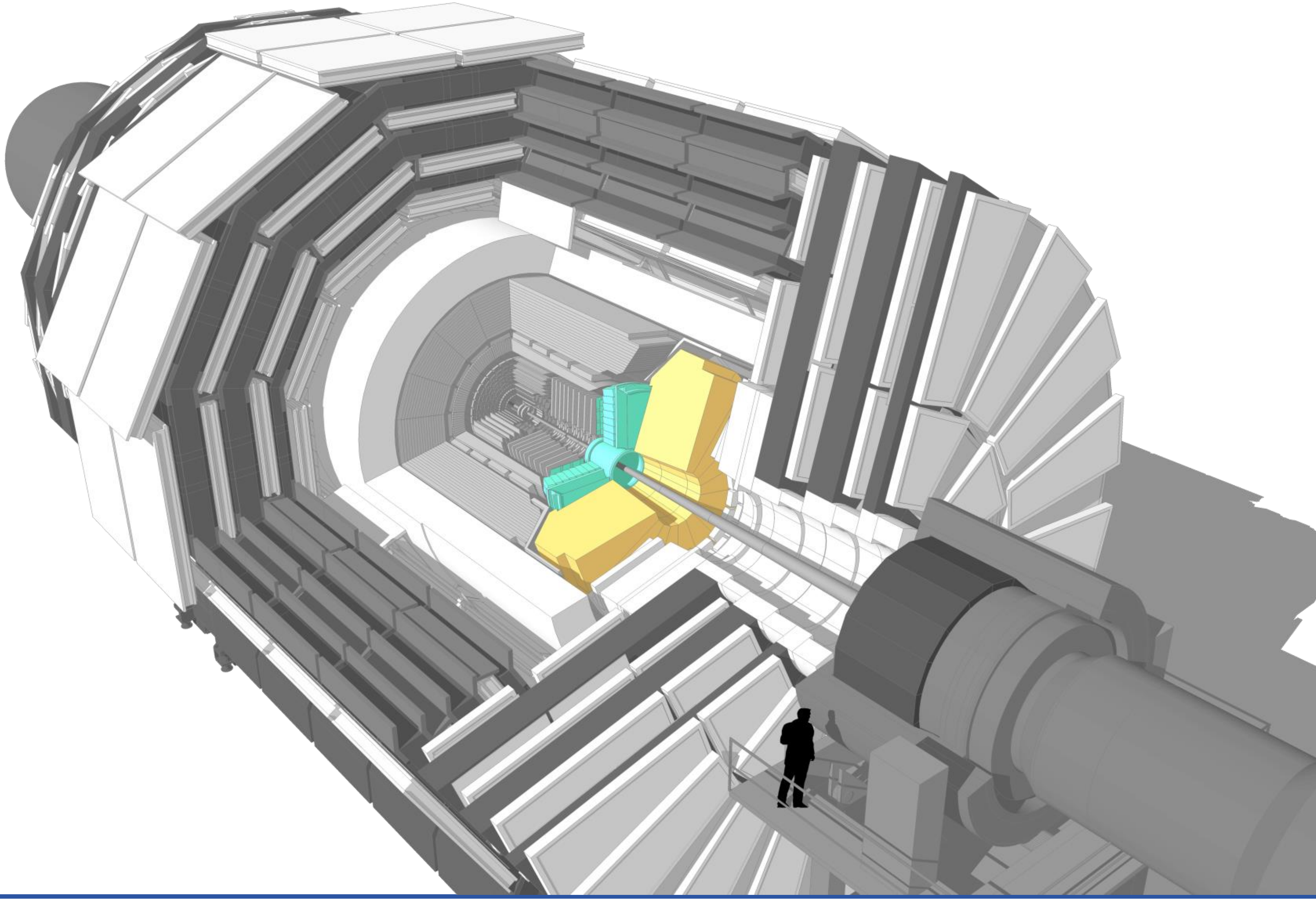
DC-coupled

Biasing via
punch-through

AC-coupled

Biasing via
polysilicon resistors

~ 600 m^2 silicon in the calorimeter endcap (CE)



~ 600 m^2 silicon in the calorimeter endcap (CE)

High-granularity calorimeter (HGCAL)

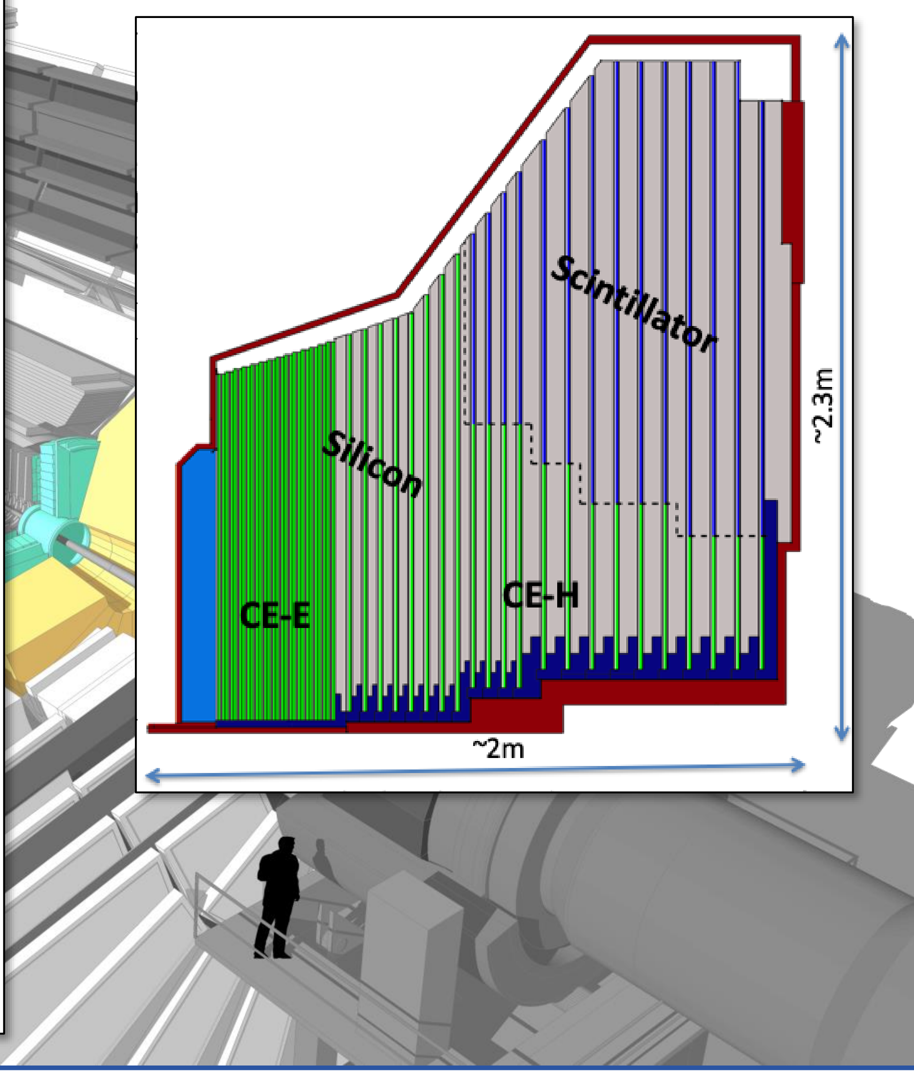
Electromagnetic compartments (CE-E):

- ~ 28 silicon sampling layers

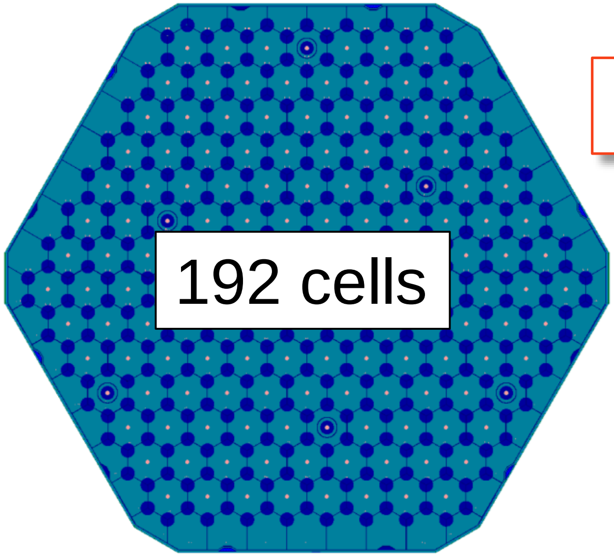
Hadronic compartments (CE-H):

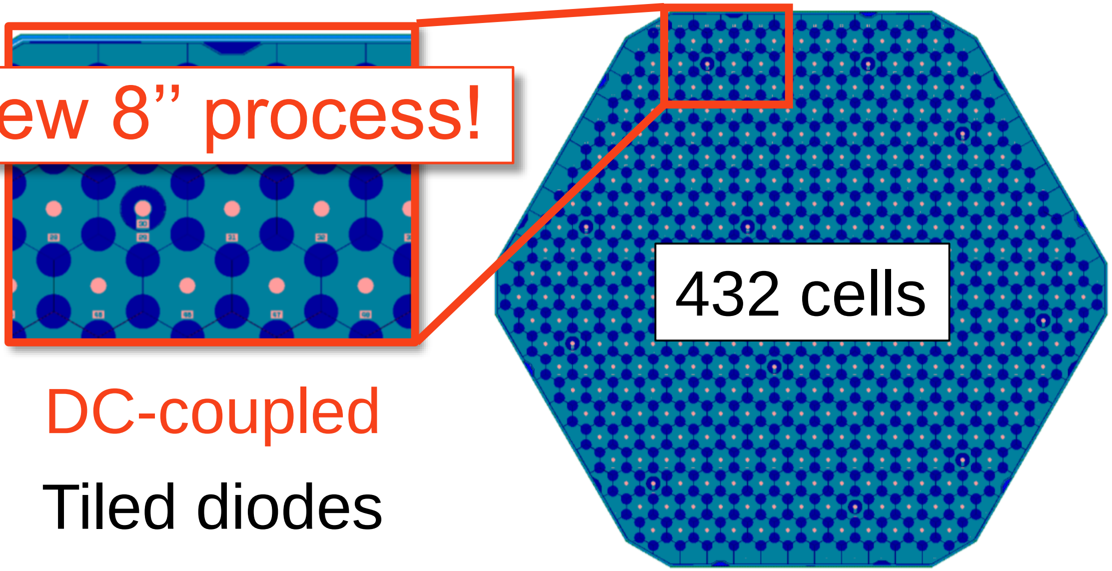
- ~ 8 silicon sampling layers
- ~ 14 layers silicon + scintillator

~ 30,000 silicon wafers



Silicon sensors for the calorimeter endcap





DC-coupled

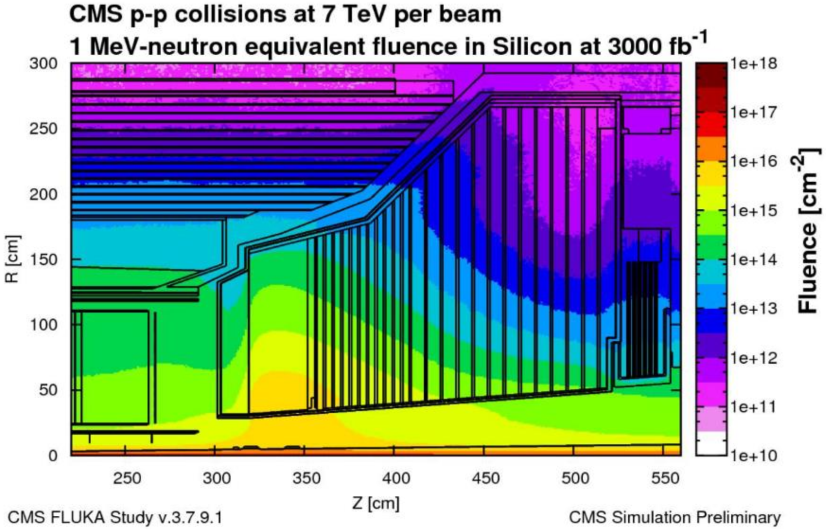
Tiled diodes

Different wafer thickness for regions with different fluence

300 µm (float zone)

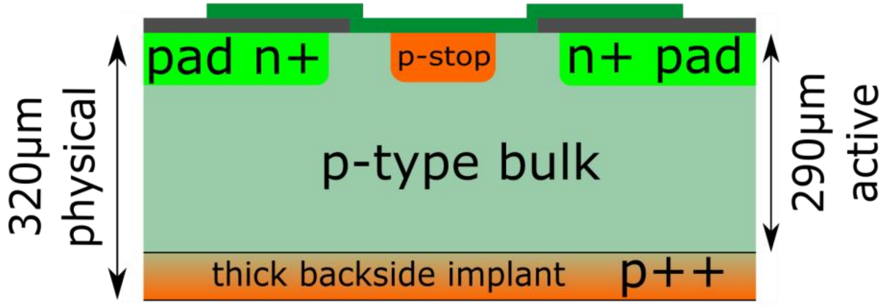
200 µm (float zone)

120 µm (epitaxial)

