Microelectronic Test Structures for the Development of a Strip Sensor Technology for High Energy Physics

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Outline

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  - Development of Strip Sensor Technologies for HL-LHC
  - Key Parameters of Strip Sensor Technology

- ❑ **Layout Design**
  - Microelectronic Test Structures for Technology Validation

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    - Full Depletion Voltage (V_{FD}) – Gamma Influence
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  - ▪ **Sensor Edge**
    - Breakdown Voltage (V_{BD}) vs. Edge Distance – Proton Influence
  - ▪ **Metal-Oxide-Semiconductor (MOS) Capacitor**
    - Flat Band Voltage (V_{FB})
    - Field Oxide Capacitance (C_{ox})
  - ▪ **Gate-controlled Diode**
    - Flat Band Voltage (V_{FB}) – Gamma Influence
    - Surface Generation Current – Gamma Influence

- ❑ **Conclusions**

Framework

Development of Strip Sensor Technologies for HL-LHC

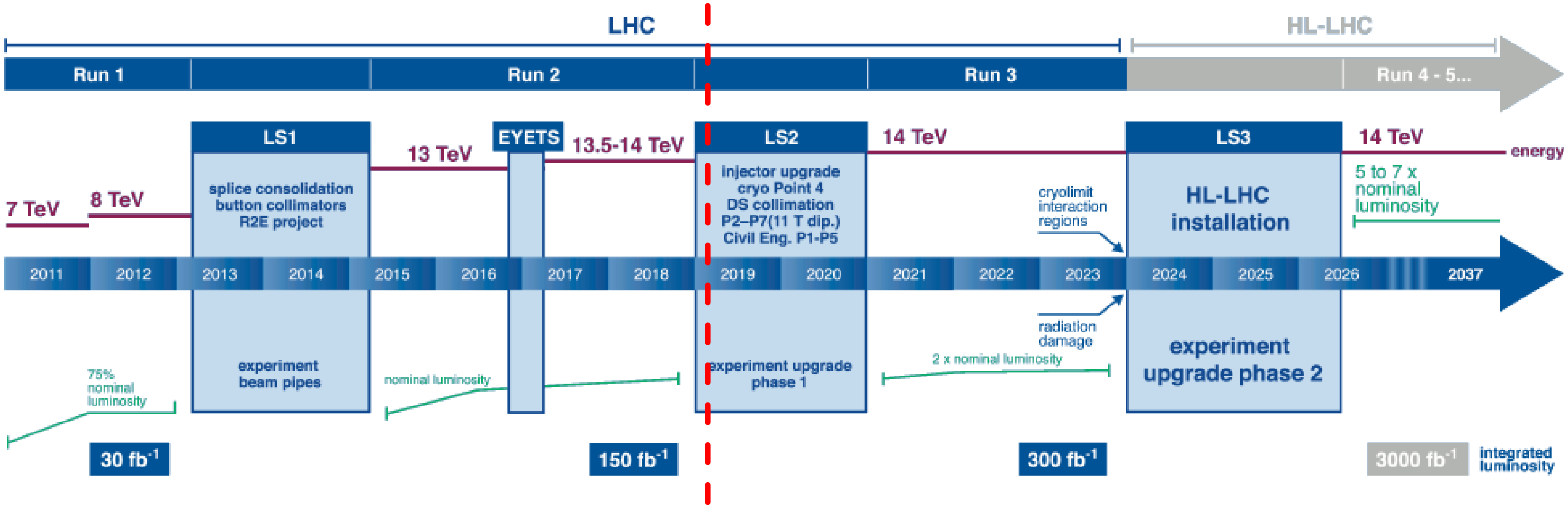
- **One order of magnitude more data will be collected in the new HL-LHC**[*]
- **Increased radiation damage** expected for the new sensors (10 times higher than LHC)
- Development, fabrication and assembly of new strip sensors needed

➢ **Key role of microelectronic test structures for technology evaluation** and development during the **Market Survey** of foundries

➢ Test structures **will be implemented for sensor pre-production** as well, for the purpose of **quality assurance/control (QA/QC)** monitoring

➢ This work presents a set of **test structures designed at CNM-Barcelona**, and included on the ATLAS barrel long-strip layout design for the evaluation of Infineon as sensor vendor

➢ Results for the newest and most relevant structures are presented



Today

(14th Trento Workshop on Advanced Silicon Radiation Detectors)

