Characterization of HV-CMOS pixel sensor prototypes

Ettore Zaffaroni

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Outline

• Introduction
• The characterized sensors
• TCT (Transient Current Technique) measurements and results
• Testbeam measurements and results
Introduction

• ATLAS will upgrade its inner tracker for HL-LHC
  - ITk, \( \sim 190 \text{ m}^2 \) of silicon,
    \( \sim 15 \text{ m}^2 \) of pixel detectors
  - High occupancy and radiation damage
• HV-CMOS developed as a possible replacement for the outermost pixel layer

• CCPDv3, CCPDv4 (ams 180 nm) small prototypes, capacitively coupled to front-end ASICs

• H35DEMO (ams 350 nm), first full scale prototype, with monolithic parts

• ATLASPix1 (ams 180 nm), fully monolithic, 3 pixel matrices

• ATLASPix2 (ams/TSI 180 nm), small scale prototype, focus on periphery and SEU tolerant memory

• ATLASPix3 (TSI 180 nm), full scale prototype, single pixel matrix
H35DEMO chip

- H35 technology by ams
  - 350 nm HV-CMOS
- 4 pixel matrices and test structures
- 250x50 μm² pixels
- 4 different resistivities
  - 20, 80, 200, 1000 Ω · cm
ATLASPIX1 chip

• aH18 technology by ams
  - 180 nm HV-CMOS
• Fully monolithic
• Same resistivities as H35DEMO
• ATLASPIX_Simple matrix tested
  - 130x40 μm² pixels
  - 25x400 matrix
  - Column-drain readout, triggerless
Transient Current Technique
TCT (Transient Current Technique)

- Generation of carriers using a laser
  - Precise location
- Carriers move under electric field, generating a current
- Current signal amplified with a RF amplifier

- TCT allows to study the space charge region
  - Depletion depth, $N_{\text{eff}}$, etc.
TCT setup

- Pulsed IR laser (1064 nm) with FWHM of 12 μm
- Detector at –27 °C using Peltier
- 1 μm step size in all axes
TCT setup

- DUT mounted vertically to reduce effects of swinging stages
- PCB with controlled impedance traces and correct termination to remove signal reflections
H35DEMO test structures

- In the periphery of the chip
- 3x3 pixel matrix (just the sensor diodes)
- Outermost pixel cathodes are connected together
  - 2 channels (central and external)
- Top bias
Irradiation campaigns

- Neutrons
  - TRIGA reactor in Ljubljana
    - One irradiation step per sample
  - Annealing

- Protons (measurements at Uni. Bern and Uni. Geneva)
  - BERN Inselspital cyclotron (16.7 MeV)
    - Multiple irradiation steps per sample
  - PS IRRAD (24 GeV)
    - One irradiation step per sample
eTCT scans

- Edge TCT scans performed
- $\sim 150-300 \times 1 \, \mu m$ steps in $y$, $\sim 70 \times 5 \, \mu m$ steps in $x$
- Several voltage steps (10 to 12 normally)
  - From 0 V to -100 or -165 V
- At each step the signal is averaged 40 times
  - To reduce noise
- All results shown for central pixel

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Data analysis - depletion

- Integration of current signal to get the charge
- Selection of the region
Data analysis - depletion

- Fit of the charge profiles
  - One fit per profile in the ROI
- Two contributions:
  - Smeared box function
  - Gaussian, to model the charge sharing
- Calculation of the FWHM
  - Max of the box function considered
Data analysis - $N_{\text{eff}}$

- $N_{\text{eff}}$ (effective doping concentration) is calculated by fitting the depletion vs voltage data with:

$$d = d_0 + \sqrt{\frac{2\varepsilon}{e N_{\text{eff}}} V}$$

- $d_0$ and $N_{\text{eff}}$ free parameters
  - $e$ electron charge
  - $\varepsilon$ silicon dielectric constant

- $d_0$: sensitive region depth at 0 V bias (due to built-in voltage and n-well finite depth)
Results - $N_{_{\text{eff}}}$

- $20 \ \Omega \cdot \text{cm}$
- $80 \ \Omega \cdot \text{cm}$
- $200 \ \Omega \cdot \text{cm}$
- $1000 \ \Omega \cdot \text{cm}$
Results - $N_{\text{eff}}$

• Significant differences between protons and neutrons and between resistivities

• Initial increase of $N_{\text{eff}}$ at very low fluences ($<10^{14}$ $n_{\text{eq}}$/cm$^2$, protons) for the 200 Ω · cm sample
  - Effect competing with initial acceptor removal?
  - Not observed in 1000 Ω · cm, data not available for 20 and 80 Ω · cm
Results – $N_{\text{eff}}$

- Plots combined by particle type, for different initial resistivities
- Tend to the same $N_{\text{eff}}$ value

- Neutrons
- Protons $16.7$ MeV
- Protons $24$ GeV
Results - annealing

- Measured on neutron irradiated samples
- Initial beneficial annealing, then reverse annealing
- Measurement will be performed on proton irradiated samples for comparison
Testbeams
Testbeams

- **Telescope**: pixel sensors used to measure tracks and generate trigger
- **DUT** read out at the same time
- **Reconstruction and analysis**

![Diagram of Testbeams system]

DCS (power, HV, cooling...) not represented
Reconstruction and analysis

Proteus software

RAW DATA

NOISE-SCAN
Remove noisy pixels

ALIGNMENT
Align telescope planes and DUT

TRACK RECONSTRUCTION
Find tracks, match with DUT hits

DATA ANALYSIS
Efficiency, timing, etc.
Telescope modules

- Planar modules from IBL
  - Innermost pixel layer in ATLAS
  - Planar silicon pixel sensor

- Read out by the FE-I4 ASIC
  - 50x250 μm² pixels
  - 80 columns, 336 rows
DAQ: CaRIBOu system

- Read-out system for ITk and CLIC sensor prototypes
- Provides power, HV and data links
- Based on a PC, a Zynq-7000 FPGA and a custom DUT board

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Telescope

• 6 FE-I4 modules
  - Spatial resolution 8x12 um
• Trigger rate up to 4 kHz
• Cold DUT box (down to -20 °C)
• Successfully used in various campaigns (SPS, FNAL) since 2014

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Measurement campaign

- Data acquisition at CERN SPS (06-10/2018)
- Simple matrix of ATLASPIX1
- Bias voltage and threshold scans
- Different irradiations
  - Protons (while operating the sensor)
  - Neutrons
Testbeam results

- High efficiency after irradiation
- Noisy pixels and neighbors masked
- Lines masked due to issues in row circuitry
  - Identified and solved in subsequent prototype submission
Testbeam results

- Efficiency vs bias voltage (left) and threshold (right)
- Above 98% for a wide range of parameters
Testbeam results

- Cluster time: difference between trigger time (telescope) and cluster time (DUT)
  - 1 bin spread given by the telescope
- Cluster value: time over threshold
Comments

- Testbeams show excellent performance of ATLASPix1 before and after irradiation
  - Efficiency up to \( \sim 99\% \) after \( 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \)
  - Excellent timing performances

- Identified issues in the circuitry, feedback provided to the designers
Conclusions

• TCT measurements
  - Initial acceptor removal observed after proton and neutron irradiation
  - Beneficial and reverse annealing observed for neutrons
  - Significant differences between neutron and protons effects

• Testbeams
  - High, uniform efficiency over a large pixel matrix after irradiation
  - Very good timing performances

• Excellent results for fully monolithic pixel sensors!

Thank you!