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

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    - Effective Doping Density ($N_{eff}$) – Gamma Influence
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  - 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

[*] 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

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 across 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)
STRIP TESTS
- Designed to study most of the (single) strip parameters
- Parameters to control:
  - Bias Resistance ($R_{\text{bias}}$)
  - Metal Resistance ($R_{\text{metal}}$)
  - Implant Resistance ($R_{\text{implant}}$)
  - Coupling Capacitance ($C_{\text{coupl}}$)
- 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)

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 $1 \cdot 10^{15} \text{n}_{eq}/\text{cm}^2$)

**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**

**Further tests:** 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 $1 \cdot 10^{15} \text{n}_{eq}/\text{cm}^2$)

- 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 $\Delta V_{FB}$) $\Delta N_{ox}$ induced by ionizing dose

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

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

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

- Further tests: Measurement of irradiated samples
Results: Gate-controlled Diodes

- Square-shaped diode surrounded by a gate ring
- Used to characterize the Si-SiO₂ interface via parametrization of the surface current
- Apply constant reverse bias voltage ($V_{\text{diode}}$) to diode and measure current through the diode as a function of gate voltage

\[ I_{\text{diode}} = I_{\text{gen,MJ}} + I_{\text{gen,FIJ}} + I_{\text{gen,S}} \]

- $I_{\text{gen,MJ}}$ = Bulk generation current under the diode (constant)
- $I_{\text{gen,FIJ}}$ = Bulk generation current under the gate
- $I_{\text{gen,S}}$ = Surface generation current under the gate

  - $I_{\text{gen,S}} = q \cdot n_i \cdot S_0 \cdot A_{\text{gate}}$
  - $S_0$ = interface recombination velocity (cm/s). Depends on interface state density

(Grove and Fitzgerald, 1966)

Square-shaped diode surrounded by a gate ring used to characterize the Si-SiO₂ interface via parametrization of the surface current. Apply constant reverse bias voltage ($V_{\text{diode}}$) to diode and measure current through the diode as a function of gate voltage.
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

**GD0 10MRad Gamma**

- After 10MRad gamma irradiation, $V_{FB}$ shifts to $\sim-50V$
- 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 (?)
- **Further tests:** 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