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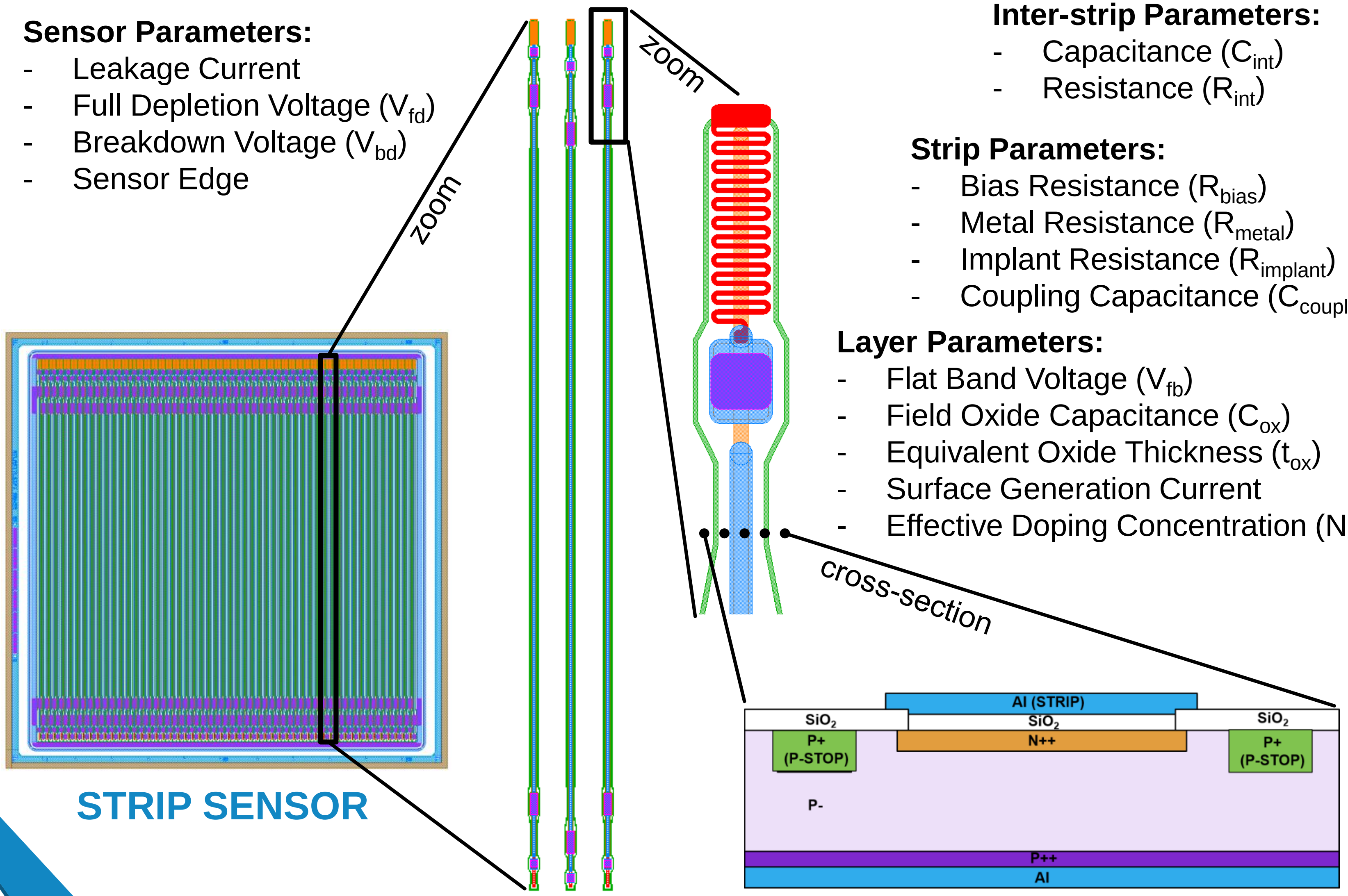
[*] The HL-LHC Project, https://hilumilhc.web.cern.ch/about/hl-lhc-project

Framework

Key parameters of Strip Sensor Technology

Sensor Parameters:

- Leakage Current
- Full Depletion Voltage (V_{fd})
- Breakdown Voltage (V_{bd})
- Sensor Edge



STRIP SENSOR

Inter-strip Parameters:

- Capacitance (C_{int})
- Resistance (R_{int})

Strip Parameters:

- Bias Resistance (R_{bias})
- Metal Resistance (R_{metal})
- Implant Resistance ($R_{implant}$)
- Coupling Capacitance (C_{coupl})

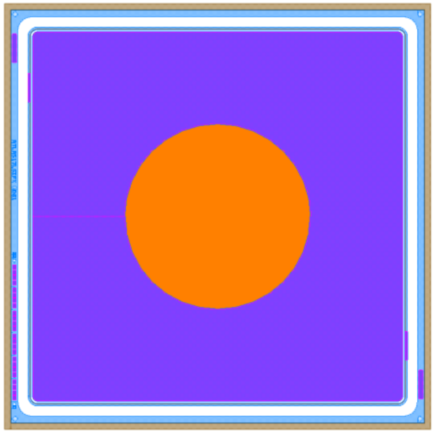
Layer Parameters:

- Flat Band Voltage (V_{fb})
- Field Oxide Capacitance (C_{ox})
- Equivalent Oxide Thickness (t_{ox})
- Surface Generation Current
- Effective Doping Concentration (N_{eff})

Layout Design

Microelectronic Test Structures for Technology Validation

(Test structures distributed accross the wafer)