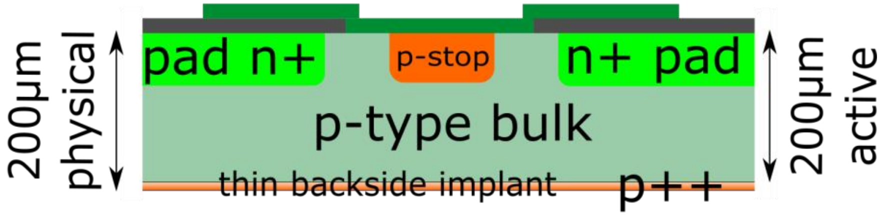


Tracker and HGCAL sensor processes

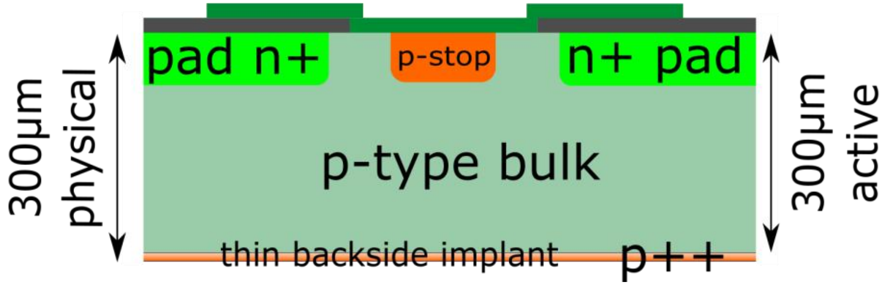
320/FZ290 6-inch



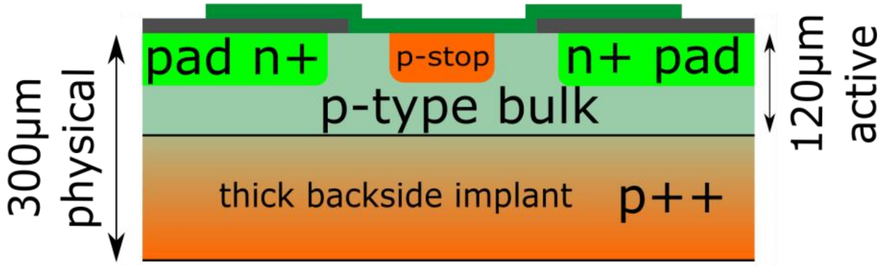
200/FZ200 8-inch



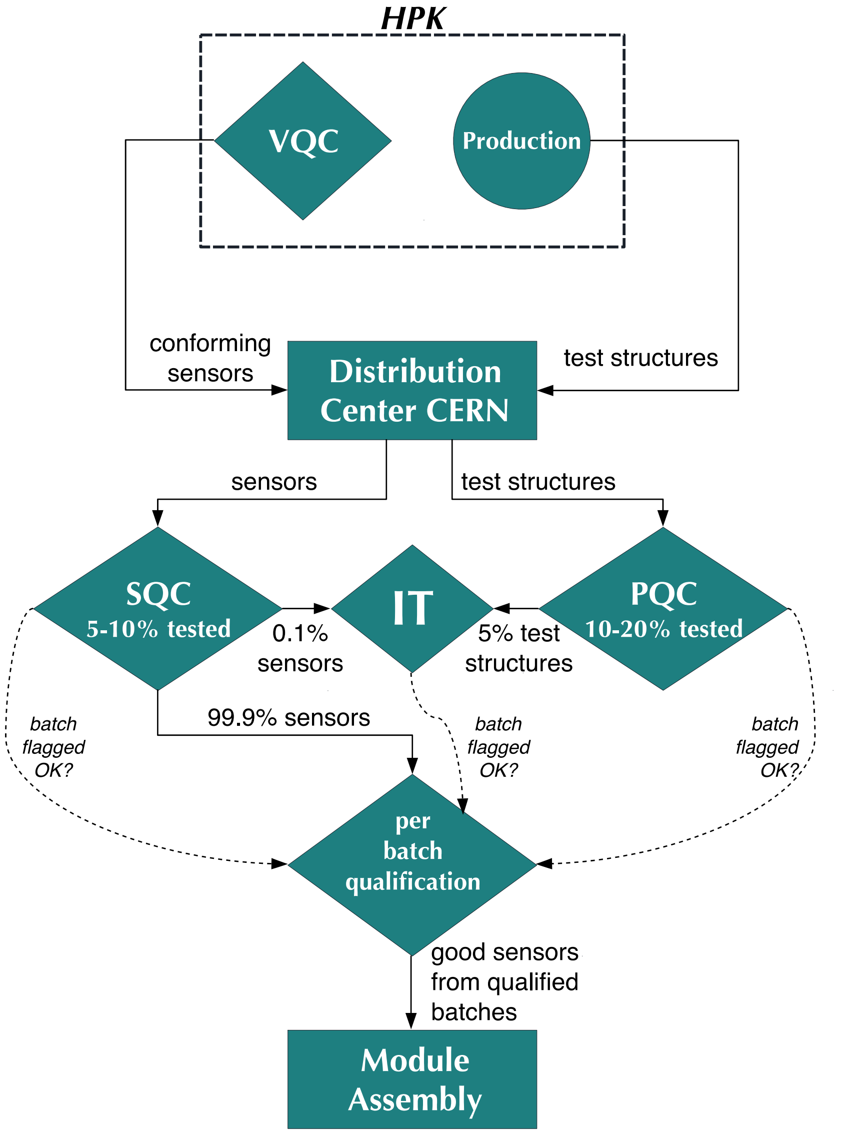
300/FZ300 8-inch



300/epi120 8-inch



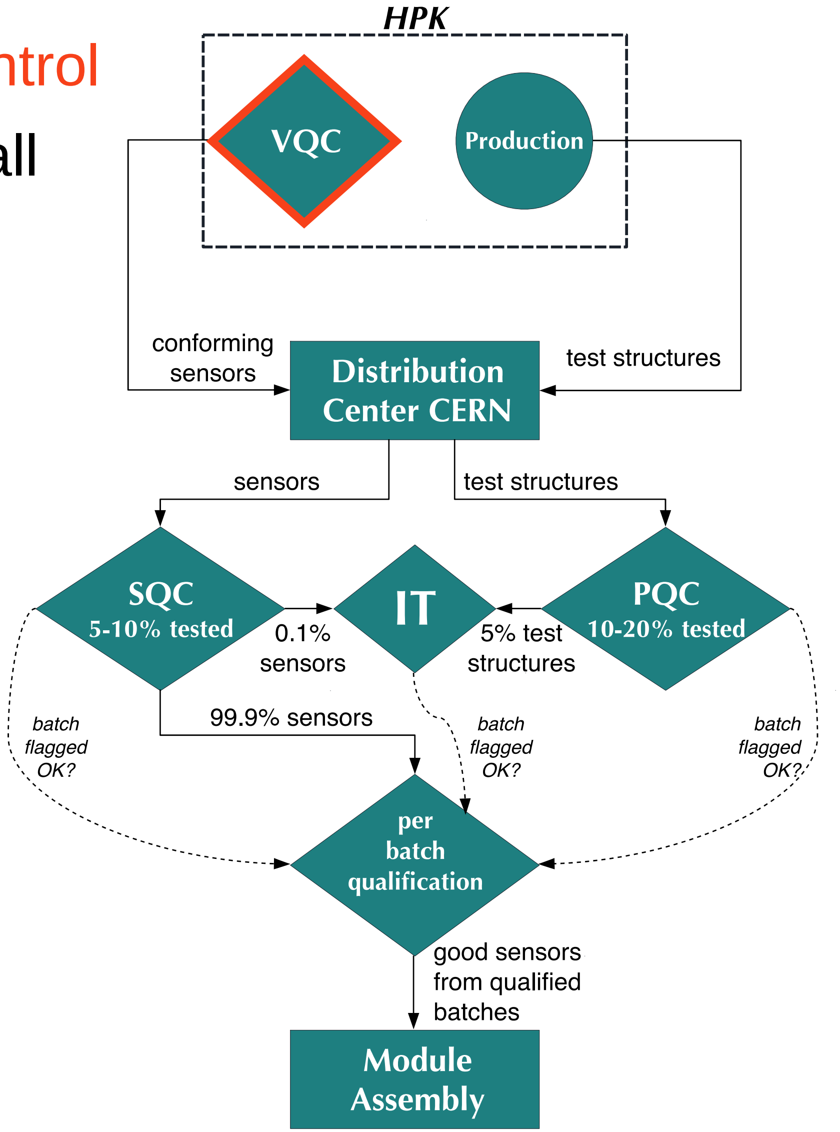
Tracker quality control process flow



Tracker quality control process flow

Vendor quality control

Hamamatsu test all sensors



Tracker quality control process flow

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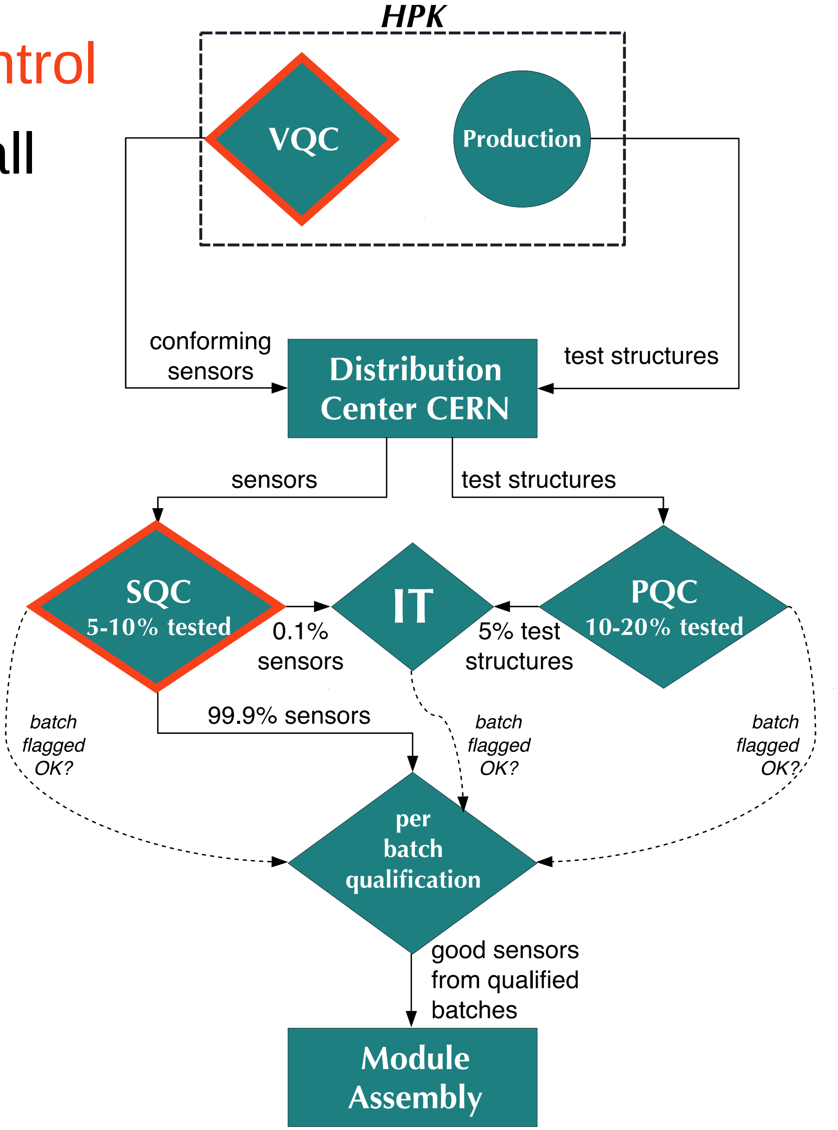
Hamamatsu test all sensors

Sensor quality control

Test centers in Brown, Rochester Karlsruhe, Delhi, Pakistan, Vienna



Tracker quality control process flow

Vendor quality control

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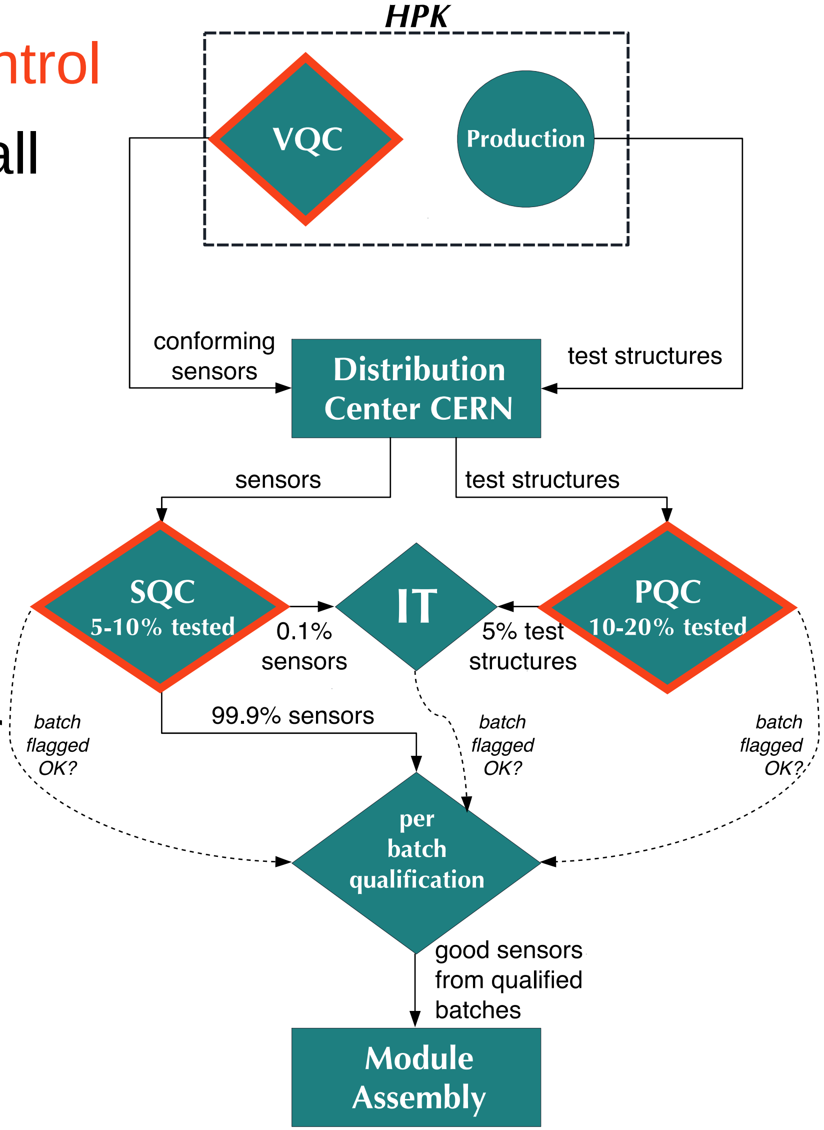
Process quality control

Test centers in Athens, Brown, Perugia, Vienna



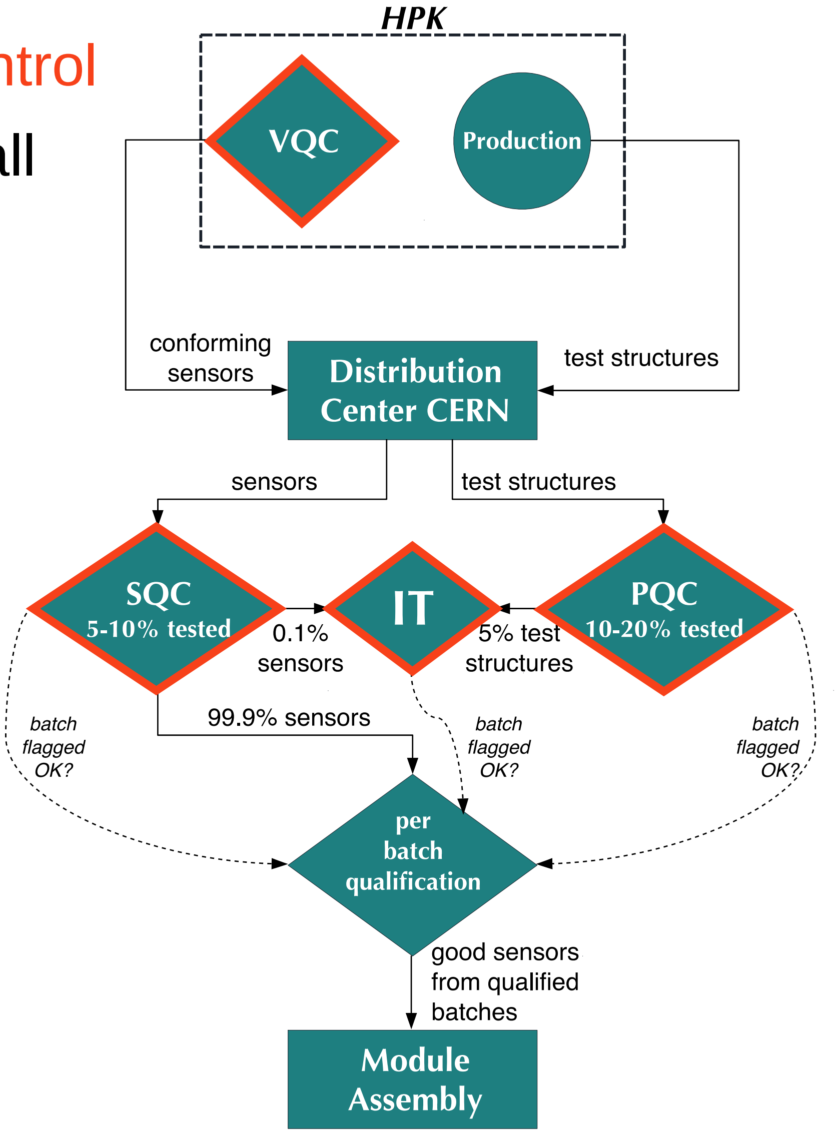
Tracker quality control process flow

Vendor quality control

Hamamatsu test all sensors

Irradiation tests

Brown, Karlsruhe



Sensor quality control

Test centers in Brown, Rochester Karlsruhe, Delhi, Pakistan, Vienna

Process quality control

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Tracker quality control process flow

