Radiation tolerance study of the first 55nm HV-CMOS pixel sensor

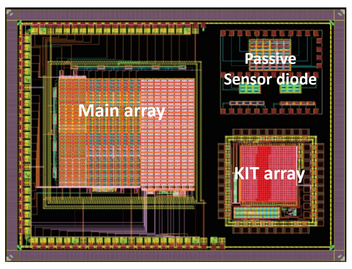
COFFEE
CMOS SENSOR IN FIFTY-FIVE NM PROCESS

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Introduction

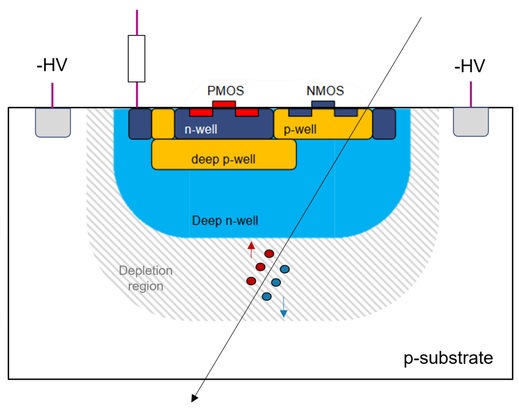
High-voltage CMOS (HV-CMOS) pixel sensors are promising candidates for tracking in future high-energy physics experiments. Developed in a commercial 55 nm HV-CMOS technology, the COFFEE2 prototype integrates pixel-level circuitry for sensor and analog front-end characterization alongside a full data-driven readout array.



To evaluate its radiation tolerance, COFFEE2 underwent proton irradiation at the Chinese Spallation Neutron Source (CSNS) and X-ray irradiation at Zhejiang University. Performance was assessed using S-curve scans and time-over-threshold (ToT) measurements as a function of threshold to characterize the effects of proton irradiation, X-ray total ionizing dose (TID), and chip power state during irradiation. These preliminary irradiation results provide initial validation of both the COFFEE2 design and the commercial 55 nm HV-CMOS process, demonstrating its viability for future detector applications.

Process Features

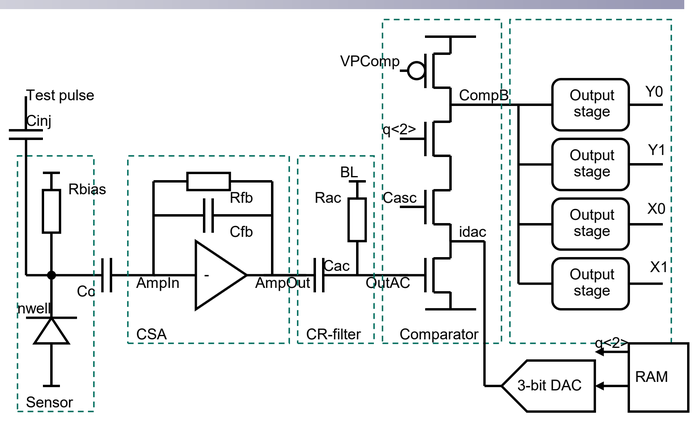
- Deep n-well — P substrate junction as collection electrode
- Triple-well process: N-well/P-well/Deep n-well
- P-type substrate resistivity: $10\Omega \cdot \mathrm{cm}$
- Guard ring: one inner N-well ring, with two P-well outer rings
- Substrate breakdown Voltage > 70V with frontside HV bias
- More design details:
  - *Z. Chen et al., Feasibility study of CMOS sensors in 55 nm process for tracking*, Nuclear Instruments and Methods in Physics Research A 1069 (2024) 169905.
  - *H. Zhang, et al., High voltage monolithic pixel sensor in 55 nm technology*, JINST 20 (2025) 03, C03023.



Working principle of HV-CMOS sensors.

