Measurements of passive structures on irradiated HV-CMOS detectors

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Bojan Hiti, Vladimir Cindro, Andrej Gorišek, Gregor Kramberger, Igor Mandić, Marko Mikuž, Marko Zavrtanik
On behalf of ATLAS Strip CMOS collaboration

Jožef Stefan Institute, Experimental Particle Physics Department (F9)
Ljubljana, Slovenia
Outline

- CHESS 2 chip introduction
- Edge-TCT measurements
- Acceptor removal parameters
- $^{90}$Sr measurements
- Summary
CHESS 2 chip

- Developed by the ATLAS Strip CMOS collaboration as a candidate for HVCMOS strip detector for ATLAS Phase II upgrade
- Design by UCSC, SLAC and KIT, produced in AMS H35 process, max. bias 120 V
  - H. Grabas, Chess2 front end readout of the multi-segmented HV CMOS sensors, FEE 2016
- Reticle size demonstrator chip, follow up of CHESS 1
  - 3 striplet arrays with fully digital encoding and readout
  - 1 pixel array with an in-strip amplifier and analog readout
  - Several passive arrays for material studies – subject of this talk
Passive test structures on CHESS 2

- **Edge-TCT arrays**, 3 x 3 pixels, pixel size: 630 x 40 μm² (six 90.2 μm x 24.3 μm nwells in each pixel)
- **Large Passive Array**, 1.3 x 1.3 mm² for ⁹⁰Sr measurements, implants ganged together (Large n-well, not used here)
- Chips produced on four different substrate resistivities
  - 20 Ω·cm, 50 Ω·cm, 200 Ω·cm, 1 kΩ·cm
- Irradiation study:
  - Samples irradiated with neutrons in Ljubljana
  - Fluences: 0, 1e14, 3e14, 5e14, 1e15, 2e15 n_{eq}/cm²
  - Total 24 chips (4 x 6)
Edge-TCT
Edge-TCT setup

TCT measurements with passive pixels (no amplifier in the n-well)
→ collecting electrode connected to the amplifier

Detector connection scheme:

( more details: www.particulars.si )
Edge-TCT measurements

- Sensors only partially depleted
- Edge-TCT allows to study the depletion depth dependence on voltage/fluence
- Charge collection width = \text{FWHM} of the charge collection profile
Charge collection width at 120 V changes with irradiation

- Increase at fluences above $5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ – initial acceptor removal
- Low substrate resistivity $\rightarrow$ late acceptor removal
Charge collection width increases up to 1e15 n$_{eq}$/cm$^2$, then reducing.

Acceptor removal finished earlier than with 20 Ω·cm substrate.
variations of charge collection width are small
Maximal width reached around $5 \times 10^{14} \, n_{eq}/cm^2$
Unirradiated sample could not be biased (breakdown)
- Initially large charge collection width $> 100 \mu m$
- Charge collection width monotonously falling with irradiation
- High resistivity $\rightarrow$ acceptor removal completed below $1e14\, n_{eq}/cm^2$
Width of charge collection region at 50% max

At $\Phi = 0$:
$N_{\text{eff}} = 6.7e14 \text{ cm}^{-3} \Rightarrow 20 \text{ \Omega \cdot cm}$

Good agreement with nominal resistivity

$\text{Width}(V_{\text{bias}}) = w_0 + \sqrt{\frac{2\varepsilon \varepsilon_0}{e_0 N_{\text{eff}}} V_{\text{bias}}}$

0 V offset

Extract value of $N_{\text{eff}}$ from fit

20 $\text{\Omega \cdot cm}$ charge collection width vs. bias voltage

20 $\text{\Omega \cdot cm}$
Width of charge collection region at 50% max

At \( \Phi = 0 \):
\[ N_{\text{eff}} = 2.3 \times 10^{14} \text{ cm}^{-3} \Rightarrow 58 \, \Omega \cdot \text{cm} \]

- 1000 \( \Omega \cdot \text{cm} \) best material in terms of depletion depth
- But sensitive breakdown behaviour
\[ N_{\text{eff}} = N_{\text{eff0}} - N_c \cdot (1 - \exp(-c \cdot \Phi_{eq})) + g_c \cdot \Phi_{eq} \]

- \( N_{\text{eff}} \) evolves differently for different initial wafer resistivities.
- Behaviour converges for fluences above 1e15 \( n_{eq}/\text{cm}^2 \).