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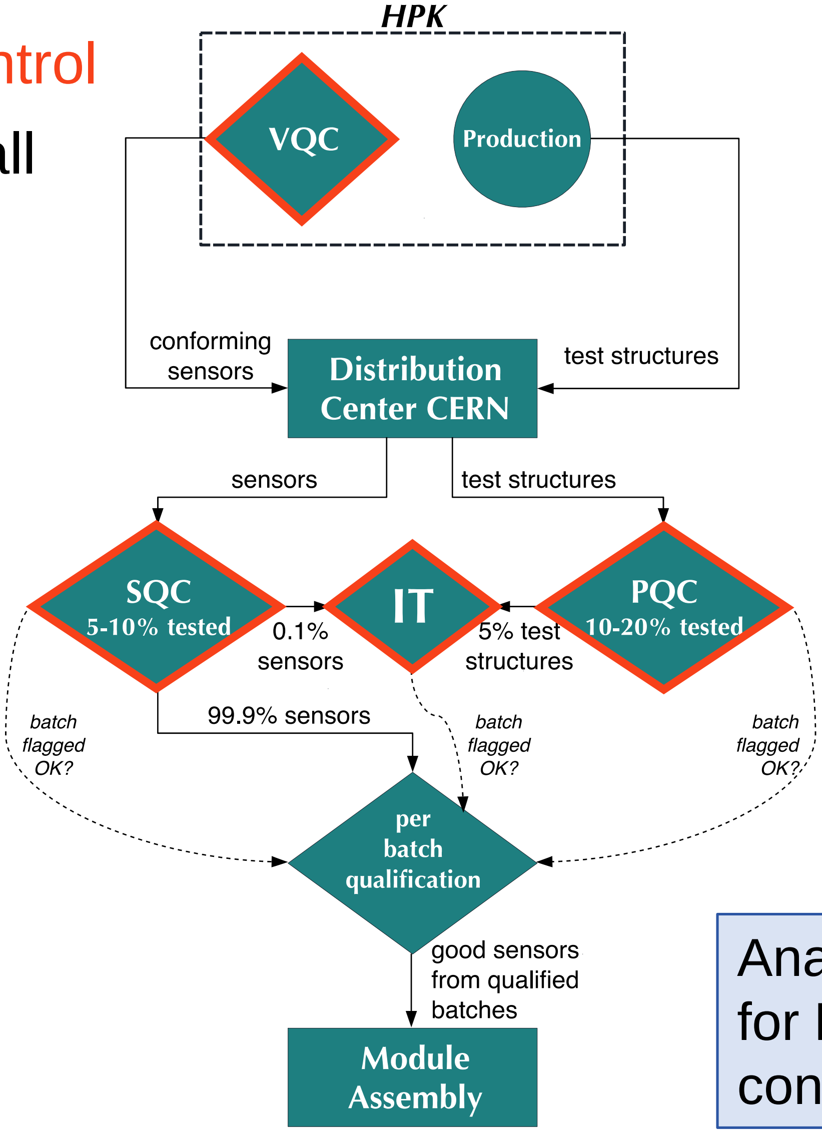


Irradiation tests

Brown, Karlsruhe

Process quality control

Test centers in Athens, Brown, Perugia, Vienna

Analogous procedure for HGCAL quality control!

Requirements for large-scale process quality control

Efficiency

Comparability

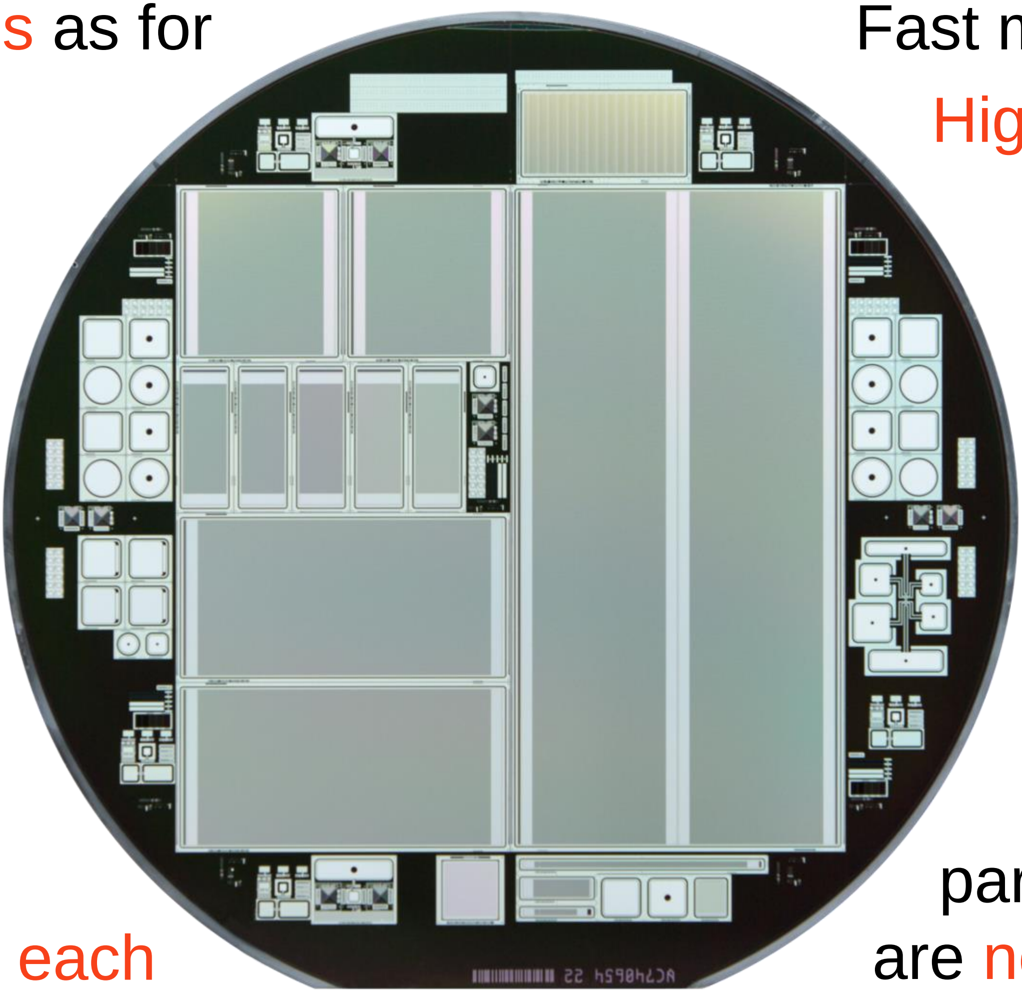
Sensitivity

Process quality control relies on test structures

Same process as for main sensor

Fast measurement

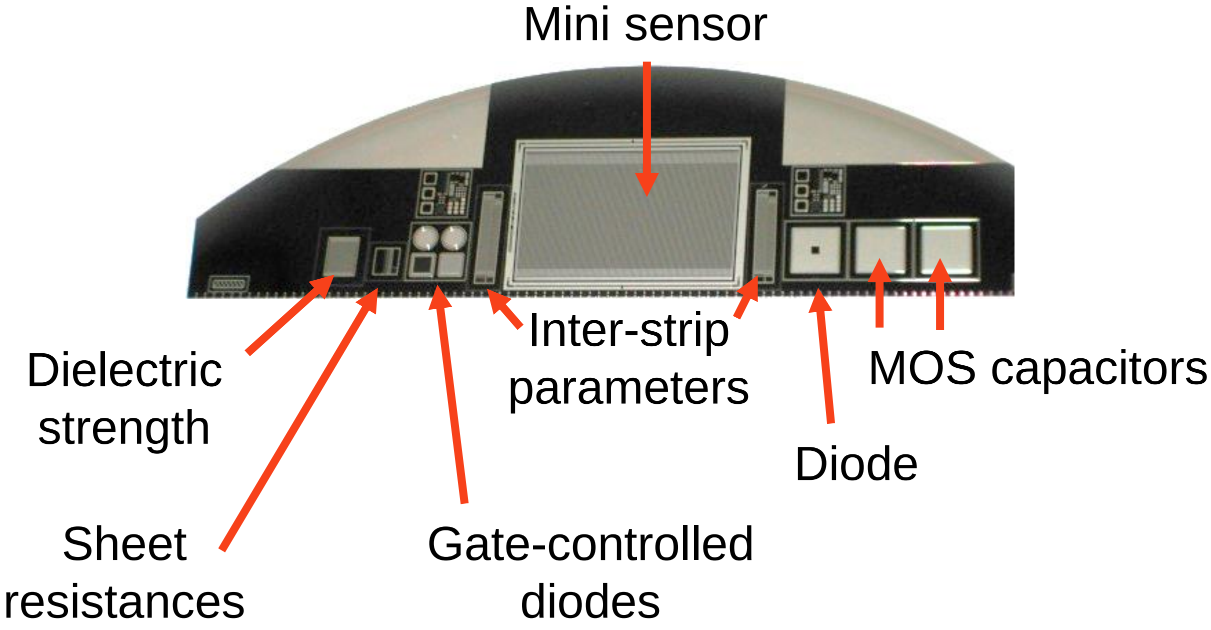
High throughput



Dedicated structures for each process parameter

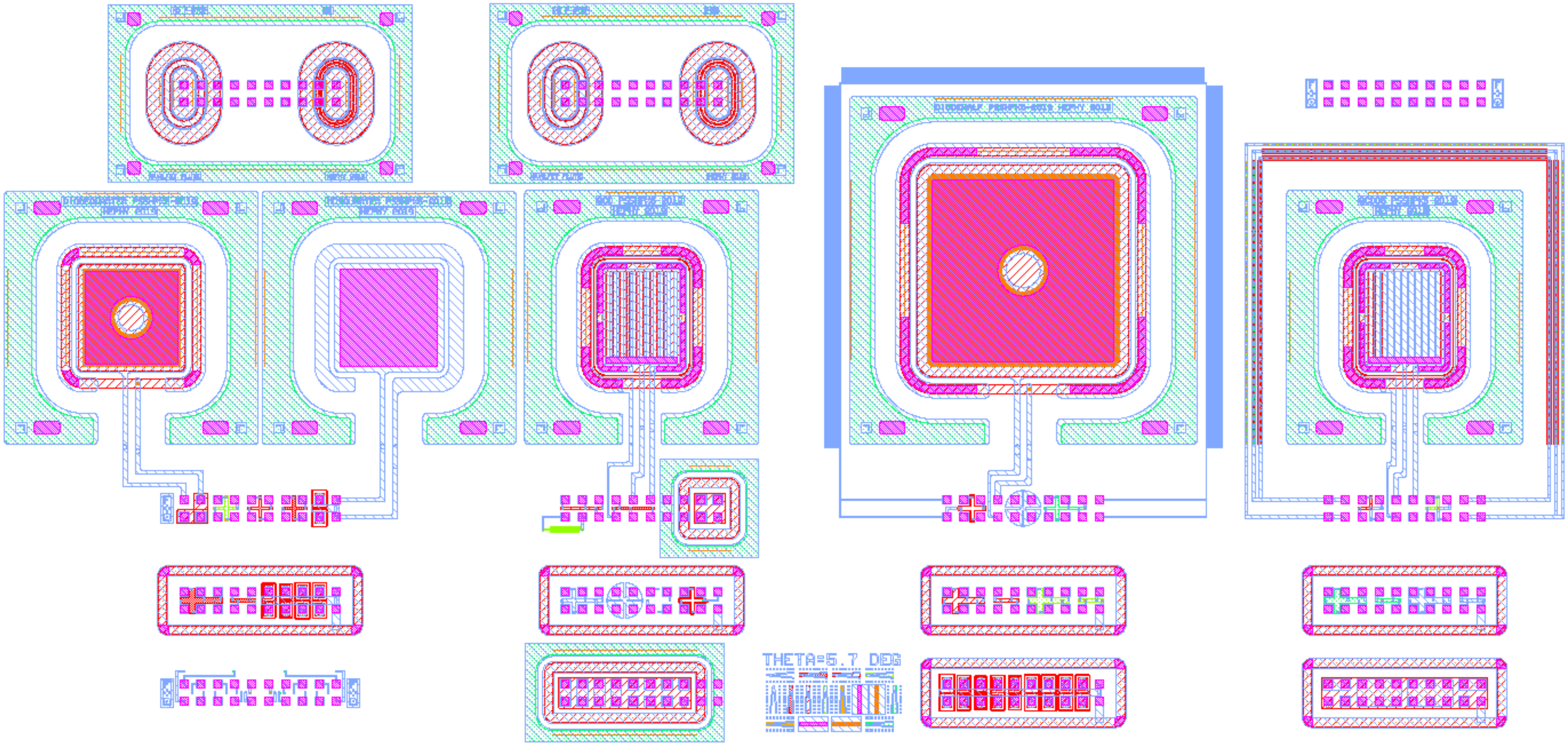
Access to parameters that are not accessible via sensor measurements

