Measurement of charge collection in irradiated miniature sensors for the upgrade of ATLAS Phase-II Strip tracker

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On behalf of ITk collaboration

Outline

- Motivation
- Irradiations
- C/V and I/V measurements
- CCE measurements with Alibava setup
- Edge TCT measurements
- Conclusions

Fluences in ATLAS ITk:

- Strips: 4 barrel layers and 6 forward disks (165 m^2) $40 \text{ cm} \leq r \leq 100 \text{ cm}$
- Strip sensors with $75.5 \text{ }\mu\text{m}$ pitch in barrel and ranging from $69 \text{ }\mu\text{m}$ to $85 \text{ }\mu\text{m}$ in disks
- Peak instantaneous luminosity up to $L = 7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (pile-up ≈ 200)
- The predictions (from ATLAS TDR) of particle fluences and ionising doses for the ITk layout assume an integrated luminosity of 3000 fb^{-1} :

Location	1 MeV n. eq. (cm^{-2})	Protons	Pions	Neutrons	Dose (kGy)
($r=28 \text{ cm}$; $z=0 \text{ cm}$)	$6.9\text{e}+14$	7.8%	38.5%	53.7%	329
($r=28 \text{ cm}$; $z=117 \text{ cm}$)	$8.9\text{e}+14$	13%	31.8%	55.2%	418
LS ($r=100 \text{ cm}$; $z=0 \text{ cm}$)	$1.7\text{e}+14$	6%	13%	81%	34
LS ($r=100 \text{ cm}$; $z=117 \text{ cm}$)	$2.1\text{e}+14$	6.2%	10%	83.8%	38

The maximum 1 MeV neutron equivalent fluences for the barrel and strip end-cap detectors are predicted to be $2.8 \cdot 10^{14} \text{ cm}^2$ and $8.2 \cdot 10^{14} \text{ cm}^2$, respectively. In addition a safety factor 1.5 is required!

Strips at $r > 40 \text{ cm}$ → neutrons have the largest contribution to the NIEL!

Miniature sensors:

The miniature sensors with n-strips in p-bulk:

- miniature sensors produced by Hamamatsu on the same high resistivity FZ 6 inch wafers as prototypes of full size R0 (the first ring in ATLAS strip endcap) sensors (previous presentation)
- outer dimension of $10 \text{ mm}^2 \times 10 \text{ mm}^2$, $\approx 325 \mu\text{m}$ thick
- 104 readout strips, 8 mm long
- three different pitches to match the variation of pitches on "Stereo Annulus" sensors
 - $75.5 \mu\text{m}$ (default)
 - $70 \mu\text{m}$ (narrow)
 - $84 \mu\text{m}$ (wide)
 - AC and DC coupled
- distributed to different labs for irradiations, electrical tests and charge collection measurements
- irradiations with protons and distribution to labs
- CV/IV measurements / Prague
- proton irradiated CCE measurements in Japan and Valencia
- neutron irradiated CCE and TCT measurements in Ljubljana
- distribution of work:

p irradi	CYRIC (Japan)	
n irradi	Ljubljana	
C/V I/V	Prague	Japan
CCE p	Japan	Valencia
CCE n, Edge TCT	Ljubljana

Irradiations with 70 MeV protons at CYRIC (Japan):

- temperature $\approx -15^{\circ}\text{C}$
- scanning with sample movement
- irradiations ≈ 1 hr
- dosimetry using $\text{Al}^{27}(\text{p}, 3\text{pn}) \text{Na}^{24}$ spallation reaction
- damage factor from RD50 (1.47)
- equivalent fluence uncertainty 10%
- 3 fluences: 5.6, 11 and $22 \times 10^{14} \text{n}_{\text{eq}} \text{cm}^{-2}$
- storage in the fridge after irradiation

Irradiations with neutrons :

- TRIGA reactor at Jožef Stefan Institute, Ljubljana
- damage factor ≈ 0.90 for fast neutrons
- irradiation flux $\approx 1.6 \cdot 10^{12} \text{ n}_{\text{eq}} \text{ cm}^{-2} \text{ s}^{-1}$ at full power (250 kW)
- uncertainty of fluences $\pm 10 \%$
- equivalent fluences: 5×10^{14} , 10^{15} and $2 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^2$
- Approx. 2 hours at RT before 1st CCE measurement

Temperature during the irradiation

Flux per unit of lethargy ($\rightarrow \ln E$) in different experimental channels