**CHESS1** 20 \( \Omega \text{cm} \)
- \( N_c/N_{\text{eff0}} \approx 1.0 \)
- \( c \approx 0.36 \times 10^{-14} \text{ cm}^2 \)
- \( g_c = 0.02 \times 10^{-14} \text{ cm}^{-1} \)

**CHESS2** 20 \( \Omega \text{cm} \)
- \( N_c/N_{\text{eff0}} \approx 1.0 \)
- \( c \approx 0.19 \times 10^{-14} \text{ cm}^2 \)
- \( g_c = 0.020 \times 10^{-14} \text{ cm}^{-1} \)

**CHESS2** 200 \( \Omega \text{cm} \)
- \( N_c/N_{\text{eff0}} \approx 1.0 \)
- \( c \approx 0.16 \times 10^{-14} \text{ cm}^2 \)
- \( g_c = 0.020 \times 10^{-14} \text{ cm}^{-1} \)

**CHESS2** 50 \( \Omega \text{cm} \)
- \( N_c/N_{\text{eff0}} \approx 1.0 \)
- \( c \approx 0.27 \times 10^{-14} \text{ cm}^2 \)
- \( g_c = 0.020 \times 10^{-14} \text{ cm}^{-1} \)

**CHESS2** 1000 \( \Omega \text{cm} \)
- \( g_c = 0.020 \times 10^{-14} \text{ cm}^{-1} \)

Removal completed below 1e14 \( n_{eq}/\text{cm}^2 \)

Preliminary!
Acceptor removal constant vs. initial doping

Measurements by Edge-TCT in Ljubljana

High resistivity \( \rightarrow \) fast acceptor removal (finished at low fluence)
Low resistivity \( \rightarrow \) slow acceptor removal (finished at high fluence)

- CHESS2 (partly) fits in this picture
- Removal constant for CHESS2 1kOhm-cm still not measured

LFoundry, Mandić et al., arXiv 1701.05033
X-Fab
B. Hiti et al., arXiv 1701.06324

HVFEI4, CHESS 1, G. Kramberger et al., JINST 2016

Blue marker – charged hadron irradiated
Red marker – neutron irradiated

CHESS 2

\( c (\text{cm}^2) \)
Charge collection width vs. fluence in CHESS 2

- Charge collection width at 100 V for different wafers/fluences
- Calculated from $N_{\text{eff}}$ measured with Edge-TCT using formula

$$\text{Width}(V_{\text{bias}}) = \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{\text{eff}}} V_{\text{bias}}}$$
${^90}\text{Sr}$ measurements
90Sr setup

- HV-CMOS: small signals, large noise $\rightarrow$ S/N very low
  - clean sample of events needed (no hits missing DUT)
  - require a large detector (trigger rate), good collimation, small scintillator
- Measurement:
  - Calibration with a 300 $\mu$m thick Si pad detector
  - 1) Record $N$ ( = 2500) waveforms
  - 2) Average over all waveforms and determine time of the signal peak
  - 3) Sample waveforms at the peak
  - 4) Fill spectrum
20 Ω·cm, $^{90}$Sr

- Diffusion contribution of approx. 1000 e\textsuperscript{−} vanishes after irradiation
- Signal increase due to acceptor removal at high fluences
- Minimal mean charge at 100 V: 1000 e\textsuperscript{−} (but would expect > 1600 el from $N_{\text{eff}}$)
50 $\Omega \cdot$cm, $^{90}$Sr

Minimal mean charge at 100 V: 1300 $e^-$ (extrapolated)
200 Ω·cm, $^{90}$Sr

Minimal mean charge at 100 V: $2000 \text{e}^{-}$ (extrapolated)
1000 $\Omega\cdot$cm, $^{90}$Sr

Minimal mean charge at 100 V: 2000 e$^-$ (extrapolated)
90\textsuperscript{Sr} comparison for different substrates

- CHESS 1 vs. CHESS 2 (20 \(\Omega\cdot\text{cm}\)) : trend is similar, but mean charge differs could be due to a different wafer composition \(\rightarrow\) different acceptor removal
- More than 2000 el in whole fluence range for 200 Ohm-cm and 1 kOhm-cm
- Measured charge after irradiation smaller then expected from depleted depth calculated from \(N_{\text{eff}}\)
Summary

