Investigation of carrier lifetime temperature variations in the proton irradiated silicon by MWA transients

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Problem
Role of oxygenation in modification of the recombination characteristics in proton irradiated silicon

Outline

- proton irradiated samples – fabricated in Helsinki
- RT characteristics: lateral, intensity, irradiation fluence, initial//irradiated
- lifetime temperature variations,-comparison of Helsinki&Hamburg samples
- possible recombination flow redistribution processes and simulated characteristics
**Initial material and proton irradiated Si samples**

<table>
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<th>5</th>
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<th>9</th>
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<tbody>
<tr>
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<td>p</td>
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<td>n</td>
<td>p</td>
<td>p</td>
<td>n</td>
<td>n</td>
<td>p</td>
<td>p</td>
<td>n</td>
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<td>TD treatment</td>
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<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
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**Helsinki Si pieces.** There is a picture of irradiation arrangement. Two pieces (e.g. samples #5 and #6) were irradiated at the same time.

In the picture, it is marked with red approximately the proton beam spot, when one side of the sample is more irradiated with given dose. **The beam spot has a radius of about 2.5cm.** The non-irradiated pieces are passivated with thermally grown SiO₂ (at 1100°C), so the surface recombination velocity should be lower in the latter samples.
Lateral lifetime variation due to irradiation geometry with proton beam spot of 25 mm

Short mono-exponential decay in the irradiated area

Two-componential decay with trapping effect in the non-irradiated area

Strong increase of lifetime at boundary of irradiated and non-irradiated areas
Recombination-trapping in the initial material

**p-Si**

- TD treated
  - HB01, 1064nm MWA
  - as-fabricated p-Si TD treated
  - BI off: $\tau_1 = 238 \mu s$, $\tau_2 = 1670 \mu s$
  - BI on: $\tau_1 = 105 \mu s$, $\tau_2 = 514 \mu s$

- no TD treatment
  - BI off: $\tau_1 = 274 \mu s$
  - BI on: $\tau_1 = 290 \mu s$

**n-Si**

- TD treated
  - HB03, 1064nm MWA
  - as-fabricated n-Si TD treated
  - BI off: $\tau_1 = 1350 \mu s$, $\tau_2 = 2920 \mu s$
  - BI on: $\tau_1 = 1253 \mu s$, $\tau_2 = 2090 \mu s$

- no TD treatment
  - BI on: $\tau_1 = 196 \mu s$, $\tau_2 = 230 \mu s$
  - BI off: $\tau_1 = 218 \mu s$, $\tau_2 = 273 \mu s$
Decay variation with excitation intensity in the initial and irradiated samples at RT

Trapping is inherent for initial material and decreases with excitation

No significant trapping at RT in the irradiated samples
**Reciprocal lifetime vs. protons irradiation fluence at RT**

- **Graph 1:**
  - **Y-axis:** Reciprocal lifetime ($\tau^{-1}$, $\mu$s$^{-1}$)
  - **X-axis:** Irradiation fluence (cm$^{-2}$)
  - Data points represent different treatments and conditions:
    - p-Si TD treated
    - BI on $\tau_{\text{non-irradiated}}$
    - p-Si no TD tr
    - irradiated
    - n-Si TD treated
    - irradiated
    - n-Si no TD tr
    - irradiated

- **Graph 2:**
  - **Y-axis:** Effective decay lifetime ($\tau_{\text{eff}}$, ns$^{-1}$)
  - **X-axis:** Irradiation fluence (cm$^{-2}$)
  - Data points include:
    - l/Hm
    - H n-Si
    - H p-Si TD

- **Graph 3:**
  - **Y-axis:** Reciprocal lifetime ($\tau^{-1}$, $\mu$s$^{-1}$)
  - **X-axis:** Fluence (cm$^{-2}$)
  - Data points show MWA decay lifetime in irradiated Si:
    - $\tau_{\text{ex}}=30$ ps HMB/10ns HLS, $\lambda_{\text{ex}}=1064$ nm
    - no O treatments
    - TD
    - no TD tr
    - irradiated
    - p-Si TD treated
    - irradiated
    - n-Si TD treated
    - irradiated
    - n-Si no TD tr
    - irradiated

- **Graph 4:**
  - **Y-axis:** Reciprocal lifetime ($\tau^{-1}$, $\mu$s$^{-1}$)
  - **X-axis:** Fluence (cm$^{-2}$)
  - Data points for MWA decay lifetime in irradiated Si:
    - no O treatments
    - TD
    - no TD tr
    - irradiated
    - p-Si TD treated
    - irradiated
    - n-Si TD treated
    - irradiated
    - n-Si no TD tr
    - irradiated
Effective lifetime dependence on temperature in the initial material and in the irradiated samples
Variation of the partial decay amplitudes
Correlation between lifetime vs. kT plots in the proton irradiated samples fabricated in Hamburg and Helsinki

Hamburg

Helsinki
Possible trapping processes and characteristics

\[ E_r = 0.43 \text{ eV}, \quad E_{tr} = 0 \]

- \[ E_{tr} = 0.2 \text{ eV} \]
- \[ 0.3 \]
- \[ 0.35 \]
- \[ 0.4 \]
- \[ 0.45 \]
- \[ 0.5 \]

\[ \tau_I \ (\text{a.u.}) \]

\[ \frac{1}{kT} \ (\text{eV}^{-1}) \]

\[ M_{tr} = 1 \times 10^{15} \text{ cm}^{-3} \cdot \text{cm}^{-2} \]

\[ E_p = 0.3 \text{ eV} \]

\[ M_i = 1 \times 10^{16} \text{ cm}^{-3} \cdot \text{cm}^{-2} \]

\[ 5 \times 10^{16} \]

\[ 1 \times 10^{17} \]

\[ 5 \times 10^{17} \]

\[ \text{without trapping} \]
Possible trapping processes and characteristics

Metastable centres TD, V-O, etc.

$TD_{Si}$

$O_i + V_{Si} \rightarrow O_{Si} \rightarrow +V_{nnSi} \rightarrow O^{+}_{Si} V^{-}_{nSi}$

$O^{+}_{Si} V^{-}_{nSi} \rightarrow O^{2+}_{Si} V^{-}_{nSi} + e^- \Rightarrow O^{2+}_{Si} A^{-}_{nSi} + e^{-}$

$A^{-}_{nSi}: \text{irr } V_{Si}; \text{Cu}_{Si}; \text{Al}_{Si}$

$\Rightarrow O^{2+}_{Si} A^{-}_{nSi} A^{-}_{2nSi}$
Methodological summary
The decay of photoconductivity excited by short light pulse enables one to distinguish the slow trapping and recombination processes.

The determined lifetime values in proton irradiated Cz Si for fluences in the range of $5 \times 10^{12} - 2 \times 10^{13}$ cm$^{-2}$ fits into the earlier revealed lifetime fluence dependency, but an existence of the dominant defect type change still requires further, the more detail examination of this lifetime vs. fluence characteristic.

The trapping effect is observable in the temperature range of 240-120 K for these proton irradiated samples, but application of the simple recombination-trapping model is complicated due to the quite abrupt lifetime changes in its temperature dependency.
Technological potential

The temperature dependent trapping effect is inherent for all the irradiated samples, irrespective of TD treatment → is dominant the interaction between oxygen and the radiation defects in TD transformations? The post-irradiation history of lifetime variations would enable to reveal these TD transformations.

The MWA photo-response decay controller, the “τ-meter”, allows a non-invasive monitoring of the trapping-recombination processes.

Thank you for your attention