Defect level identification of ATLAS ITk Strip Sensors using DLTS

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Introduction

Motivation:

➢ implement trap parameters in TCAD (see poster contribution by C. Jessiman)
➢ precise simulations of irradiated ITk sensors

• measurements on MD8 diodes
  • square 8mm x 8mm n*-in-p diodes
  • produced as test structure on same wafers as main ITk Strip Sensors

• tests performed on unirradiated and irradiated devices
  • unirradiated halfmoons from batch with high current main sensors + reference samples from ‘normal’ batch
  • irradiated samples with irradiation done at CYRIC with 70 MeV protons
  • 3 different fluences (10% uncertainty) and annealed 80min@60°C:
    4.57e14 n_{eq}/cm^{2}  8.34e14 n_{eq}/cm^{2}  1.54e15 n_{eq}/cm^{2}

• samples mounted on heatsinks and wire bonded contacts for implant and GR
IV scans

UNIRRADIATED

- IV curves taken at room temperature on DLTS setup
- W153-179 from a batch with high current main sensors; W418-421 for reference
- Incidentally W153, W418, W420 with highest current

IRRADIATED

- QA results
- Leakage current shows clear scaling with fluence
- Higher currents allow for use of I-DLTS, but can limit usefulness of capacitance transients
CV scans

**UNIRRADIATED**
- CV scans did not show significant differences between samples.
- Depletion width and doping concentration can be derived from CV curves.

**IRRADIATED**
- Full depletion still present at highest irradiation level.
- Limited acceptor removal, $N_{\text{eff}}$ similar to before irradiation.
- DLTS setup can only bias up to 10V,
  - Low bias readings of irradiated samples not useful for calculation of depletion width and carrier concentration.
Measurement methods: DLTS/I-DLTS

1. DUT is under constant reverse bias
2. filling pulse with specific voltage $V_P$ and duration is applied, adjusted to trap states of interest
   - $V_P$ as reduced reverse bias $\rightarrow$ majority carrier traps (holes)
   - $V_P$ slight forward bias $\rightarrow$ minority carrier traps (electrons), if capture rate much larger than competing majority traps
3. bias back to prior level, measure transients
   - capacitance or current transients, depending on sample
   - usually average $O(100)$ transients per temperature point
   - plot $\Delta C$ or $\Delta I$ vs. temperature for fixed rate window corresponding to emission rate
   - analysing spectrum for varying rate window $[t_1; t_2]$ yields Arrhenius plot of trap levels
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Unirradiated diodes: DLTS spectra

- DLTS measurements performed for different bias voltage and filling pulse settings
  - common trap at ~175K seen in all diodes
  - negative offset observed, mitigated with GR at GND
  - peaks at ~100K not consistent between different scan parameters; no clear Arrhenius plot

➢ only true additional defect observed for W153 at ~225K
  ➢ confirmed over multiple runs and 2 diode samples
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Unirradiated diodes: Arrhenius analysis

- good trap saturation for 10ms filling pulse
  - flat relative trap concentration as indicator
- increased transient amplitude for larger bias
  - no changes to overall spectrum
- Arrhenius plots from rate window analysis
  - derive trap parameters from linear fits

<table>
<thead>
<tr>
<th>$T_{\text{median}}$ [K]</th>
<th>$E_T$ [meV]</th>
<th>$\sigma$ [cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>175 (common)</td>
<td>310 – 390</td>
<td>$10^{-14} - 10^{-13}$</td>
</tr>
<tr>
<td>225 (W153 only)</td>
<td>443 ± 6</td>
<td>$7.5 \times 10^{-15} \pm 1.4X$</td>
</tr>
</tbody>
</table>

\[
\ln(\tau_c T^2) = -\ln \left( \sigma_{n,p}^{\text{eff}} \Gamma_{n,p} \right) + \frac{E_A}{k_B T}
\]
Measurement methods: DDLTS, Capture Kinematics

- Double-Pulse DLTS (DDLTS) measured at temperature of observed trap

- progressively increasing filling pulse at fixed bias ⇒ **deep level trap profile**

- fixed pair of filling pulses at increasing measurement bias ⇒ **field strength dependence**; indicates acceptor/donor state

- increasing filling pulse duration ⇒ **capture kinematics**; defect type

Fermi level crosses trap level

signal difference = trap concentration in region X₁-X₂
Unirradiated diodes: deep level profile & capture process