Tracker “Phase-0” process quality control

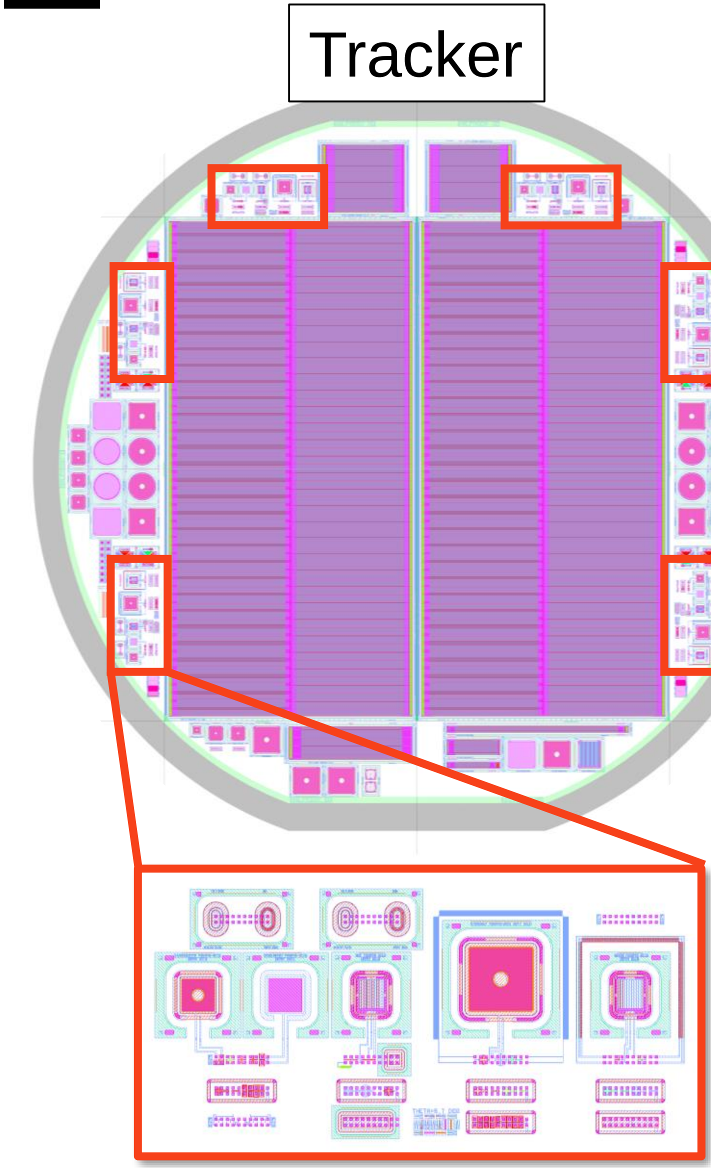


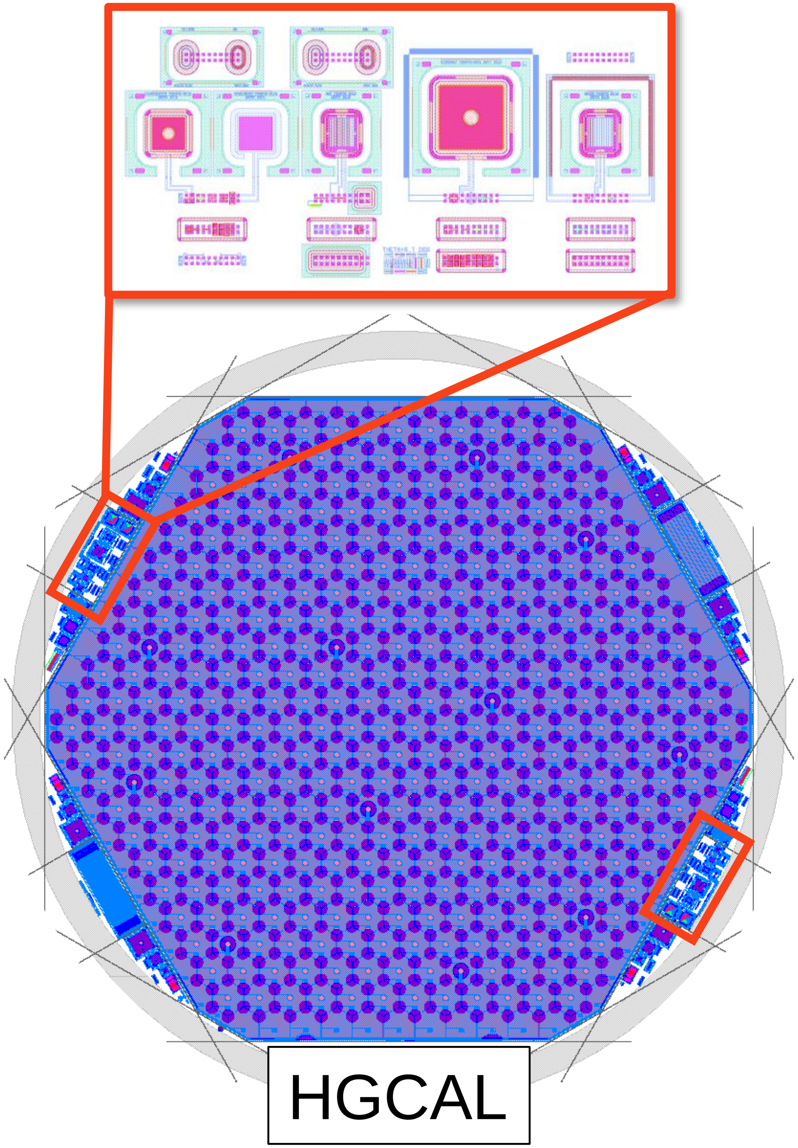
More problems were spotted with process quality control than during sensor tests!

A universal set of test structures

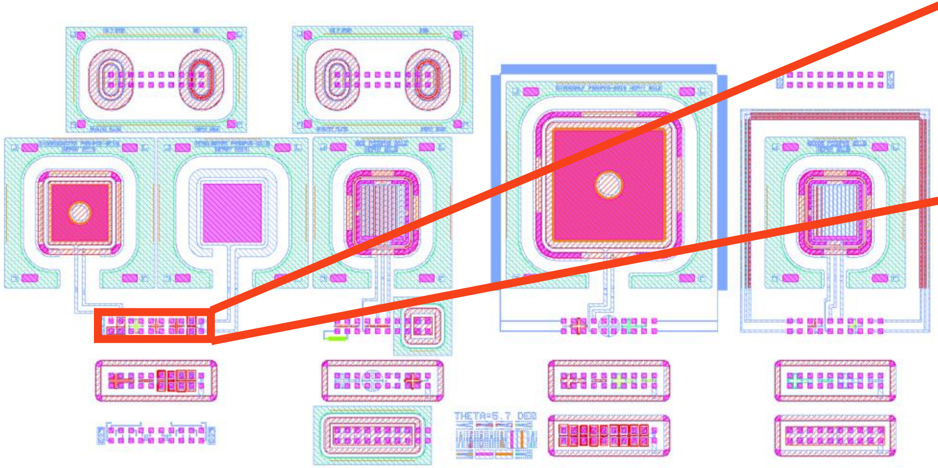


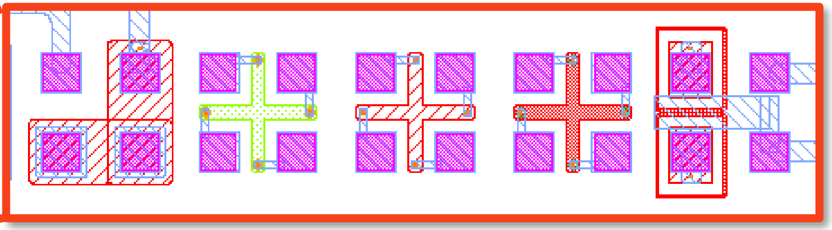
The set is implemented on each wafer





The “flute” concept

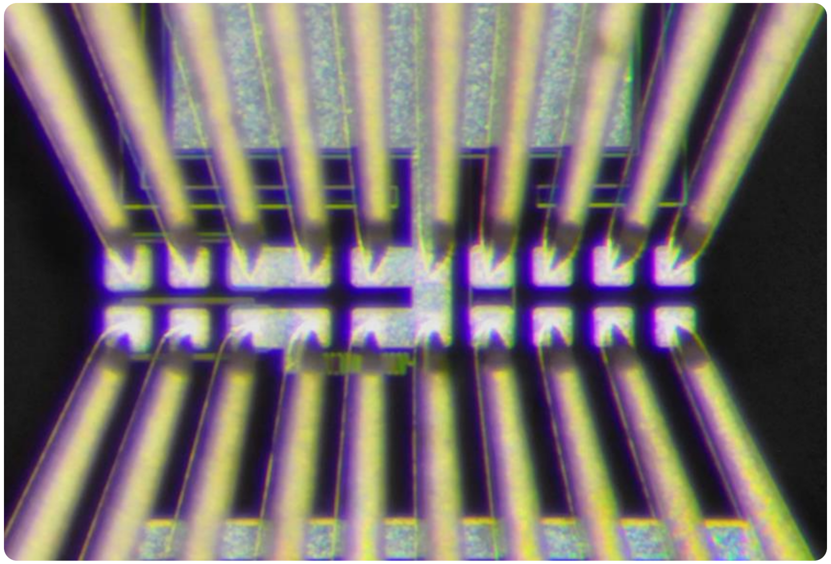


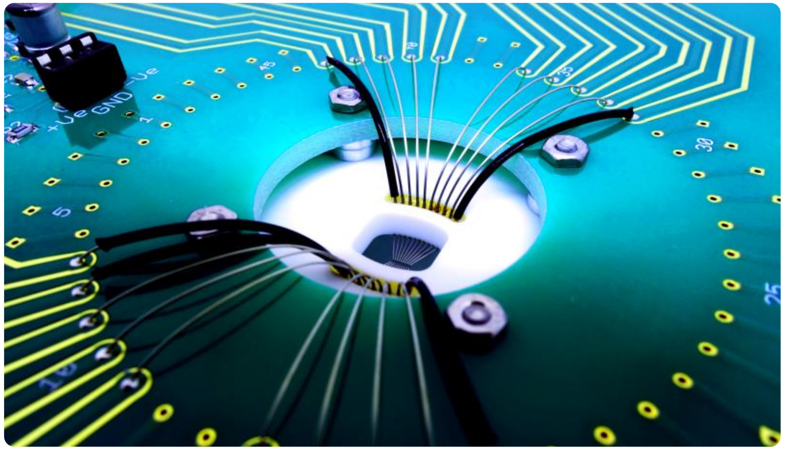


Array of 2 x 10 contact pads

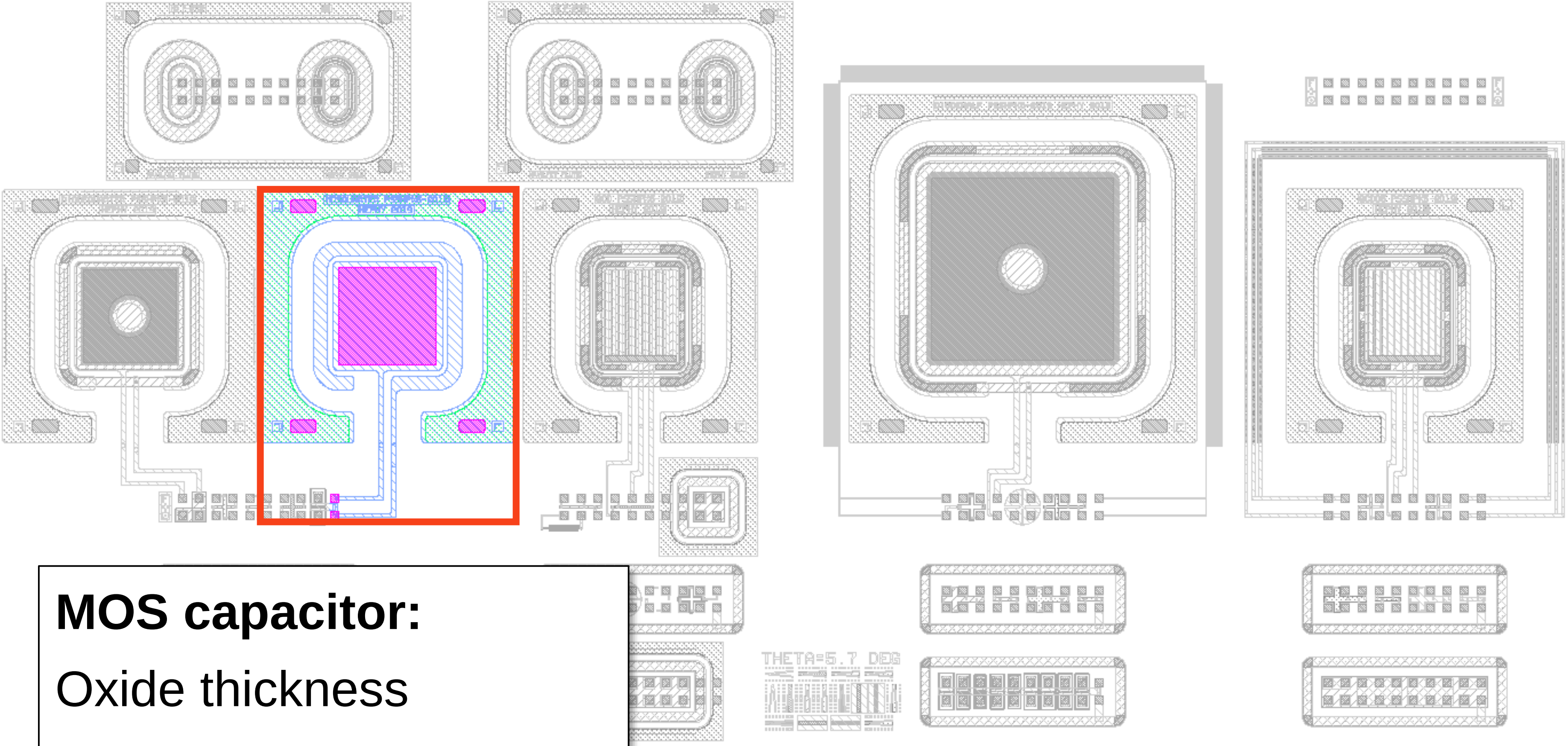
Facilitates probe card measurements

Inspired by industry





Oxide quality

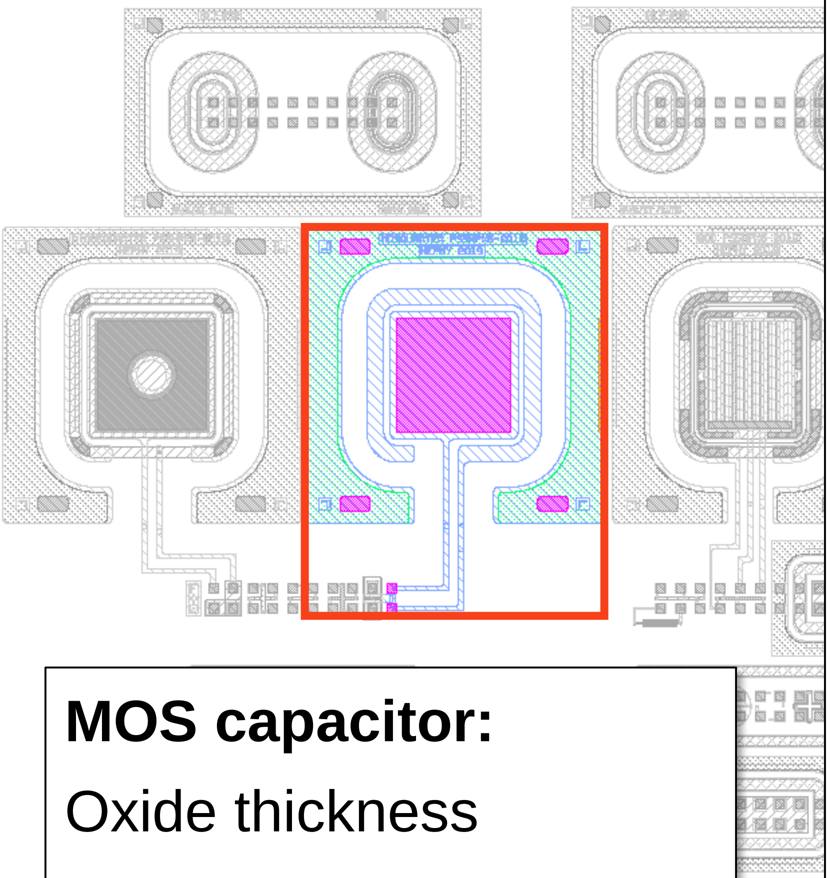


MOS capacitor:

Oxide thickness

Oxide fixed charges (V_{fb})

Oxide quality



MOS capacitor:

Oxide thickness

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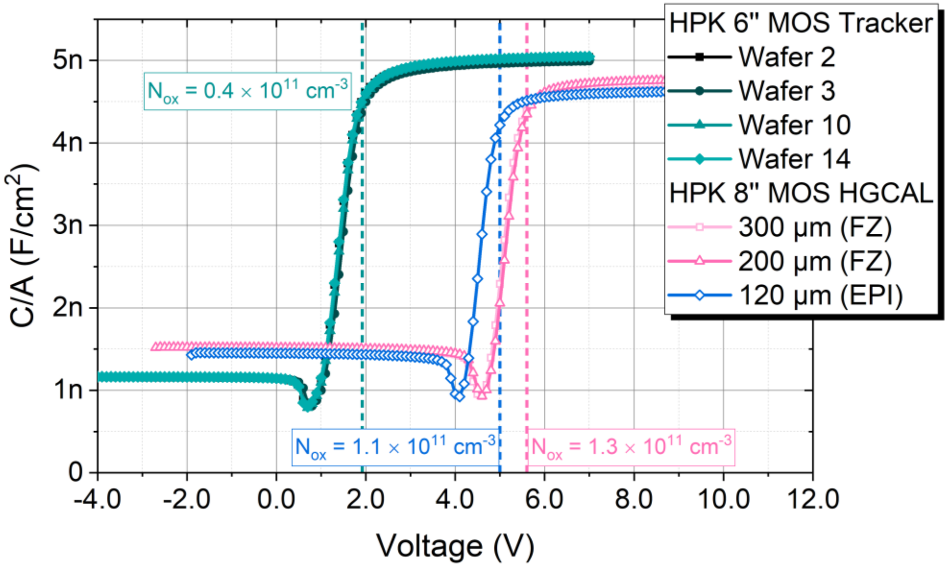
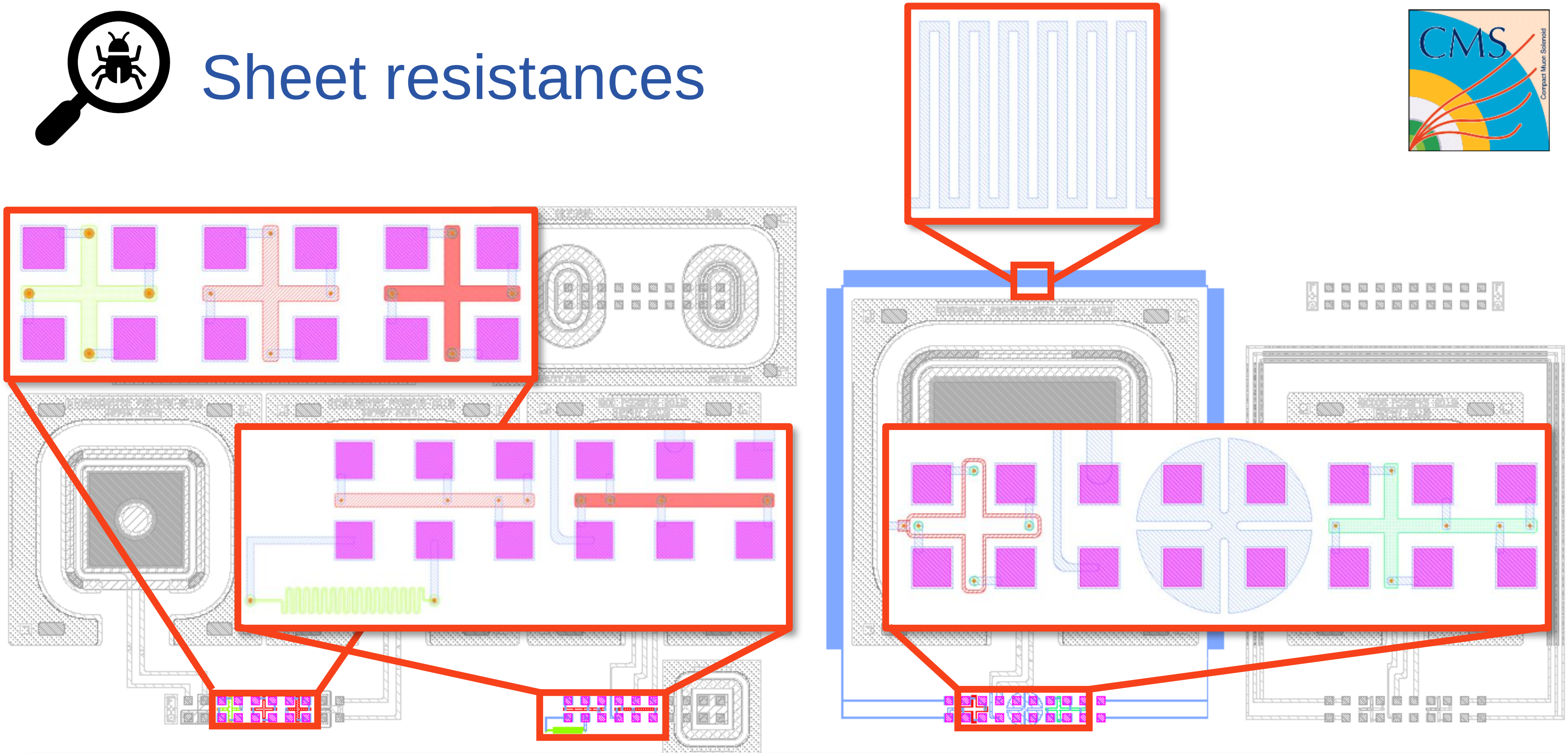


Differences between 6” and 8” process!

Differences between standard float zone and epitaxial process!

Sheet resistances



Van-der-Pauw structures:

Resistivity of thin films

Doping concentration

Film thickness

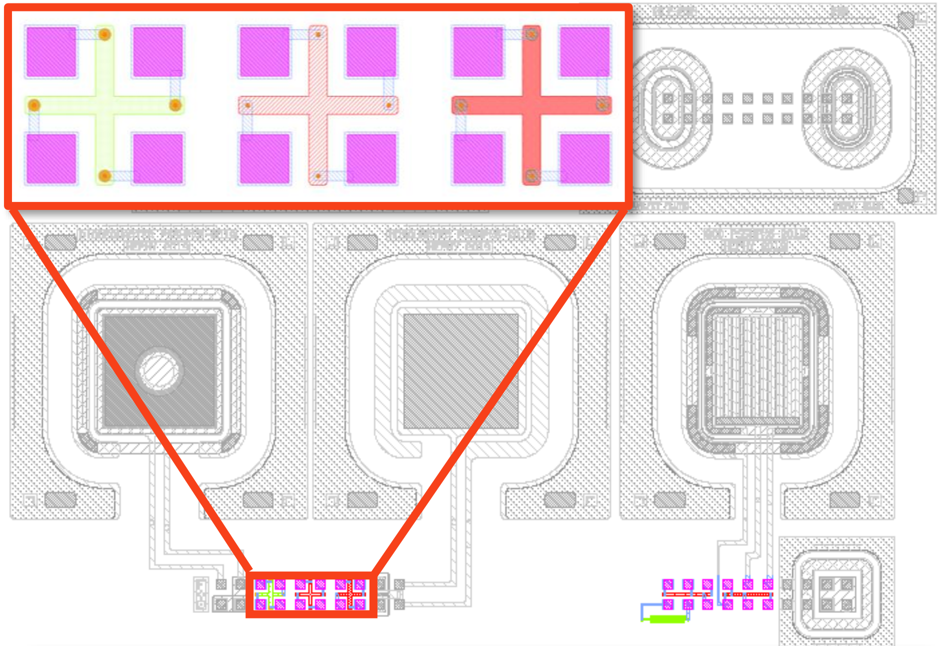
Meander structures:

Bias resistor

Metal sheet resistance

Complementary measure

Sheet resistances



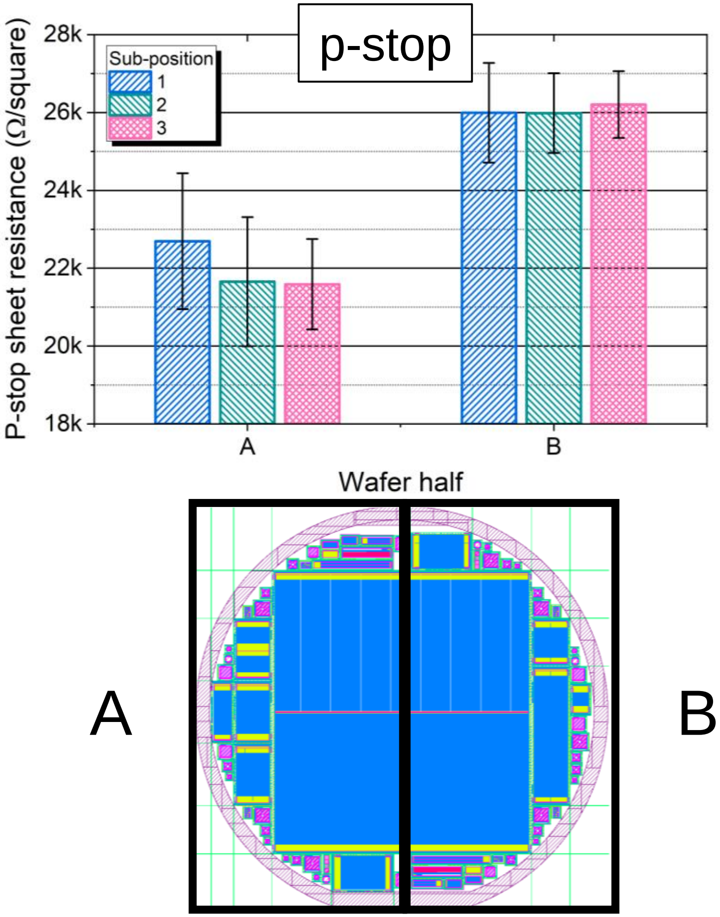
Van-der-Pauw structures:

Resistivity of thin films

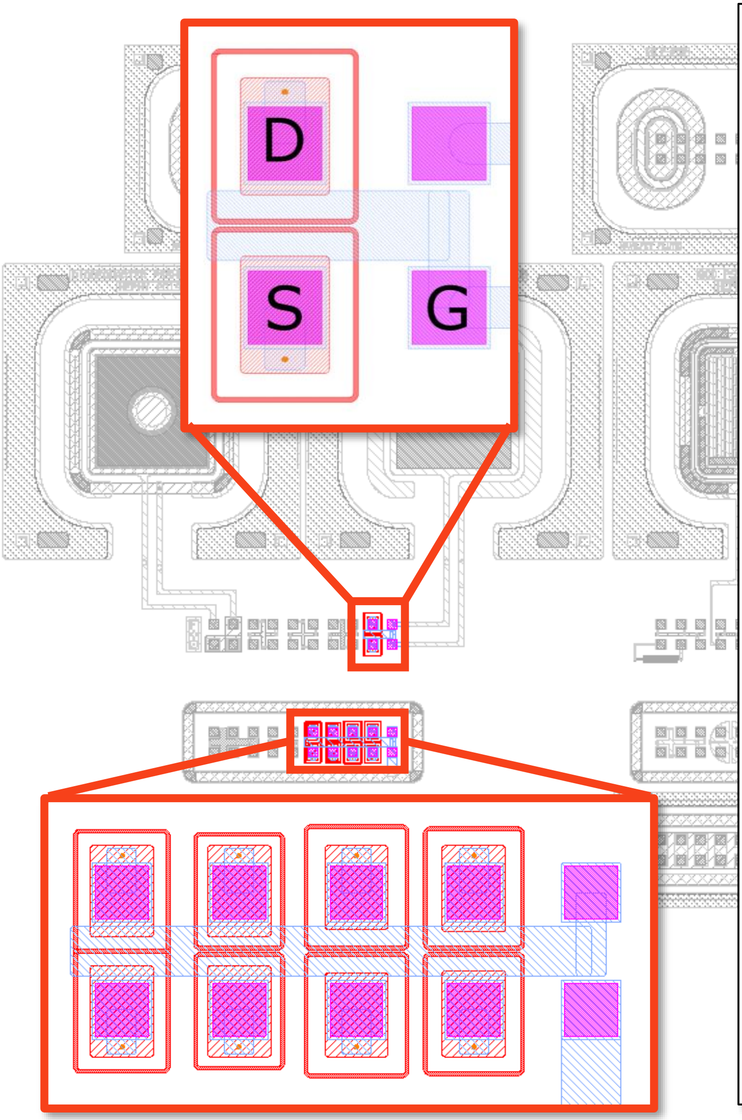
Doping concentration

Film thickness

Detect variations along wafer area



Inter-channel resistance



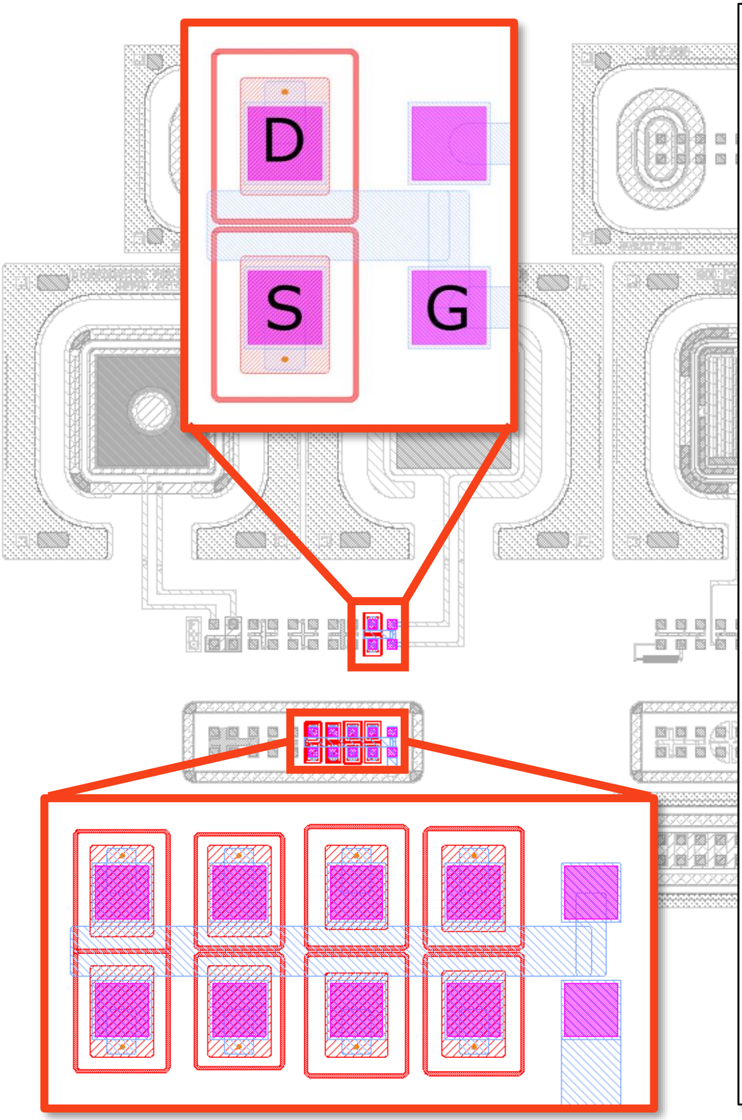
Field-effect transistors:

Threshold voltage

Sensitive to variations in p-stop parameters

Relates to inter-channel resistance

Inter-channel resistance



Field-effect transistors:

