Defect level identification of ATLAS ITk Strip Sensors using DLTS

Christoph Klein

J. Dandoy, D. Duvnjak, C. Jessiman, J. Keller, T. Koffas, E. Staats, R. Vandusen, V. Fadeyev, Y. Unno, M. Ullan

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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:
    \[ 4.57e14 \text{ n}_{eq}/\text{cm}^2 \quad 8.34e14 \text{ n}_{eq}/\text{cm}^2 \quad 1.54e15 \text{ n}_{eq}/\text{cm}^2 \]

• 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 → majority carrier traps (holes)
   - $V_p$ slight forward bias → 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>$T_{median}$ [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>

$$\ln(\tau_e T^2) = -\ln\left(\frac{\sigma_{n,p}^{\text{eff}} \Gamma_{n,p}}{k_B T}\right) + \frac{E_A}{k_B T}$$
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 $X_1 - X_2$
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 \( \gtrsim 1\text{ms} \)
  - Observed dependence indicates point defect

![Graph showing carrier concentration vs. distance from junction for ATLAS ITk Strips.](image)

![Graph showing transient amplitude vs. filling pulse width for ATLAS ITk Strips.](image)
Irradiated diodes: I-DLTS spectra

- Capacitance transients did not yield reliable results
  - Insufficient trap saturation, high trap concentration
  - Exponential increase in capacitance for T > 260K
- 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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Unirradiated diodes: 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

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<tr>
<th>$\Phi$ [n$_{eq}$/cm$^2$]</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>
</tr>
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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>248</td>
<td>457 ± 28</td>
<td>7.3 x 10$^{-15}$ ± 3.6X</td>
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<td>8.34e14</td>
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<td>539 ± 9</td>
<td>1.4 x 10$^{-12}$ ± 1.5X</td>
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<td></td>
<td>254</td>
<td>686 ± 42</td>
<td>1.9 x 10$^{-10}$ ± 6.8X</td>
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Measurement methods: TAS

- Thermal Admittance Spectroscopy (TAS)
- measure $C/R/G/\text{Phase}$ 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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Discussion and Conclusion

Discussion

➢ $T_{\text{peak}}$ and $E_T$ of common H(175) defect in unirrad. diodes consistent with interstitial carbon - interstitial oxygen ($C_iO_i$) 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 unirrad. 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