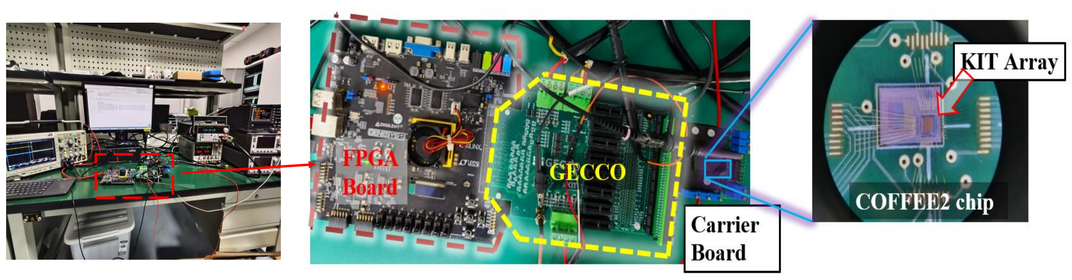
KIT Pixel Electronics

- Pixel electronics (25 μm × 25 μm)
  - Sensor diode
  - Charge Sensitive Amplifier (CSA)
  - CR filter
  - Comparator
  - RAM and tune DAC
  - Output stages
- Work principle
  - Charge collected by pixel n-well
  - Converted to voltage signal by Charge Sensitive Amplifier
  - Analog voltage pulse shaped and converted to digital signal by comparator
  - Output stage generates current
  - Current is sent via address line to the transimpedance amplifier outside matrix
  - Address lines have constant potential – no cross talk



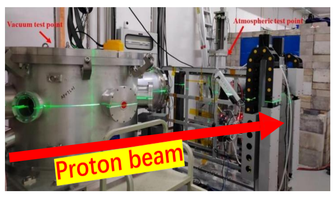
H. Zhang, etl. High voltage monolithic pixel sensor in 55nm technology
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Bench test setup

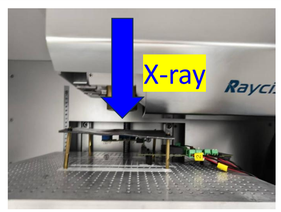


- Genesys2 FPGA Board
  - Translates commands from the PC into the precise low-level digital protocol
- GECCO Control Readout Board
  - It integrates power delivery and controls and supplies all required electrical
  - potentials for testing the chip
- Carrier Board (with wire-bonded COFFEE2 chip)
- Signal Generator
  - Provide charge injection to the chip through the GECCO board

Irradiation Test



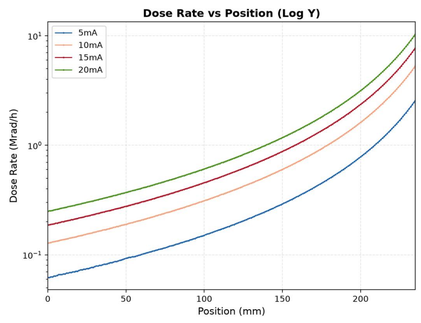
Proton irradiation at CSNS





X-ray irradiation at Zhejiang University (ZJU)

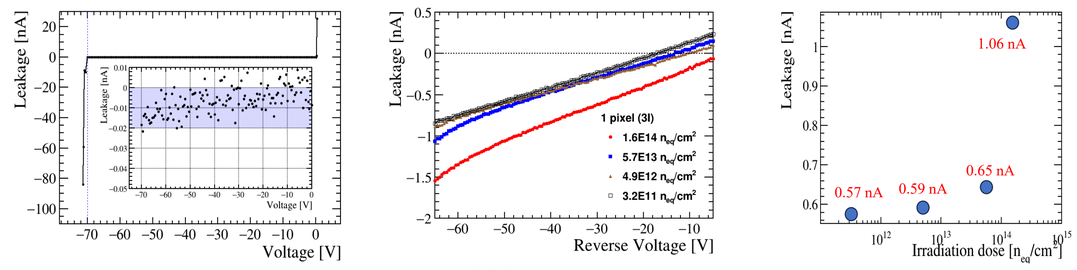
- Proton irradiations at CSNS(Chinese Spallation Neutron Source), Oct 2021, at -28℃, to a fluence of $5.7 \times 10^{13} \mathrm{n_{eq}/cm^2}$
- X-ray irradiation at Zhejiang University (ZJU) was performed at different operating voltages and currents to achieve different dose rates.
- The right panel shows the dose rate (Mrad/h) as a function of position at different currents, with the dose rate plotted on a logarithmic scale.