Threshold voltage

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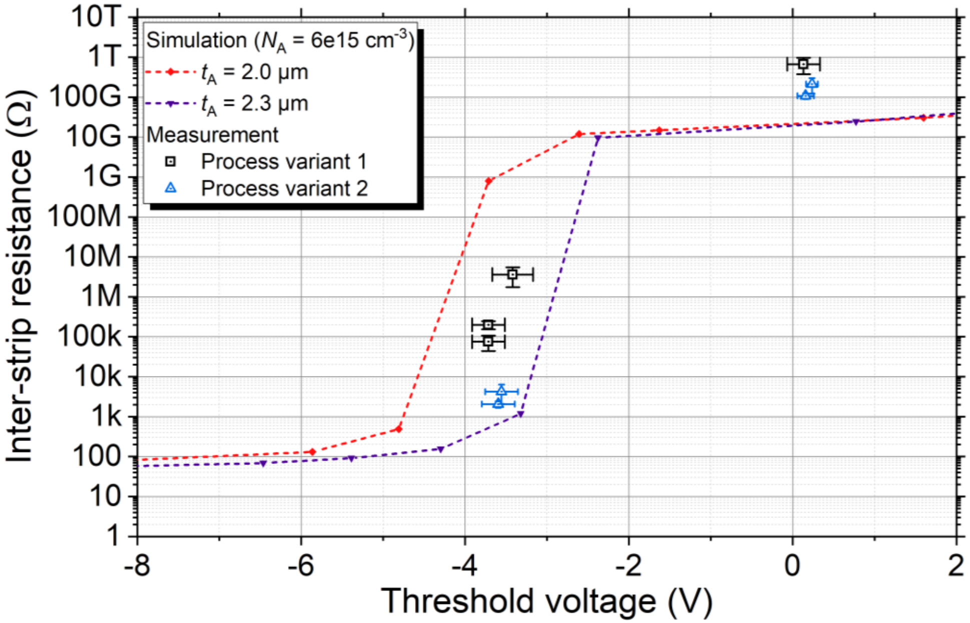
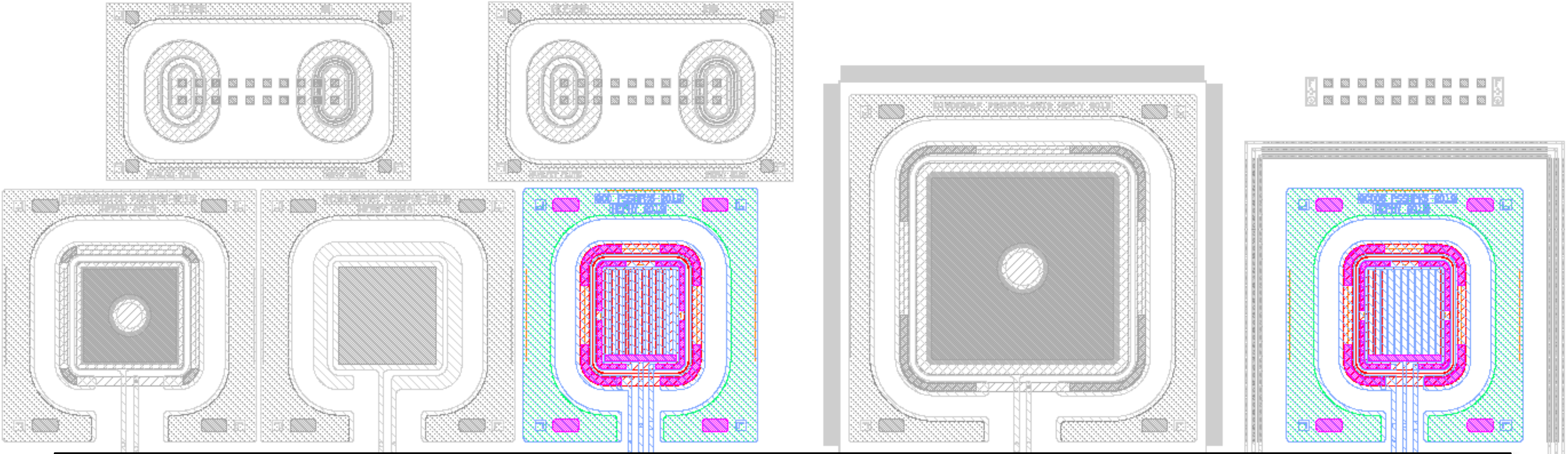


Silicon bulk, oxide quality

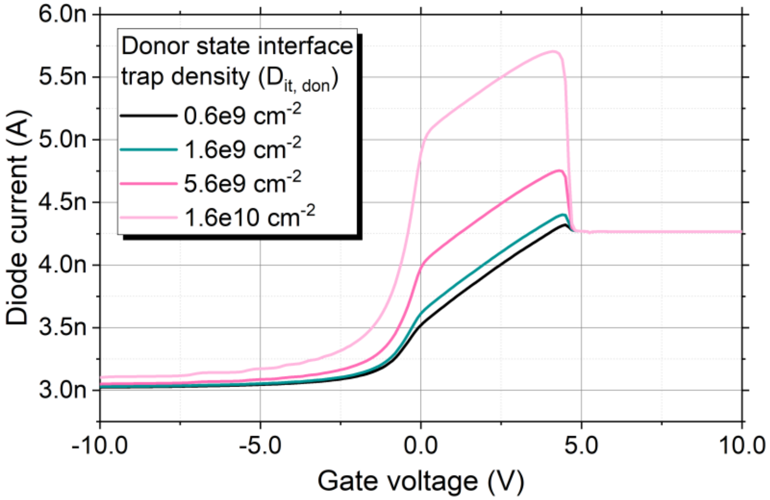


Gate-controlled diodes:

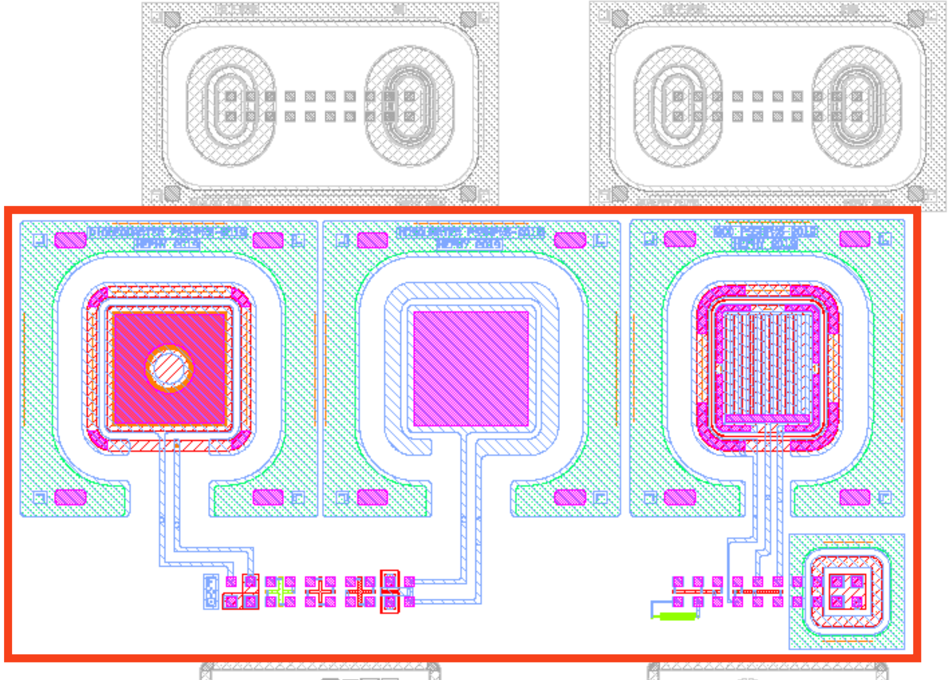
Interface traps

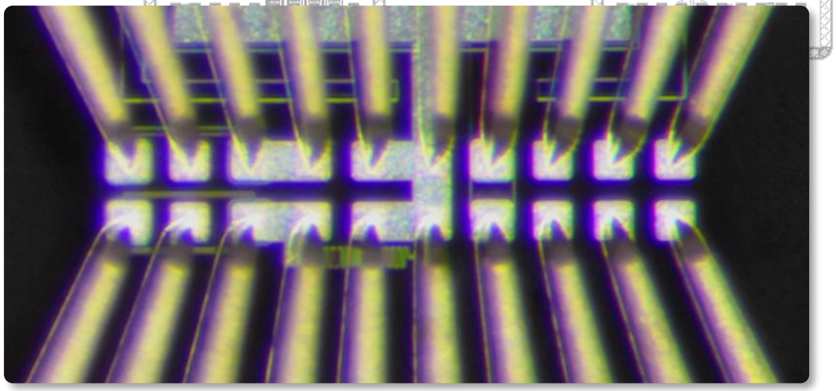
Generation lifetime

Different gate widths



Initial characterization in 30 minutes





2 standard flutes

Designed for automated measurement with probe card

Access to most relevant process parameters

Substrate resistivity

Oxide quality

Si/SiO_2 Interface

Sheet resistances

Inter-strip resistance

Summary and Outlook

~ 800 m^2 silicon and > 50,000 wafers for CMS tracker and calorimeter endcap

Process quality control concept relies on

Efficiency Comparability Sensitivity

Universal set of test structures optimized for probe card measurements

Initial analysis in ~ 30 minutes per wafer

Pre-production starts in March 2020

Combined sensor and process quality control and irradiation tests

DEMOKRITOS

Istituto Nazionale di Fisica Nucleare

Istituto Officina dei Materiali

ÖAW AUSTRIAN ACADEMY OF SCIENCES

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

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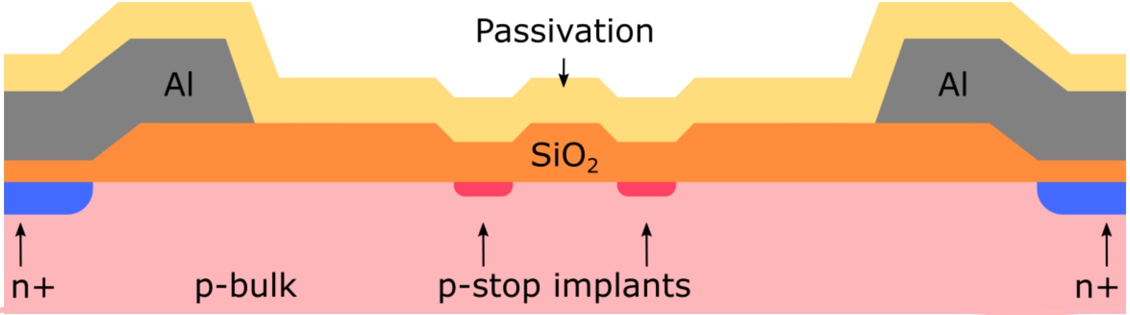
Spares

Process parameters



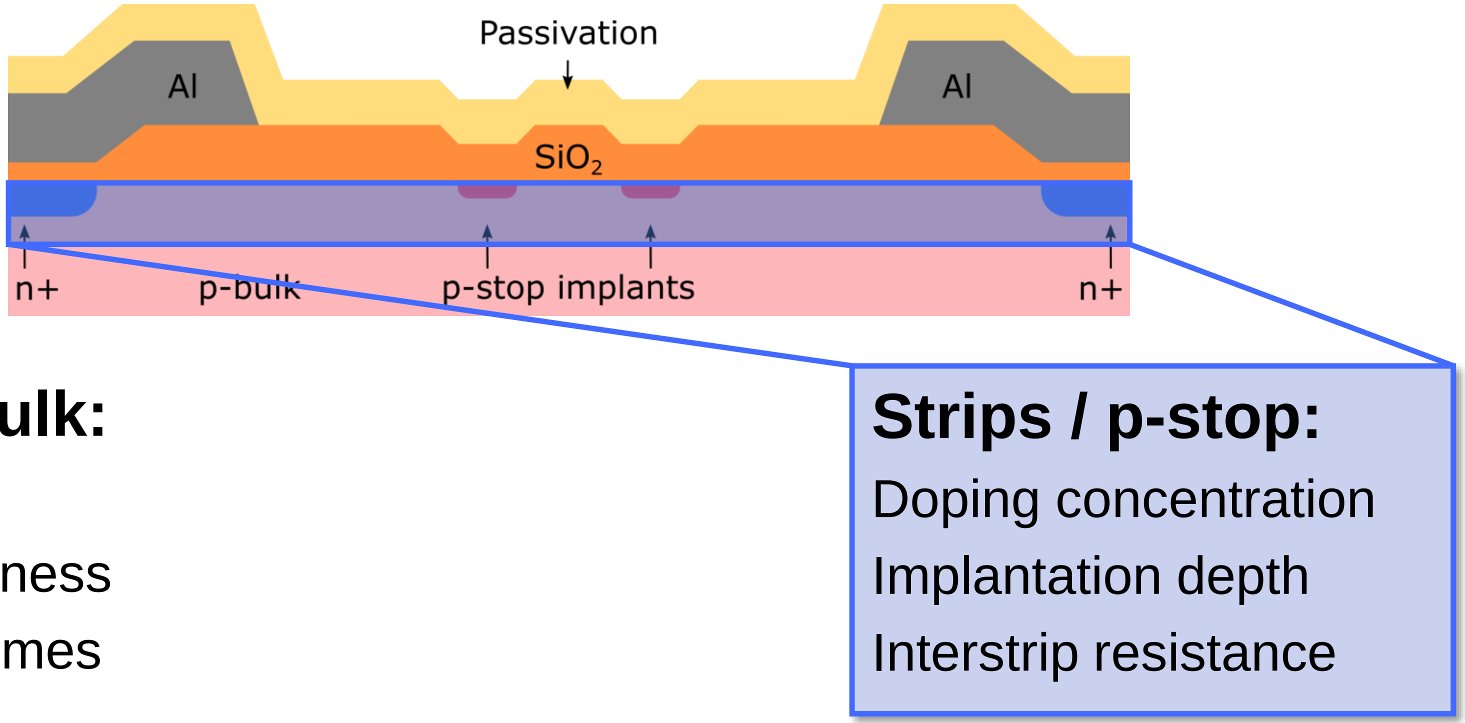
Silicon bulk:

Resistivity

Active thickness

Carrier lifetimes

Process parameters



Silicon bulk:

Resistivity

Active thickness

Carrier lifetimes

Strips / p-stop:

Doping concentration

Implantation depth

Interstrip resistance

Process parameters

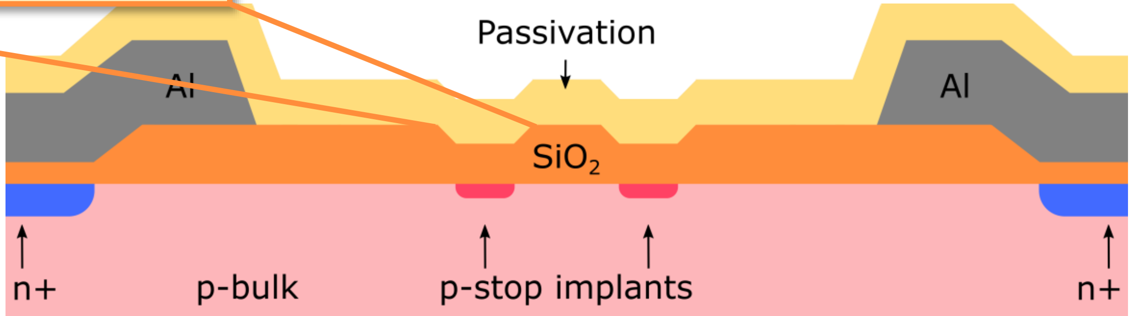
Oxide:

Oxide charges

Thickness

Si/SiO_2 Interface

Dielectric strength



Silicon bulk:

Resistivity

Active thickness

Carrier lifetimes

Strips / p-stop:

Doping concentration

Implantation depth

Interstrip resistance

Process parameters

Oxide:

Oxide charges

Thickness

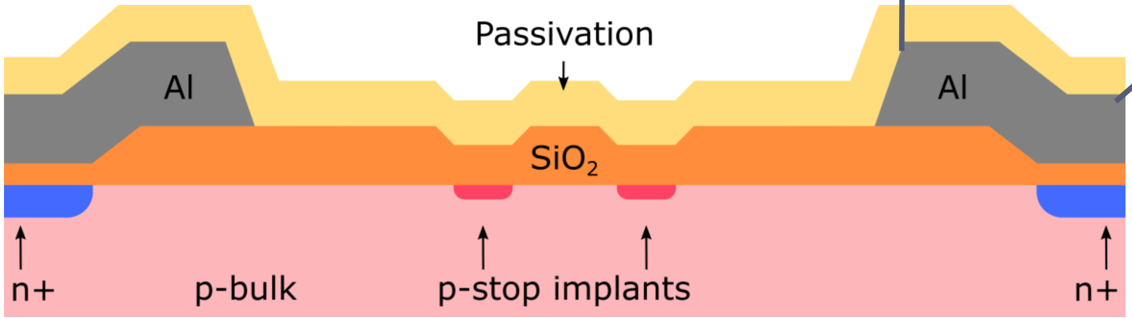
Si/SiO_2 Interface

Dielectric strength

Metal:

Over-etching

Sheet resistance



Silicon bulk:

Resistivity

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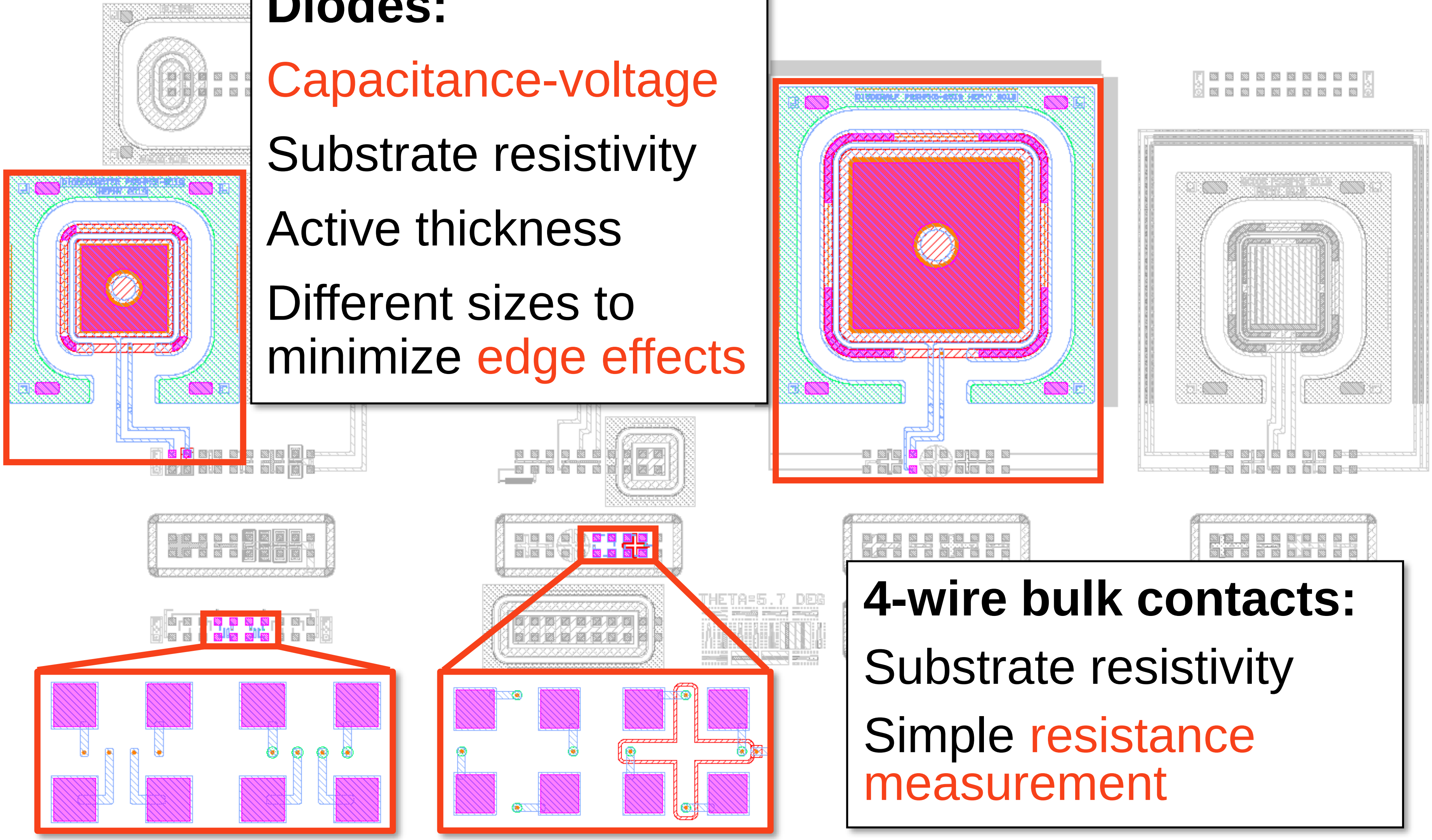
Interstrip resistance

Silicon bulk



Diodes:

Capacitance-voltage

Substrate resistivity

Active thickness

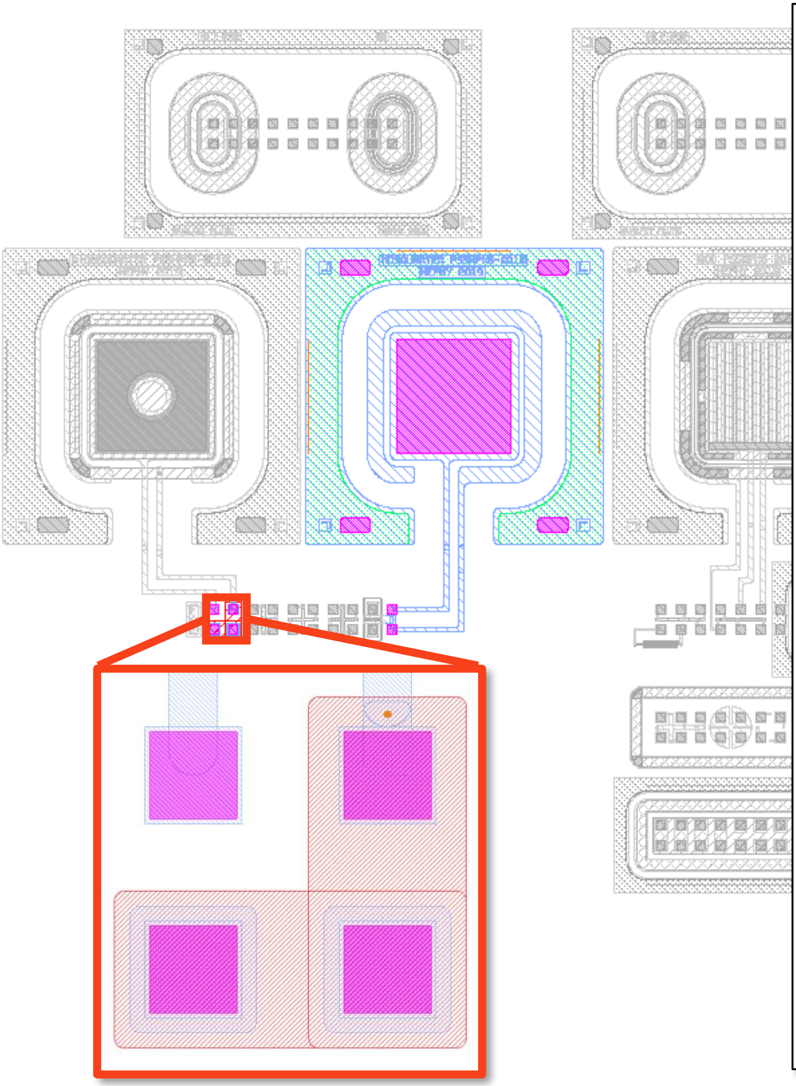
Different sizes to minimize edge effects

4-wire bulk contacts:

Substrate resistivity

Simple resistance measurement

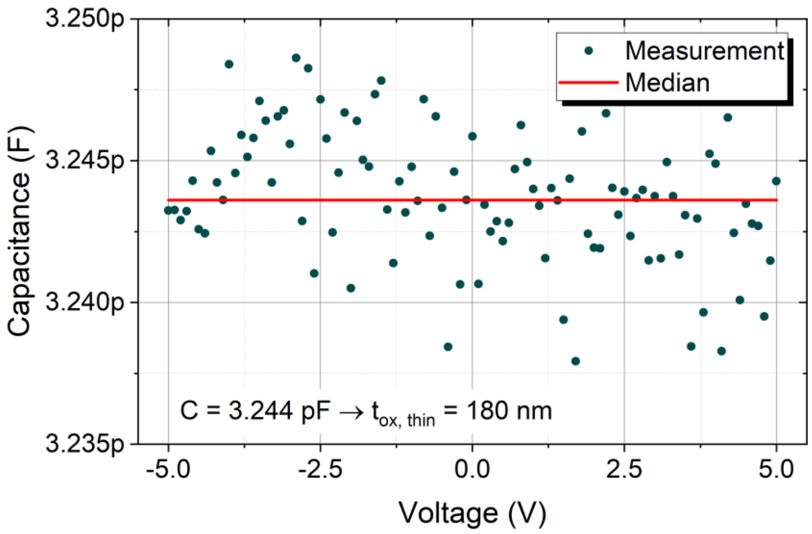
Oxide quality



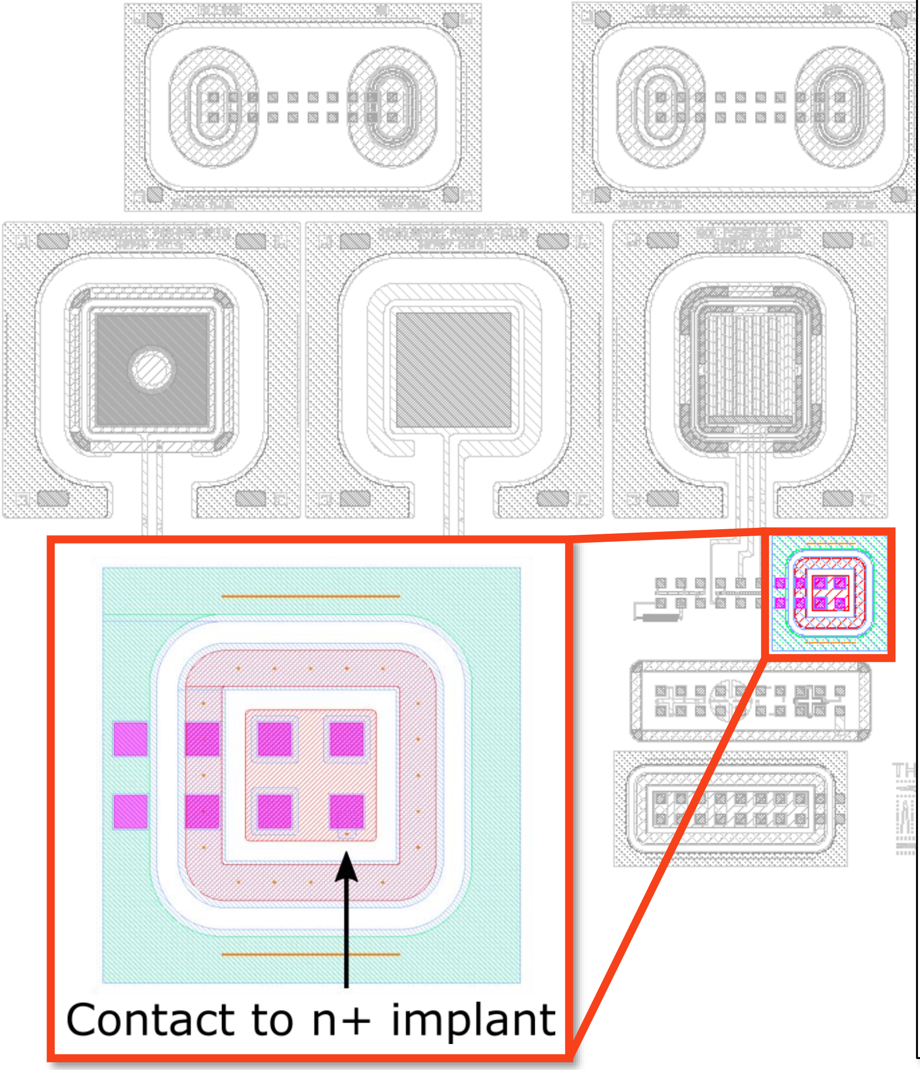
Capacitors over n+ implant:

Coupling capacitance

Thickness of the coupling dielectric



Oxide quality

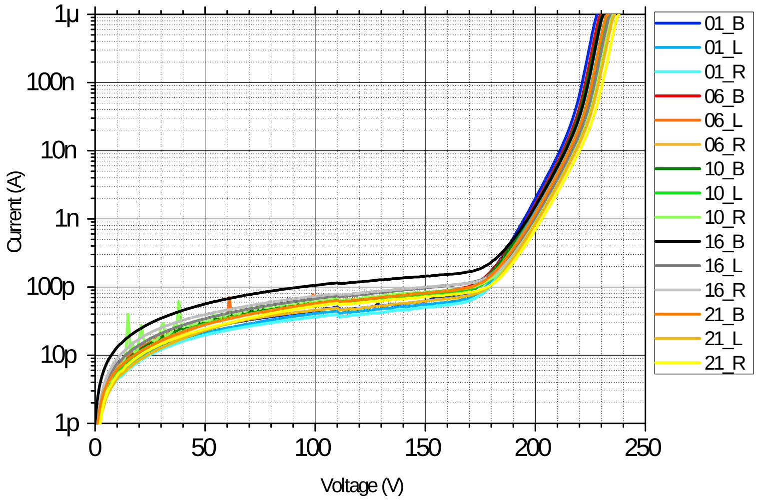


Dielectric breakdown test structure:

Dielectric strength

Voltage ramps

Destructive!

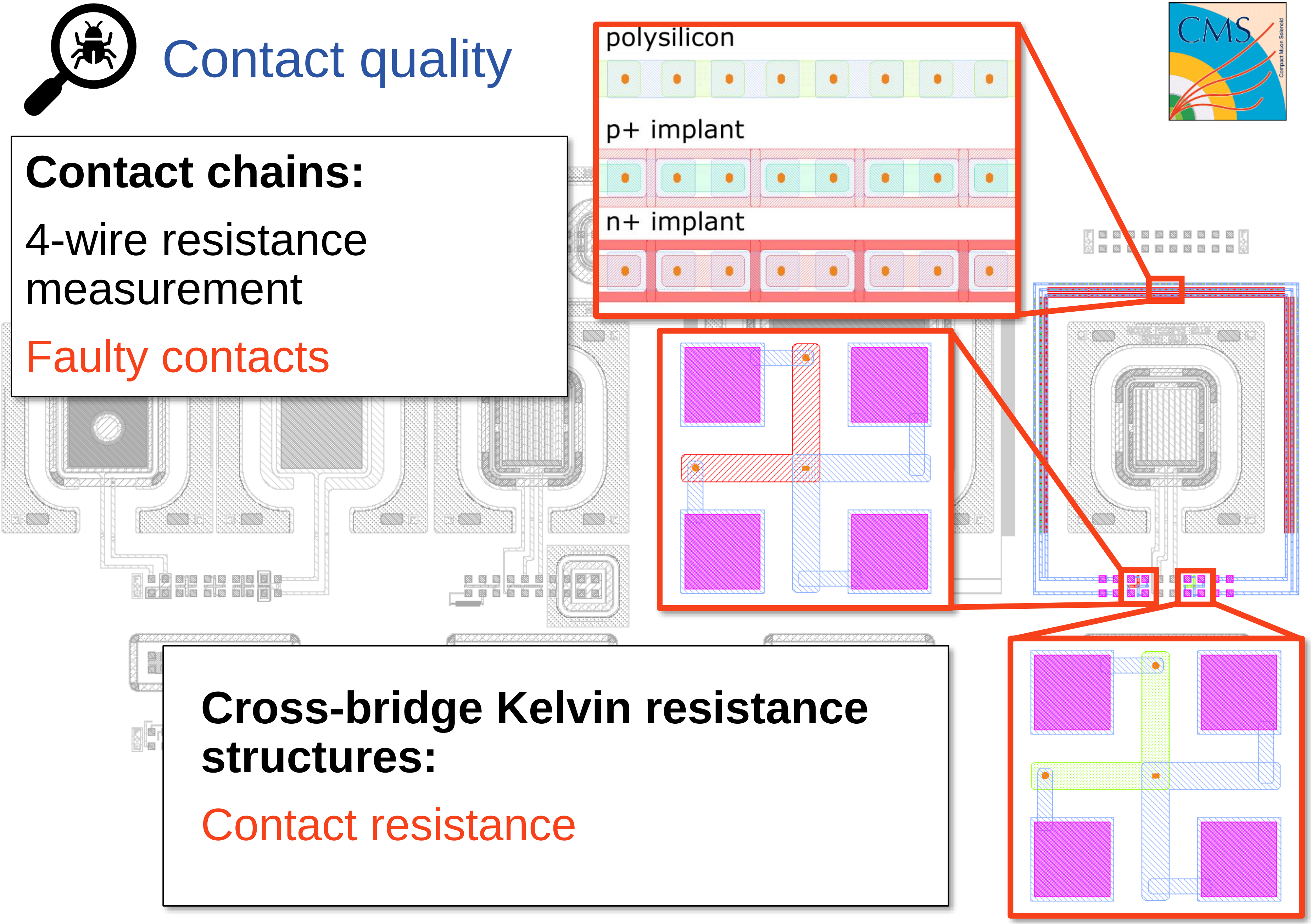


Contact quality

Contact chains:

4-wire resistance measurement

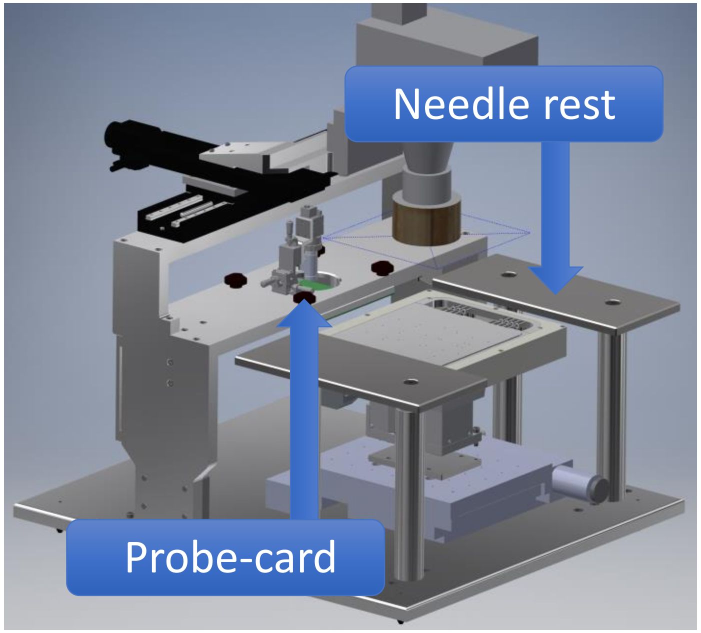
Faulty contacts

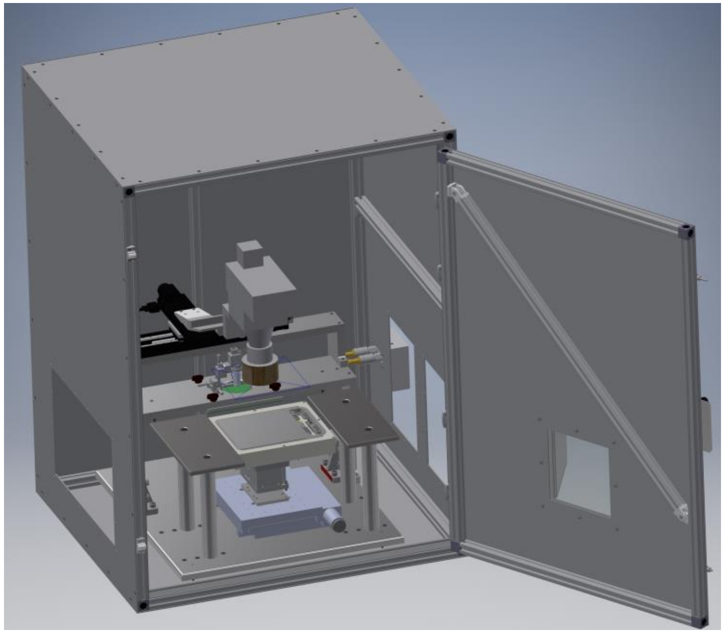


Cross-bridge Kelvin resistance structures:

Contact resistance

Probe station





Automated probe card measurements using camera

Manual positioner measurements using microscope

Measurement equipment

Switching system:

Keithley 707B main frame, 7072(-HV)

Source Measure Units:

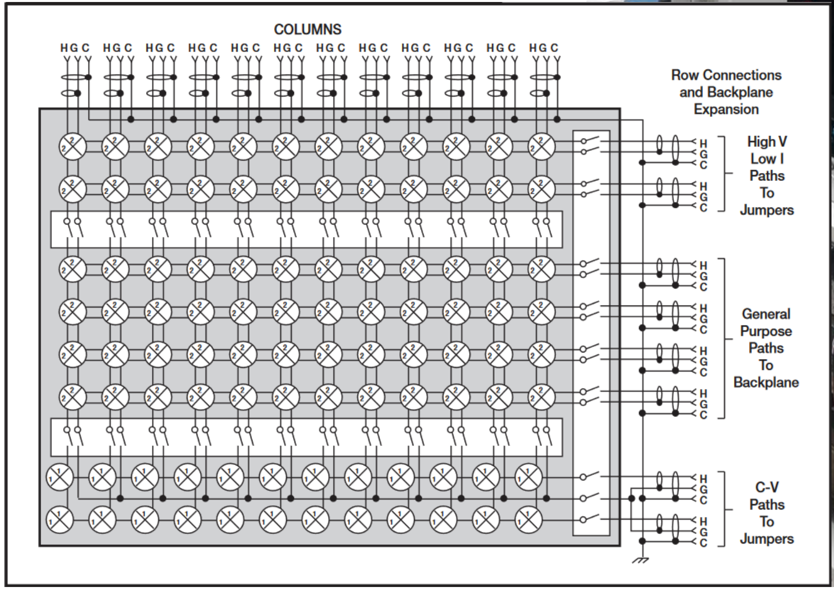
Keithley 2657A, 2410, 237

Electrometer:

Keithley 6485, 6517A/B

LCR Meter:

Keysight E4980A



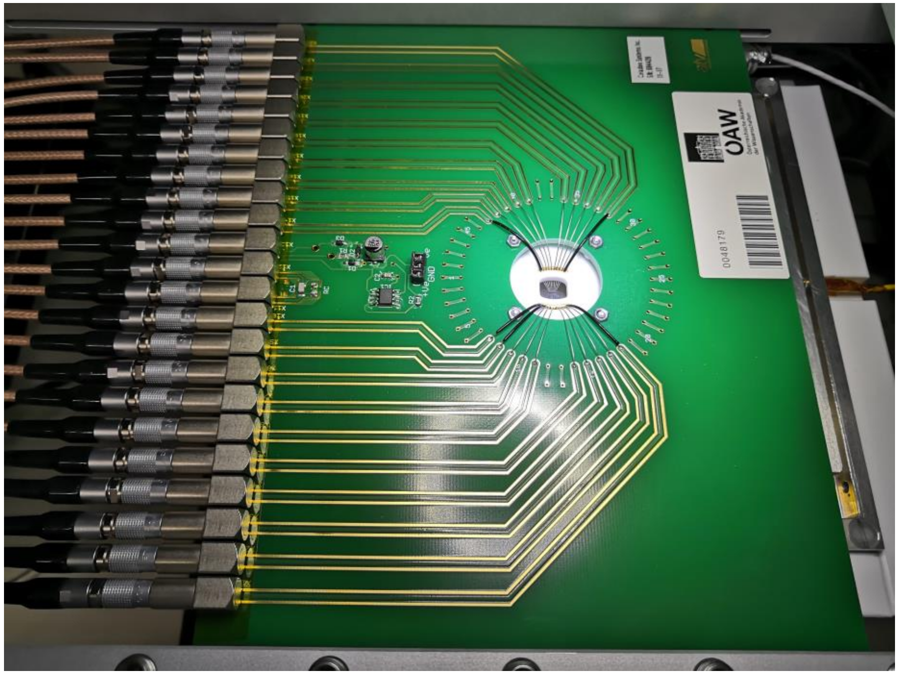
7072-HV card

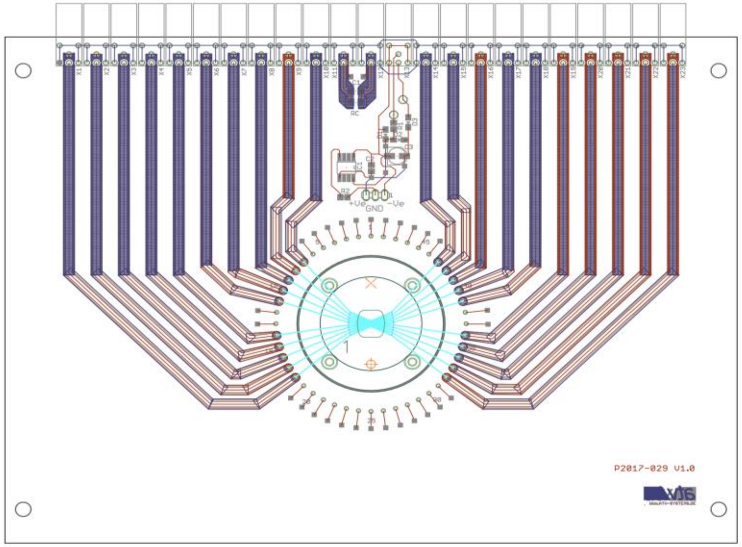
Probe card

Celadon Systems

Custom PCB (includes temperature sensor and test RC circuit)

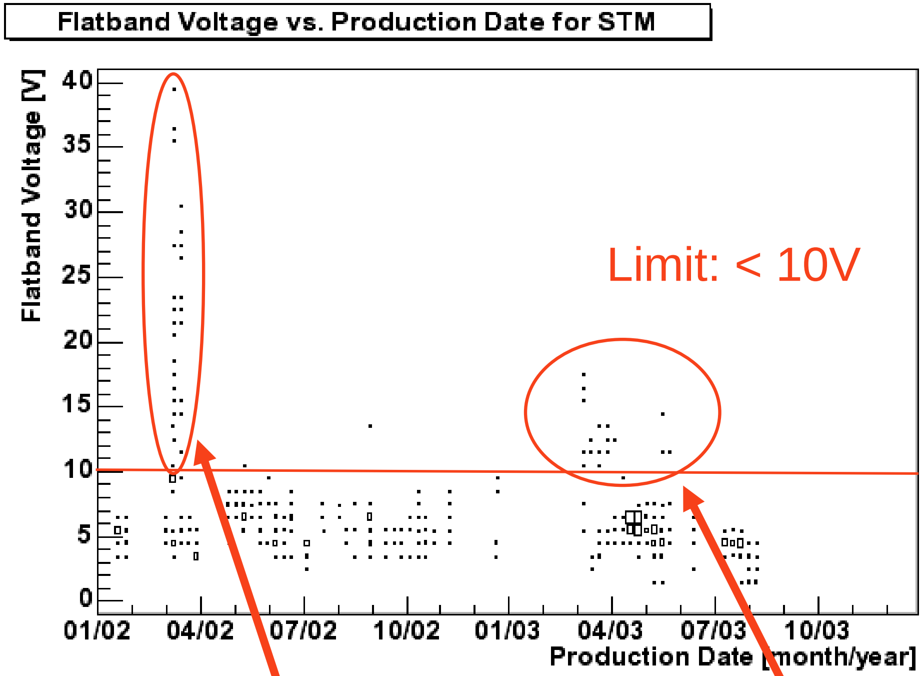
23 LEMO-00 Triax connectors



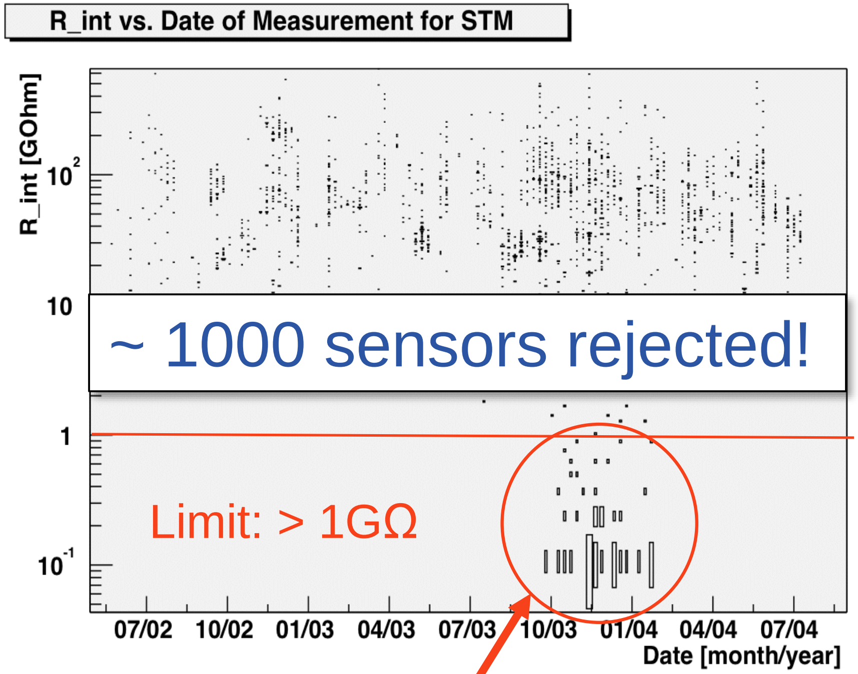


Tracker “Phase 0” example:
Flat-band voltage and inter-strip resistance

Flat-band voltage



Inter-strip resistance



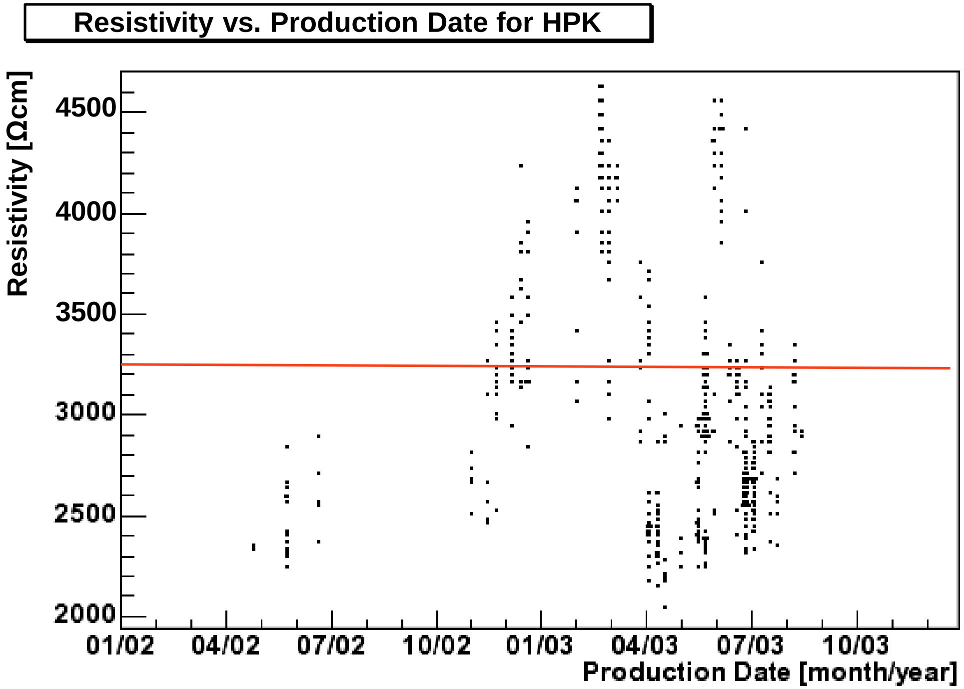
~ 1000 sensors rejected!

High flat-band voltages at STM around March 2002

Later batches above limit

Inter-strip resistance below limit

Tracker "Phase 0" example: Substrate resistivity



Requirement:

$V_{dep} < 400V$ after 10 years of LHC operation

$1.25 < \rho < 3.25$ kΩcm for inner tracker thin sensors by HPK

Agreement:

→CMS accepted all wafers

→Wafers with lower resistivity are used in inner layers