- Completed measurements of charge collection on passive structures on CHESS 2
  - 4 wafer resistivities 20 – 1000 Ω·cm, each wafer 6 neutron fluences up to 2e15 n/cm²
  - Edge-TCT and ⁹⁰Sr MIPs

- Edge-TCT:
  - Study of charge collection width for different substrates / irradiation levels
  - Charge collection width may increase with irradiation → acceptor removal
  - Determined parameters of the acceptor removal model

- ⁹⁰Sr
  - Mean collected charge at least 1000 electrons for any substrate and fluence
  - Collected charge roughly follows the behaviour from Edge-TCT (increase due to acc. removal)
  - Mean signals more than 2000 e⁻ in whole fluence range for 200 Ω·cm and 1000 Ω·cm
  - 200 Ω·cm: smallest changes over whole fluence range
BACKUP
I-V characteristics

Measured on a TCT array (3 x 3 pixels, pixel size 630 x 40 μm²)
At room temperature
not all measurement are good
Depletion zone shape at large depths

- Large peak at the back side of charge collection profiles is commonly observed (especially with high resistivity samples)
- This is due to an expansion of the depletion zone along the direction of the beam (pear shape)
- Extra charge is due to an increased path of the beam in the sensitive region
- This occurs for depleted depth ≥ structure width and on narrow structures (few neighbours)

Case A: depleted depth << structure size  
no back peaks

Case B: depleted depth ≈ structure size  
pear shape
2d Edge-TCT scan

200 Ω·cm, 3e14 n$_{eq}$/cm$^2$

Good response uniformity – no gaps between n-wells
Comparison of results from Edge-TCT and $^{90}$Sr

- From Edge-TCT ($N_{\text{eff}}$) calculate depleted depth $W$
- Assume 1000 e from diffusion before irradiation
- Simulate charge collection in a pad detector of thickness $W$ to estimate trapping loss

\[
\text{Width}(V_{\text{bias}}) = \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{\text{eff}}} V_{\text{bias}}}
\]

- Observation: with $^{90}$Sr less charge is collected than expected from Edge-TCT
- The reason is not understood: maybe simple pad detector approximation not correct, hints: different behaviour of border vs. central pixels (see backup)
Top TCT 1

- On irradiated samples charge from $^{90}\text{Sr}$ measurements systematically less than expected for the depletion depth measured by Edge-TCT
- Investigation with top TCT
  - IR light – 980 nm, absorption depth in Si 100 μm → no reflections from back plane

![CCE at V bias = 100 V](image)

W19 5e14
Large pass. array for $^{90}\text{Sr}$ (1.3 mm x 1.3 mm)

Gaps between pixels due to metalization on top of the chip

But on the large scale intensity in central pixels less than on edges!
Difference in the collected charge indicates a larger depletion depth on the edges of the $^{90}\text{Sr}$ array.

Edge-like pixels also measured in Edge-TCT. This may be a reason for discrepancy between the measurements.
Sr90 calibration procedure
• using epitaxial diodes with known thickness \(d = 50\) and \(100\ \mu\text{m}\) – similar thickness to CHESS 2, well known response
• after epi-layer is fully depleted extract scaling factor \(A = d \times 100\ \text{pairs/\mu m / V}_{\text{sig}}\)

Only n-type diodes could be biased highly enough for calibration p-type breaks down at 60 V, before full depletion
Results:

Calibration with n-type epi diodes

Unirradiated CHESS 2 devices are compatible with the calibration

Irradiated CHESS 2 devices (different wafers) have less charge than expected:

* Depleted depth for CHESS 2 is determined from the formula: 

\[ d = \frac{2\varepsilon_0}{e_0 N_{\text{eff}} \cdot V_{\text{bias}}} \]
$^{90}$Sr spectra 1000 $\Omega \cdot \text{cm}$

- High resistivity wafer - Relatively good separation between signal and noise
- No peak around 0 in signal spectrum $\rightarrow$ misalignment does not seem to be the main factor for smaller charge

1e14 100 V
- Noise
- Signal

3e14 100 V
- Noise
- Signal