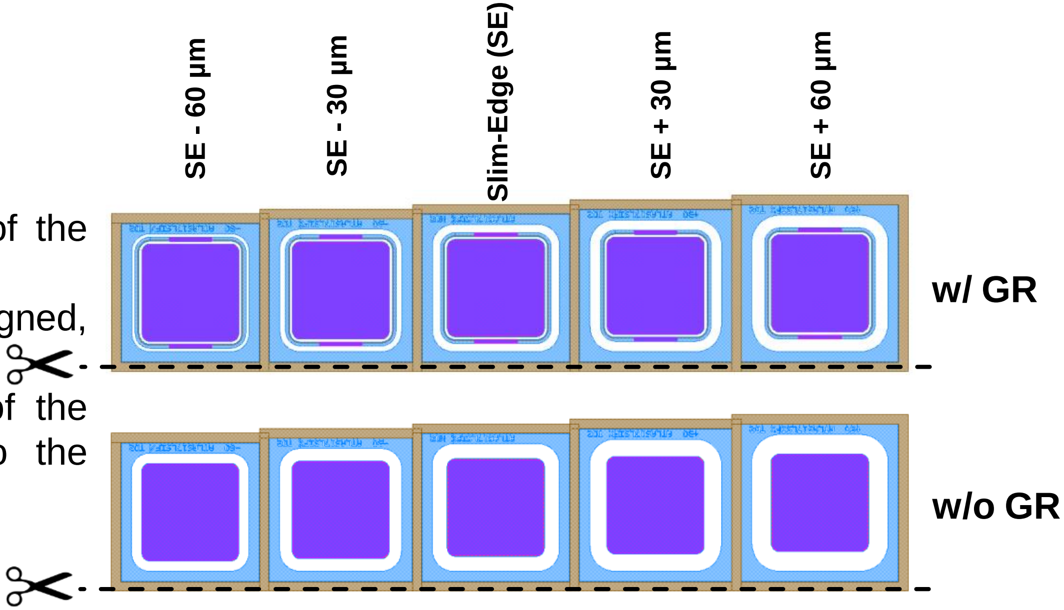


MONITOR DIODES

- 8x8 mm^2 Diode, p-type substrate, 300 µm thickness
- Central metal opening for laser tests
- Guard Ring pads included
- Parameters to control:
  - Leakage Current
  - Full Depletion Voltage (V_{fd})
  - Effective Doping Concentration (N_{eff})
  - Breakdown Voltage (V_{BD})

SENSOR EDGE TESTS

- 5 2x2mm^2 diodes with variations of the edge distance
- 2 different test structure sets designed, with and without Guard Ring (GR)
- Designed to study the influence of the sensor physical edge (respect to the active area)



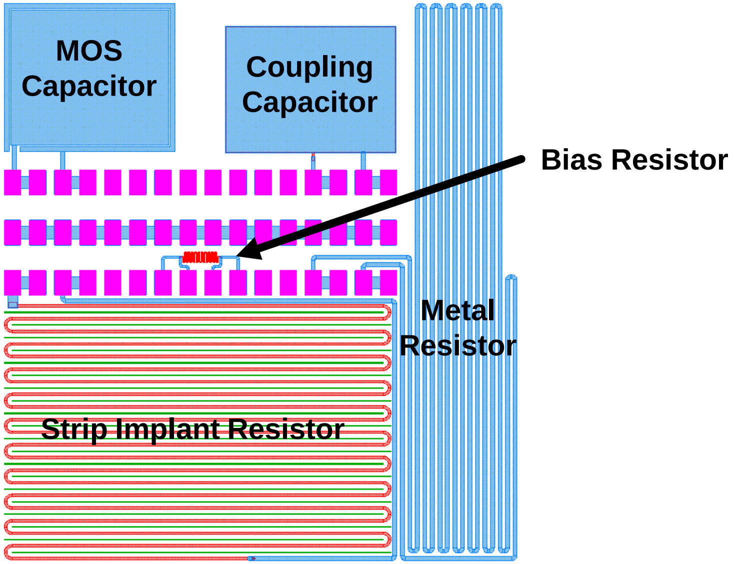
Layout Design

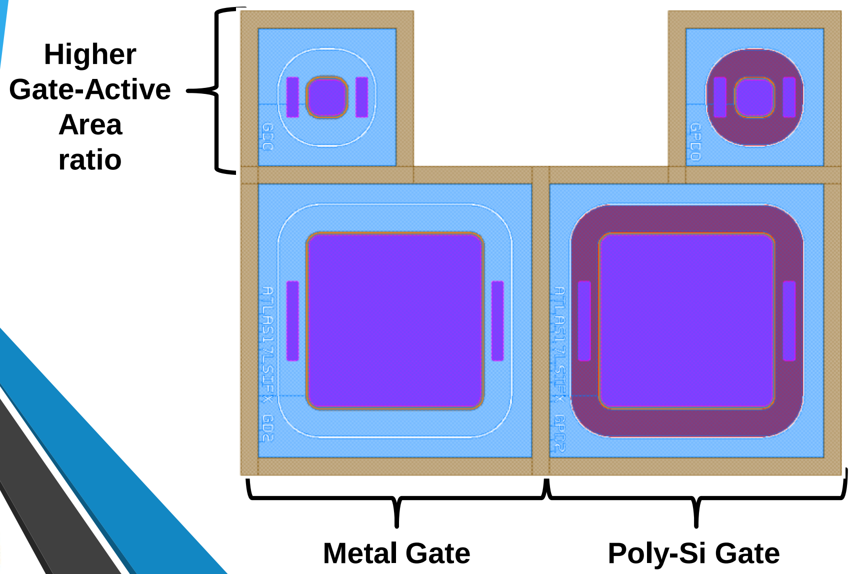
Microelectronic Test Structures for Technology Validation (cont'd)

(Test structures distributed accross the wafer)

STRIP TESTS

- Designed to study most of the (single) strip parameters
- Parameters to control:
  - Bias Resistance (R_{bias})
  - Metal Resistance (R_{metal})
  - Implant Resistance ($R_{implant}$)
  - Coupling Capacitance (C_{coupl})
- Flat Band Voltage (V_{fb}) or Oxide thickness (t_{ox}) can be also extracted