K. Ambrožič et. al. Applied Radiation and Isotopes 130 (2017) 140-152

Total Leakage Current: Pre- and post proton irradiation ATLAS12EC

- Smooth behaviour up to 600V/1000V
- No breakdown voltage observed in measured interval
- Leakage current increases with increasing fluence

Leakage current per cm² of proton irradiated mini's

Comparison A12A, A12M, A07 and A12EC

- Total number of sensor tested **126**:
- Proton Irradiations: Karlsruhe, Birmingham, CYRIC
- Temperature normalized to -15°C,

$$I(T_{-15}) = I(T_M) * (T_{-15}/T_M)^2 * \exp[-E/2k_B * (1/T_{-15} - 1/T_M)], \text{ with } E=1.2\text{eV}$$

- Sensors annealed 80 minutes at 60°C
- Current normalized to 1cm² area;
- Active area - Inner dimension of bias ring => A(EC) = 0.69 cm², A(barrel, A12EC) = 0.637 cm²
- Alfa (+20°C) = 4e-17 A/cm, temperature correction coefficient between +20°C and -15°C : 33

- Leakage currents of new A12EC (R0) sensors are consistent with A12A, A12M and A07

CV Characteristics for Full Depletion Voltage (FDV) estimation: Pre- and post proton irradiation ATLAS12EC – R0

Non-irradiated sensors:

- FDV = 280 - 290V ($\rho=3.1 \text{ k}\Omega\text{cm}$)
- C_{bulk} at full depletion is 25pF

Irradiated sensors:

- “FDV” increased up to 600 V at $2.2e15 n_{\text{eq}}/\text{cm}^2$
- increase comparable to other batches

CCE measurements (Alibava setup)

- based on analogue Beetle chip
- 25 ns peaking time
- 40 MHz clock
- ^{90}Sr source
- different cooling systems (cold box, Peltier)
- triggering with scintillator
- same settings of Alibava in all labs (kazu.ini)
- normalization to MIP MPV – 23100 e-h pairs in 300 μm of depleted unirradiated silicon (77 pairs/ μm)

^{90}Sr source holder

Al support in thermal contact with cooling block

Neutron irradiated sensors – before (dashed) and after (solid) annealing 80 min at 60°C:

- annealing increases charge
- no difference for different pitches and voltages below 800 V
- wider pitch gives higher signal before annealing at the highest fluence and above 800V – indication of multiplication
- this effect disappears after annealing (decrease of space charge)

Long term annealing at 60°C :

- **short term** - decrease of space charge and trapping improves CCE except at voltages above 1000 V where multiplication disappears with annealing
- **long term** - multiplication at higher voltages increases charge

Fluence dependence neutrons:

- dashed line – before annealing
- solid line after annealing 80 min at 60°C
- annealing improves CCE except at the highest fluence
- Wider pitch – more multiplication!

Comparison with A12:

R0 AC def sensors full lines
A12 dashed lines

- A12 (measured in 2014) – lower nominal resistivity (3.1 k Ω) than R0 (3.5 k Ω)

Proton irradiated sensors:

- not annealed samples - dashed lines
- annealed samples - full lines

- 80 min annealing at 60°C increases collected charge

Fluence dependence

ITk largest fluence

- protons cause less degradation of signal than neutrons at same NIEL fluence
- @ 700 V signal above $12ke_0$ in strip ITk (without safety factor)
- @ 500 V signal above $9 ke_0$

Edge TCT measurements:

- raise of signal $\rightarrow$ velocity (E field) profile
- integral of signal $\rightarrow$ charge profile

Comparison R0 – ATL12 – before irradiation

Velocity profile (below depletion:)

Charge profile (above depletion)

RO sensors were not polished!

Both sensors have same active thickness – 300 μm

Results consistent with higher resistivity (lower FDV) of R0 material compared to A12

Comparison R0 – ATL12 – after irradiation with neutrons:

Velocity (E field) profile

Charge profile

$\Phi = 5 \cdot 10^{14} \text{ ncm}^{-2} \rightarrow$

$\Phi = 2 \cdot 10^{15} \text{ ncm}^{-2}$

- A12 nominal resistivity 3.1 k Ω , R0 nominal resistivity 3.5 k Ω
- A12 and R0 are more similar at the highest fluence – indication of acceptor removal

Conclusions:

- pitch variation does not influence signal up to 800 V at all fluences
- at the highest fluence multiplication at high voltages
- wider pitch → more multiplication
- short term annealing improves signal at lower voltages
- protons cause less degradation of signal than neutrons

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Signal/Noise

Multiplication increases signal faster than noise
Values are for Beetle chip, short strips, low temperature !!