- 175K trap has constant concentration throughout depletion width
- 225K trap has decreased concentration close to junction
- Trap saturation plateaus for filling pulse $\geq 1\text{ms}$
  - Observed dependence indicates point defect
Irradiated diodes: I-DLTS spectra

- Capacitance transients did not yield reliable results
  - Insufficient trap saturation, high trap concentration
  - Exponential increase in capacitance for \( T > 260 \text{K} \)

- I-DLTS spectra very clean
  - Peak >270K could not be fully explored due to high current

- Slight shift of median peak temperature

- Additional traps observed using injection pulse in double-pulse setting
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Irradiated diodes: I-DLTS Arrhenius analysis

- good trap saturation for 100ms filling pulse
- higher trap concentrations in devices irradiated to higher fluences
- no significant variation in trap parameters with higher fluence

<table>
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<tr>
<th>$\Phi$ [$n_{eq}$/cm$^2$]</th>
<th>$T_{peak}$ [K]</th>
<th>$E_T$ [meV]</th>
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<tr>
<td>4.57e14</td>
<td>229</td>
<td>452 ± 4</td>
<td>2.7 x 10$^{-14}$ ± 1.2X</td>
</tr>
<tr>
<td>8.34e14</td>
<td>228</td>
<td>442 ± 7</td>
<td>1.5 x 10$^{-14}$ ± 1.5X</td>
</tr>
<tr>
<td>1.54e15</td>
<td>233</td>
<td>469 ± 3</td>
<td>3.2 x 10$^{-14}$ ± 1.2X</td>
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Irradiated diodes: I-DLTS Arrhenius analysis

- forward injection pulse
  - remove large signal with double-pulse measurement
- 2-Gaussian deconvolution yields second trap contribution in peak flank
  - larger uncertainties on fit results of secondary peak component

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<td>6.9 x 10$^{-13}$ ± 1.4X</td>
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<tr>
<td></td>
<td>248</td>
<td>457 ± 28</td>
<td>7.3 x 10$^{-15}$ ± 3.6X</td>
</tr>
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<td>8.34e14</td>
<td>237</td>
<td>539 ± 9</td>
<td>1.4 x 10$^{-12}$ ± 1.5X</td>
</tr>
<tr>
<td></td>
<td>254</td>
<td>686 ± 42</td>
<td>1.9 x 10$^{-10}$ ± 6.8X</td>
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<td>465 ± 41</td>
<td>4.2 x 10$^{-15}$ ± 6.5X</td>
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Measurement methods: TAS

- Thermal Admittance Spectroscopy (TAS)
- measure C/R/G/Phase as a function of temperature and frequency
  - steady-state measurement
  - defect contribution depending on test signal frequency and temperature
- steps in C or peak in G/R temperature dependence indicate thresholds for new traps contributing
  - steps/peaks yield Arrhenius plots of corresponding trap states
Irradiated diodes: TAS

- TAS yielded good results for irradiated diodes
  - no need to optimize filling pulse parameters for trap saturation
- trap parameters consistent with results from I-DLTS
  - no changes at different levels of irradiation

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\( V_{\text{bias}} = -5 \text{V} \)
\( f_{\text{AC}} = 100 \text{Hz} - 200 \text{kHz} \)

**ATLAS ITk Strips**

MD8 diode (irrad.)
TAS Arrhenius analysis

\( T^2 / e \ [\text{K}^2 \text{s}] \)

1/\( kT \) [eV\(^{-1}\)]
Discussion and Conclusion

Discussion

➢ $T_{\text{peak}}$ and $E_T$ of common H(175) defect in unirradiated diodes consistent with interstitial carbon - interstitial oxygen (C$_i$O$_i$) complex and other carbon-related defects (e.g. K-centre/VOC complex)

➢ common H(230) defect in irradiated diodes consistent with reported vacancy-clusters

➢ H(225) defect in unirradiated W153 has similar parameters

➢ also found in CMS test structures with major contribution to high leakage current

Conclusion

• multiple trap parameters obtained for both unirradiated and irradiated diode samples of ITk Strip Sensors

• DLTS setup proven effective
  • standard C-DLTS and double-pulse variants yield precise results for unirradiated devices
  • I-DLTS and TAS more effective in highly irradiated samples due to significant trap concentration

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Backup
Double-Pulse DLTS (DDLTS): capture process

- transients with filling pulse from 5us to 200ms
- trap saturation for filling pulse $\geq 1$ms