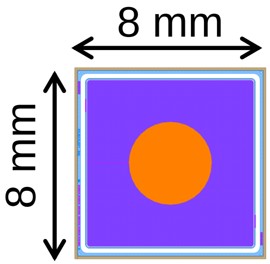




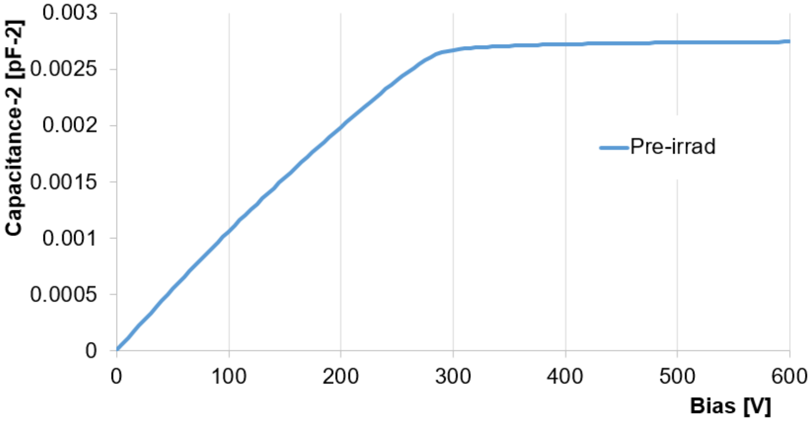
SURFACE TESTS

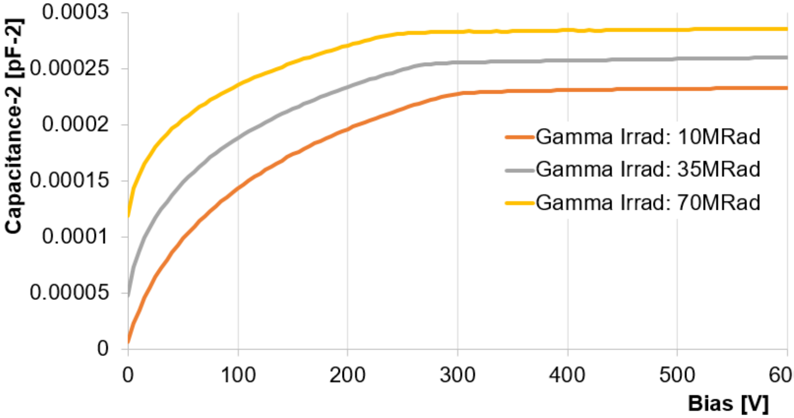
- Designed to study the surface current
- 2x2 mm^2 gated-diode + 1x1 mm^2 gated-diode (active area with increased perimeter-to-area ratio). A pair of these gated-diodes with metal gate and other pair with poly-Si gate
- Parameters to control:
  - Flat Band Voltage (V_{fb})
  - Surface Generation Currents

Results: Monitor Diodes

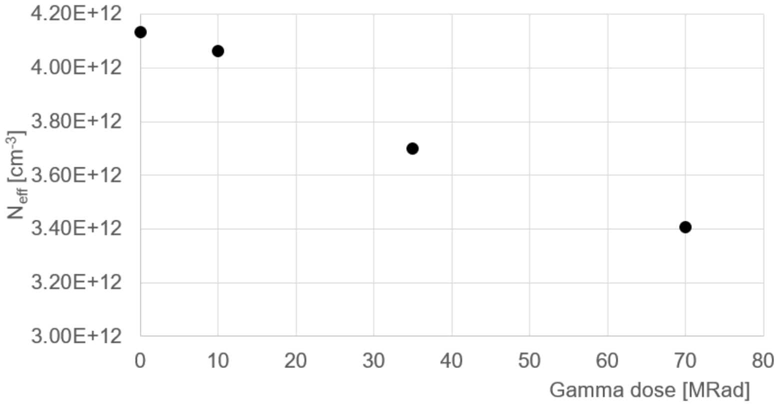


- Full Depletion Voltage (V_{fd}) extracted from CV measurements at 10 kHz
- Influence of high gamma irradiation (up to 70 MRad)





Dose	Unirradiated	10 MRad	35 MRad	70 MRad
V_{FD}	285 V	280 V	255 V	235 V
N_{eff}	$4.13 \cdot 10^{12}$ cm^{-3}	$4.06 \cdot 10^{12}$ cm^{-3}	$3.70 \cdot 10^{12}$ cm^{-3}	$3.41 \cdot 10^{12}$ cm^{-3}

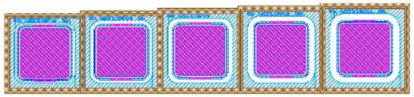


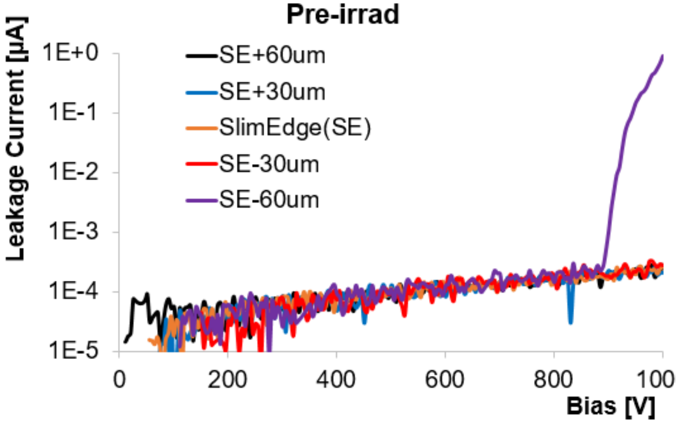
Influence of high gamma irradiation:

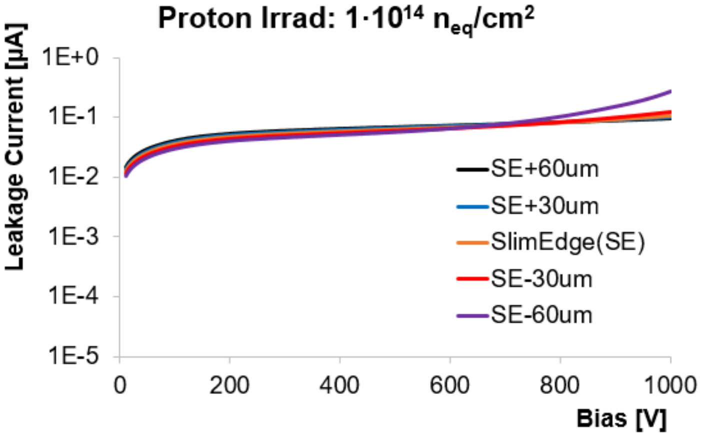
- V_{FD} and N_{eff} decrease
- Displacement damage probably due to secondary particles (electrons)