Main results

Proton-Induced I-V Changes

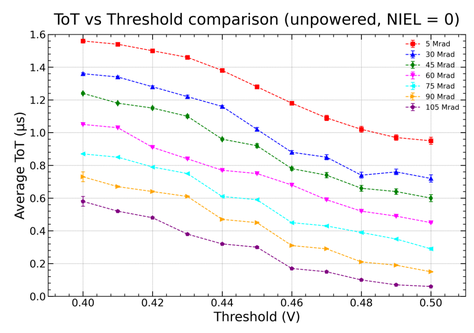
Under 50V setup, Leakage current increased from ~ 10 pA to ~ 1nA after irradiated. The magnitude of leakage current is proportional to the irradiation fluence



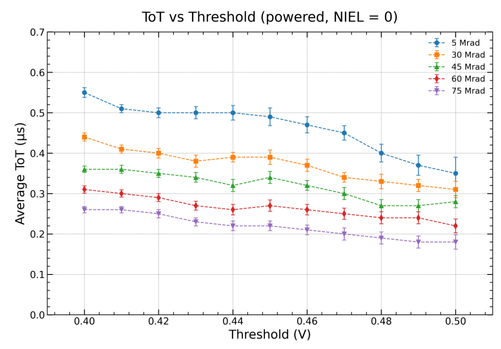
IV test results of COFFEE2 in different irradiation fluence

Irradiation Tolerance Evaluation

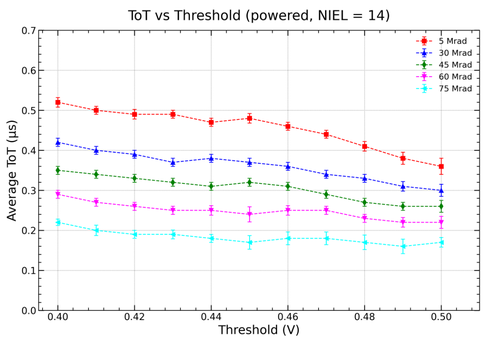
- Measuring time-over-threshold (TOT) as a function of threshold helps assess radiation tolerance by revealing irradiation-induced changes in the analog front-end response.
- Panels (a)–(c) show time-over-threshold (TOT) versus threshold at different X-ray doses (Mrad): (a) for an unpowered chip, (b) for a powered chip, and (c) for a powered chip previously irradiated with protons to a fluence of $10^{14}\ \mathrm{n_{eq}/cm^2}$



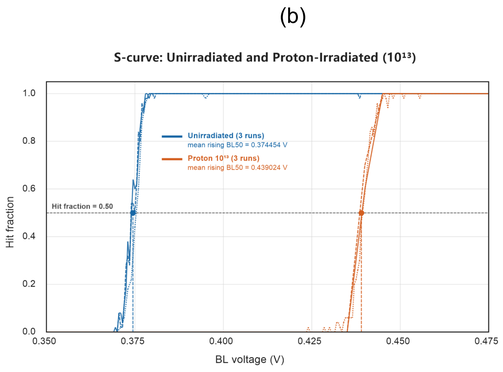
(a)



(b)



(c)



(d)

- S-curve measurements before and after irradiation reveal changes in threshold and noise, helping assess the stability of the chip's response to radiation.
- Panel (d) compares the S-curves of an unirradiated chip and a chip irradiated with protons to $10^{13}\ \mathrm{n_{eq}/cm^2}$, showing a threshold shift from 0.37 V to 0.43 V following irradiation.

Summary & Outlook

The radiation tolerance of COFFEE2, developed in a commercial 55 nm HV-CMOS process, was investigated through proton and X-ray irradiation. I–V measurements, time-over-threshold (TOT) versus threshold curves, and S-curve scans were used to assess performance under different fluences, TID levels, and chip power conditions. The preliminary results support the potential of COFFEE2 and the technology for future tracking detectors. Further studies will extend the irradiation range, quantify changes in threshold and noise, and evaluate long-term stability and full-array readout performance.

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