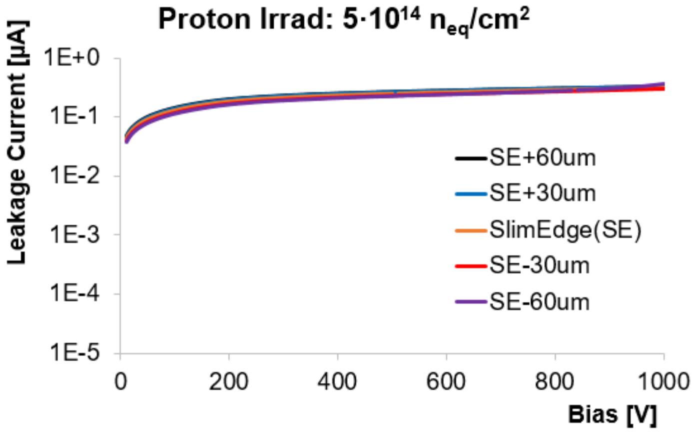
Results: Sensor Edge WITH Guard Ring

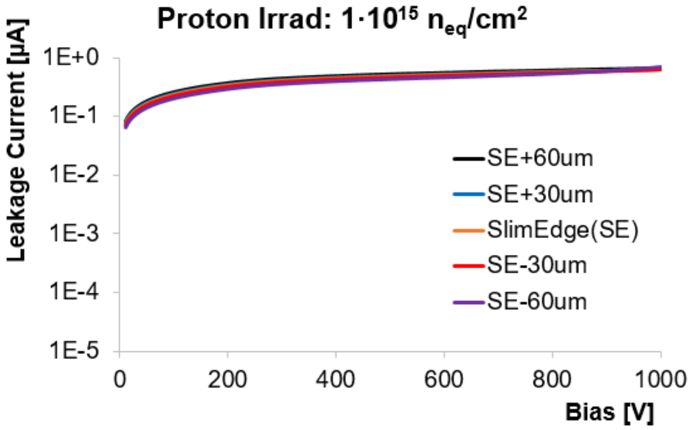
- Study of device breakdown voltage varying the distance between the active area and the silicon edge
- Influence of high proton irradiation (up to $1{\cdot}10^{15}$ n_{eq}/cm^2)




Pre-irrad


Proton Irrad: $1{\cdot}10^{14}$ n_{eq}/cm^2

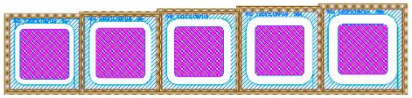

Proton Irrad: $5{\cdot}10^{14}$ n_{eq}/cm^2


Proton Irrad: $1{\cdot}10^{15}$ n_{eq}/cm^2

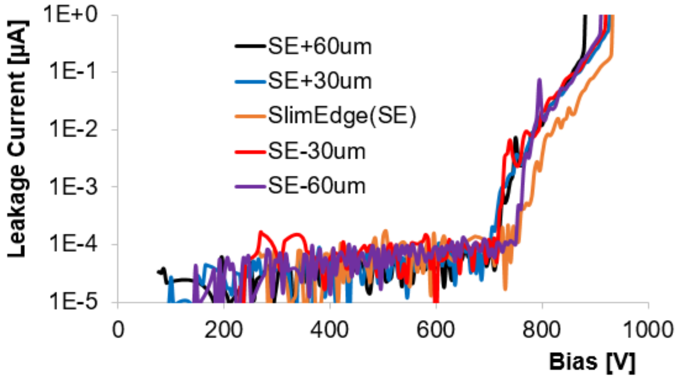
- Pre-irradiated diode with lower edge distance, showing “soft” breakdown at 900 V
- After proton irradiation, increase of leakage current, but also the breakdown voltage
- Slim Edge (SE) distance for Infineon technology tested with good results
- <u>Further tests</u>: Planning measurements biasing above 1000 V

Results: Sensor Edge WITHOUT Guard Ring

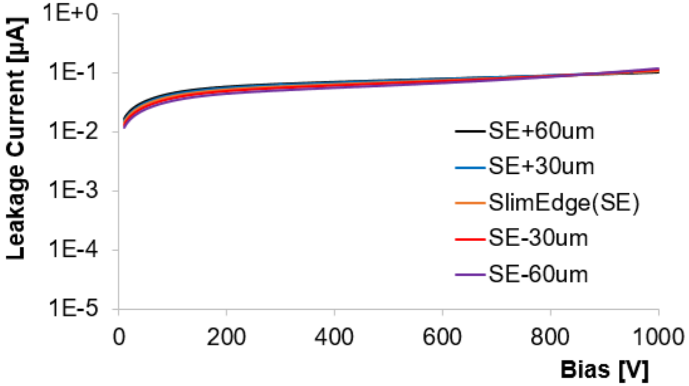
- Study of device breakdown voltage varying the distance between the active area (without guard ring) and the silicon edge
- Influence of high proton irradiation (up to $1 \cdot 10^{15}$ n_{eq}/cm^2)



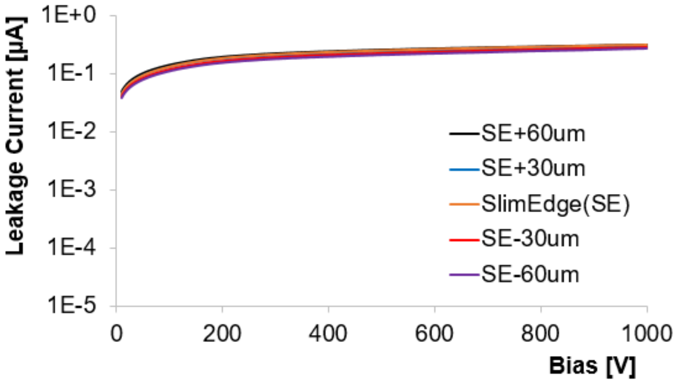
Pre-irrad



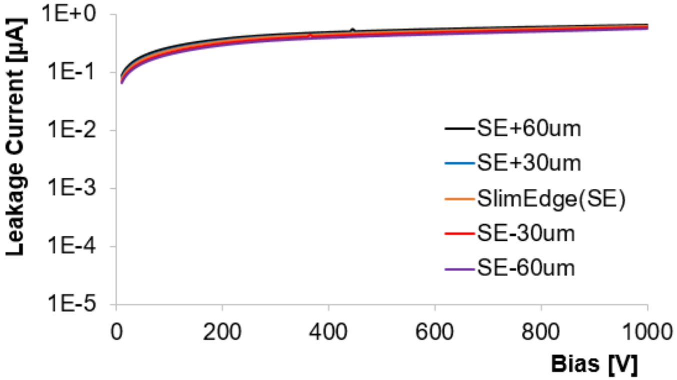
Proton Irrad: $1 \cdot 10^{14}$ n_{eq}/cm^2



Proton Irrad: $5 \cdot 10^{14}$ n_{eq}/cm^2



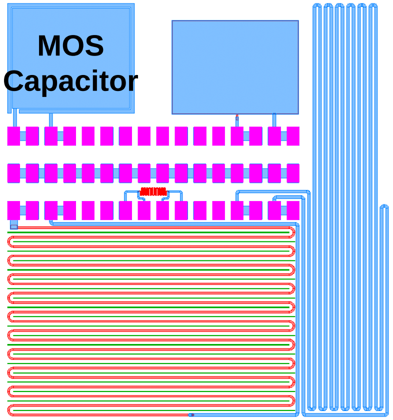
Proton Irrad: $1 \cdot 10^{15}$ n_{eq}/cm^2

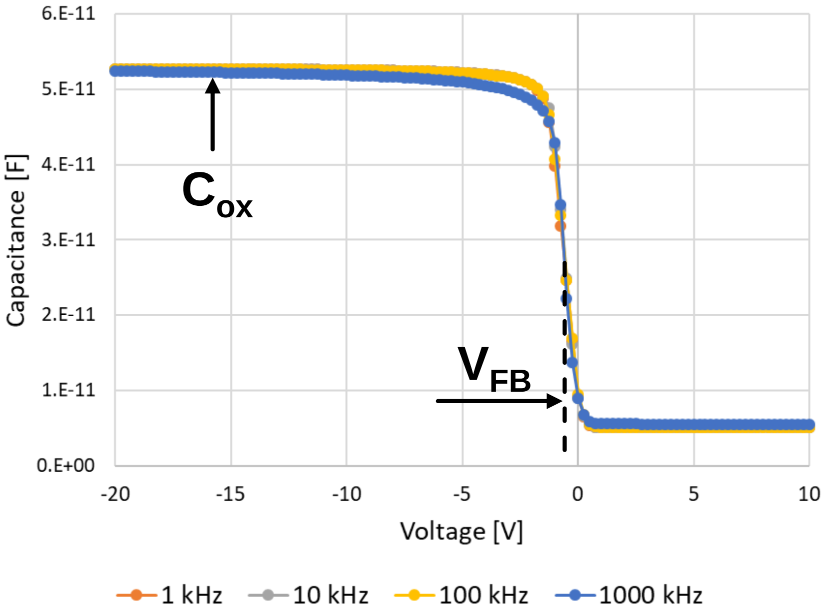


- Pre-irradiated diodes showing “soft” breakdown at 700-750 V, and breakdown at 900 V
- After proton irradiation, increase of leakage current but also the breakdown voltage
- Infineon guard ring effectively protects the device from premature breakdowns
- Further tests: Planning measurements biasing above 1000 V

Results: MOS Capacitor

- MOS capacitor with the same dielectric as the inter-strip oxide (“field oxide”) in the main detector
- For determination through CVHF measurements of relevant device parameters:
  - Field oxide capacitance C_{ox} and flat band voltage V_{FB}
- And extraction of:
  - Oxide thickness t_{ox}
  - Oxide charge density N_{ox}
  - (Through ΔV_{FB}) ΔN_{ox} induced by ionizing dose





$$C_{ox} = \varepsilon_{ox} \times \frac{A}{t_{ox}}$$

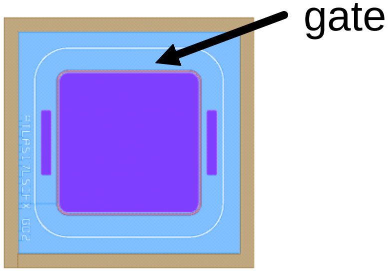
$$Nox = (\Phi_{MS} - V_{FB}) \cdot \frac{C_{ox}}{q \cdot A}$$

MOS capacitor non-irradiated:
$V_{FB} \approx -0.5$V

- Further tests: Measurement of irradiated samples

Results: Gate-controlled Diodes

- Square-shaped diode surrounded by a gate ring
- Used to characterize the Si-SiO_2 interface via parametrization of the surface current
- Apply constant reverse bias voltage (V_{diode}) to diode and measure current through the diode as a function of gate voltage



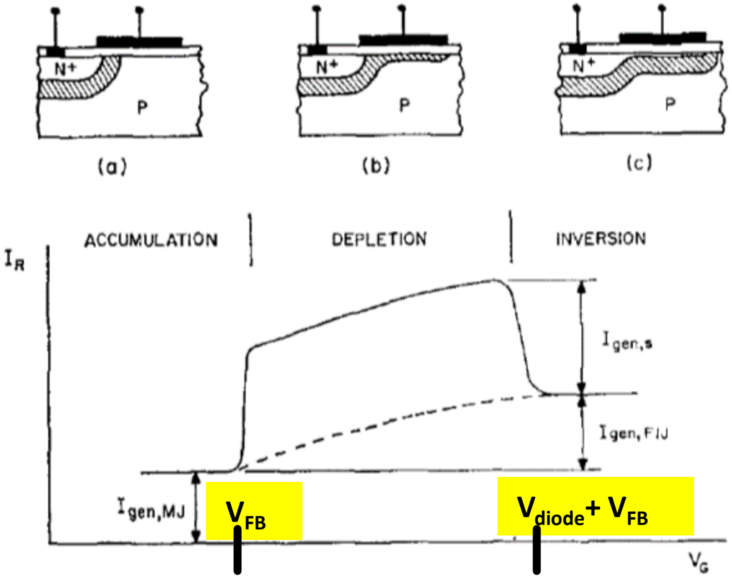
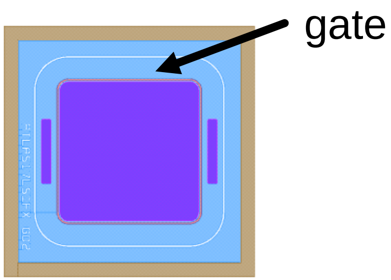


FIG. 20. Illustration of the effect of variation in the nature of the surface space-charge region on the reverse current of an n^+p diode, at a fixed reverse voltage.

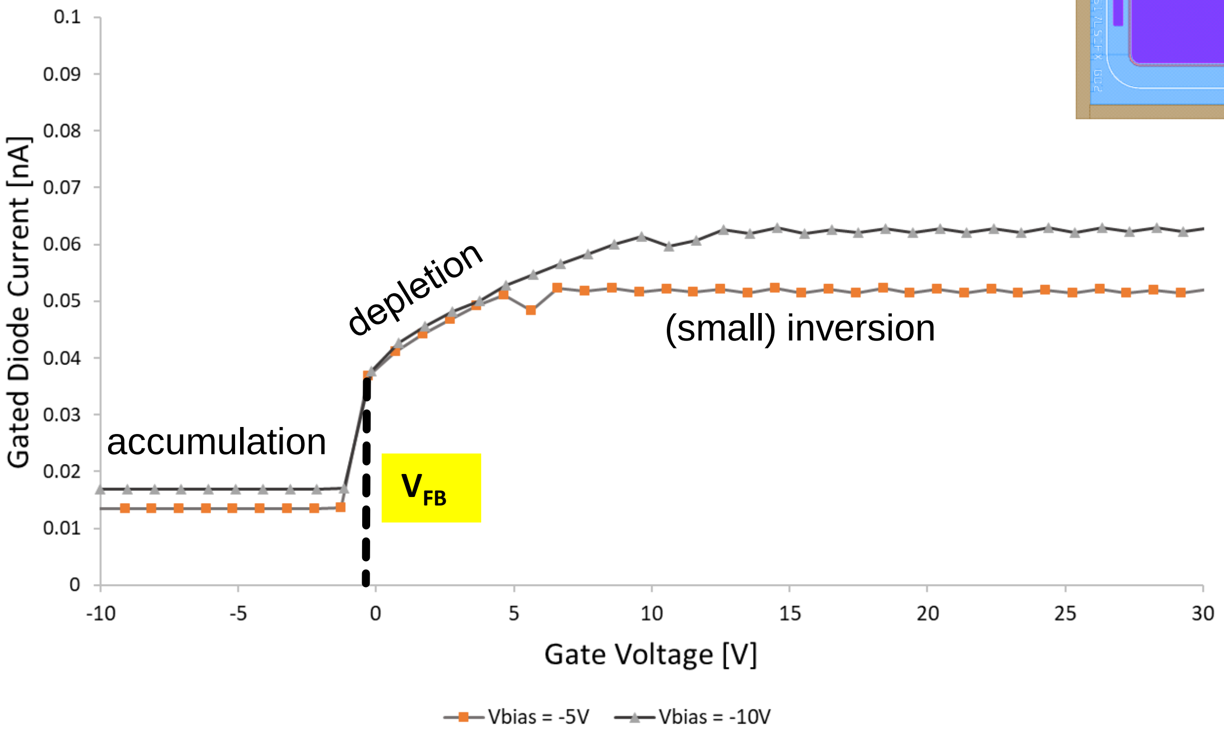
(Grove and Fitzgerald, 1966)

- Current measured is superposition of:
  - $I_{gen,MJ}$ = Bulk generation current under the diode (constant)
  - $I_{gen,FIJ}$ = Bulk generation current under the gate
  - $I_{gen,S}$ = Surface generation current under the gate
    - ○ $I_{gen,S} = q \cdot n_i \cdot S_0 \cdot A_{gate}$
    - ○ S_0 = interface recombination velocity (cm/s). Depends on interface state density

Results: Gate-controlled Diodes



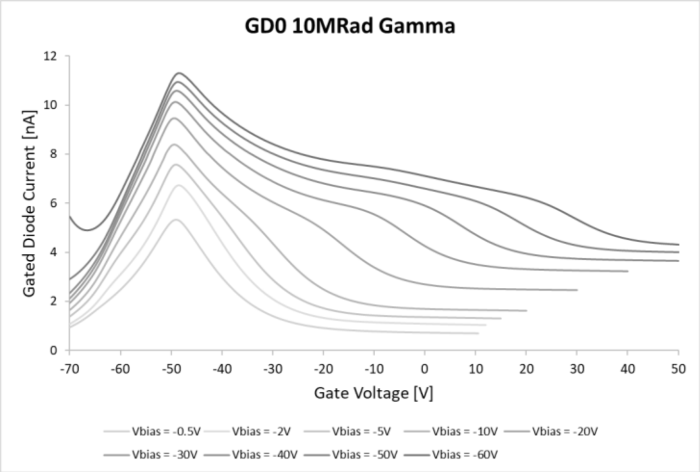
- Measurements of pre-irradiated devices

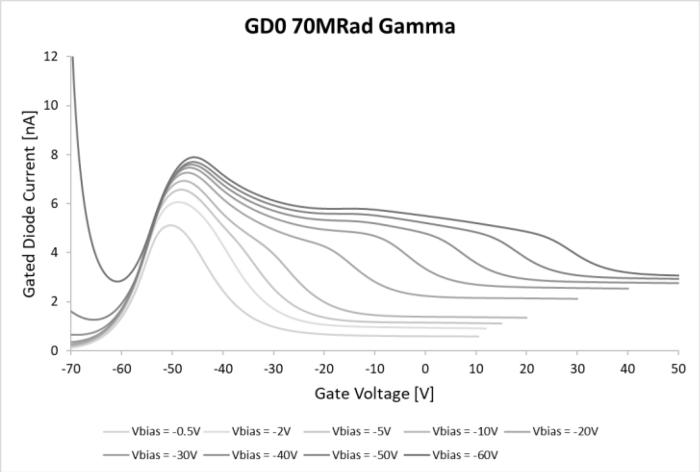


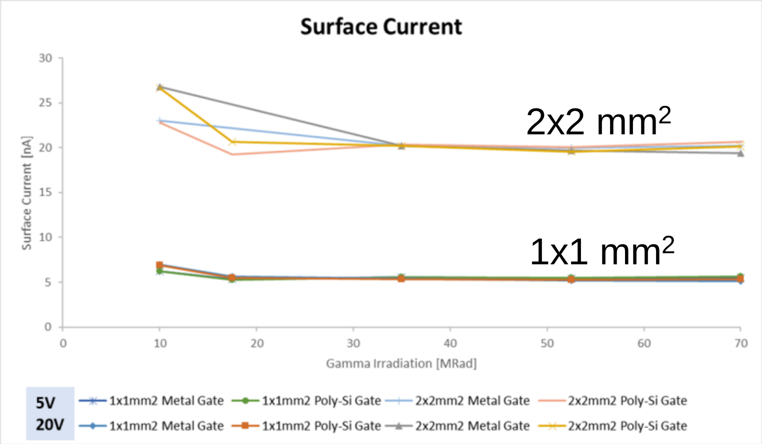
- For the non-irradiated gate-controlled diodes, the surface current is too low to measure
  - ✓ Good quality of the Si/SiO$_2$ interface
- V$_{FB}$ =-0.5 V, in agreement with the measured with the MOS capacitors (slide 10)

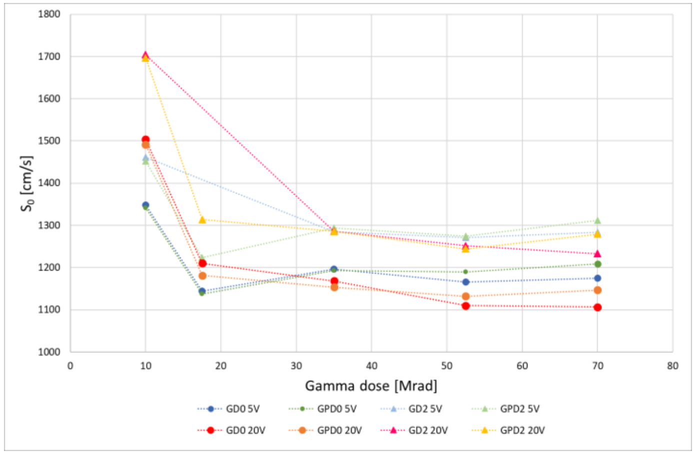
Results: Gate-controlled Diodes

- Measurements of gamma irradiated devices









- After 10MRad gamma irradiation, V_{FB} shifts to ~-50V
- Surface generation current does not depend on gate material or diode voltage (as expected)
- Interface recombination velocity (S_0) stable after 37.5MRad dose
- Unexpected S_0 value for 10MRad due to different annealing status (?)
- <u>Further tests</u>: Measurement with equivalent device annealing

Conclusions

- Layout designs of microelectronic test structures for technology evaluation are presented

- Test structures **capable to evaluate key parameters** of strip sensor technology

- Results:

  Monitor diodes
  - **Full depletion voltage (V_{FD}) and effective doping concentration (N_{eff}) decreased after high gamma irradiation**
  - Devices seem to be affected by **displacement damage** (probably) due to secondary electrons

  Sensor edge tests
  - Infineon **edge sensor structure** tested showing **high breakdown voltage results** (V_{BD} > 900 V), **even** for devices **without guard ring**

  MOS and gate-controlled diodes
  - Gate-controlled diodes showing **low surface current for non-irradiated devices**, hence, good quality of Si/SiO_2 interface
  - **Surface current independent of gate material**
  - Stable interface recombination velocity (S_0) after 37.5 MRad gamma irradiation