Si and GaN for large fluence irradiation monitoring

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Outline:

• Motivation
• Samples and irradiations, anneals
• Measurement Techniques: Temperature dependent carrier trapping lifetime (TDTL), Pulsed photoionization spectroscopy (PPIS), Deep-level transient spectroscopy (DLTS)
• Results on Fz and Cz Si irradiated by electrons and hadrons
• Results on multicrystaline Si irradiated by 8 MeV protons
• Results on GaN irradiated by 1MeV neutrons
• Commercial GaN LED structures as dosimeters of 1.6 MeV proton irradiation
• Summary
Our work is based on these effects:

Comparison of characteristics of the pion, neutron and proton as irradiated and isothermally ($T_{an} = 80$ C) annealed Si

Comparison of exciton spectra in SI-GaN (MOCVD) irradiated to different hadron fluence.
Motivation

● The better understanding of radiation damage of Si particle detectors is important in order:
  ● to extend sensor lifetime and their radiation hardness or
  ● to restore their functionality after degradation caused by irradiations – one of the ways to recover detector operational features is heat treatment at technically acceptable temperatures.

● Multicrystalline silicon (mc-Si) use for the detection of charged particles – inexpensive material for mass production.

● Semi-insulating GaN is a promising material for particle tracking detectors and for imaging detectors – there still remains a lack of detailed studies of the defects in the as-grown material and their interaction with radiation induced defects, particularly in heavily irradiated samples.
### Si samples and irradiations

<table>
<thead>
<tr>
<th>Type of irradiation</th>
<th>Electrons</th>
<th>Protons</th>
<th>Pions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>6.6 MeV</td>
<td>24 GeV/c</td>
<td>300 MeV/c</td>
</tr>
<tr>
<td>Fluence range</td>
<td>$10^{16}$-5$\times$10$^{16}$ e/cm$^2$</td>
<td>$10^{12}$-$10^{16}$ p/cm$^2$</td>
<td>$10^{11}$-$3\times10^{15}$ $\pi^+$/cm$^2$</td>
</tr>
<tr>
<td>Si material</td>
<td>CZ n-Si</td>
<td>CZ p-Si</td>
<td>FZ n-Si</td>
</tr>
<tr>
<td>Dopant concentration</td>
<td>$10^{15}$ cm$^{-3}$</td>
<td>$3\times10^{15}$ cm$^{-3}$</td>
<td>$10^{12}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>

#### Anneals:
- The isochronal anneals have been performed at the temperatures in the range of 80°-280°C.
- The hadron irradiated samples were isothermally (at 80 °C) annealed up to 5 hours before isochronal (24 h) anneals.

### mc-Si substrates for commercial solar-cell production

<table>
<thead>
<tr>
<th>Type of irradiation</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>8 MeV</td>
</tr>
<tr>
<td>Fluence range</td>
<td>$10^{12}$-$10^{16}$ p/cm$^2$</td>
</tr>
<tr>
<td>Si material</td>
<td>p-Si</td>
</tr>
<tr>
<td>Dopant concentration</td>
<td>$10^{15}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>

#### Anneals:
- 1st annealing step: 80° C, 30 min
- 2nd annealing step: 1st + 200° C, 60 min
- 3rd annealing step: 2nd + 300° C, 60 min
- 4th annealing step: 3rd + 400° C, 60 min
AT GaN samples and irradiations

- semi-insulating (SI) bulk GaN
- grown by the ammonothermal method
- 450 µm thick
- doped with Mg (GaN:Mg) and Mn (GaN:Mn)

<table>
<thead>
<tr>
<th>Neutrons</th>
<th>Energy</th>
<th>Fluence range</th>
<th>GaN material</th>
<th>Dopant concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 MeV</td>
<td>(10^{12}-5\times10^{16}) e/cm(^2)</td>
<td>GaN:Mg</td>
<td>(~10^{19}) cm(^{-3})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GaN:Mn</td>
<td>(~10^{18}) cm(^{-3})</td>
</tr>
</tbody>
</table>

Commercial MOCVD GaN LED structures as dosimeters

(Optosupply OSB4XNE1E1E, peak wavelength \(\lambda=465\) nm)
Measurement Technique:
Temperature dependent carrier trapping lifetime (TDTL)

$T_{\text{peak}}$ for which the largest $K_{\text{tr}}$, ascribed to a single type trapping centres, is obtained, can be found by solving the transcendental equations:

$$\frac{\partial K_{\text{tr}}(T)}{\partial T} = 0$$

$$T_{\text{peak}} = A^{2/3} \exp\left(\frac{2}{3} \frac{E_{\text{tr}}}{kT_{\text{peak}}}\right) \times 300K, \quad \Delta n_C = \text{const}$$

$$A = \Delta n_C / N_{C,V,T=300K}$$

Simulated trapping coefficients ($K_{\text{tr}}$) as a function of temperature for trapping level with activation energy of 0.4eV and 0.23eV in Si. $N_{C,e,Ntr}(T)$ - the effective density of band states for trapped carriers, $\Delta n(T)$ - the excess carrier density.

E. Gaubas, E. Simoen and J. Vanhellemont. .

Measurement Technique:

- Deep-level transient spectroscopy (DLTS)
  - Capacitance (C-DLTS) and current (I-DLTS) spectra over temperature range of 10-300K were recorded by using a HERA-DLTS System 1030 spectrometer.
  - The PhysTech software installed within HERA-DLTS spectrometer was employed for analysing of the measured DLTS spectra.

- Pulsed photoionization spectroscopy (PPIS)
  - The PPIS were implemented using excitation by a tuneable wavelength laser and measurements of the photo-response by applying microwave probed photoconductivity transient (MW-PC) technique.
  - Here tuneable wavelength nanosecond laser Ekspla NT342B (pulse duration 4 ns, wavelength tuning from 210 to 2300 nm) were employed.
Measurement Techniques:

- Pulsed barrier evaluation by linearly increased voltage (BELIV)
- Proton induced luminescence spectroscopy (PIL)
Results on Fz and Cz Si irradiated by electrons and hadrons n-type and p-type CZ Si irradiated by 6.6 MeV electrons

- No peaks in low temperature wing were observed in heavily irradiated n- and p-type CZ samples.
- The radiation induced defects, ascribed to vacancy related complexes, TD and to H related defects have been observed in the electron irradiated Si samples.

Application of the TDTL technique allowed to identify the trapping centres appeared after heat treatment at $T_{an} \geq 80^\circ C$ even in heavily irradiated samples.
Results on Fz and Cz Si irradiated by electrons and hadrons

n-type FZ and p-type CZ Si irradiated by 26 GeV/c protons

- The predominant peaks for the n-type FZ Si samples are attributed to V- and H-related defects.
- DLTS measurement are not suitable for p-type CZ Si samples irradiated by 26 GeV/c protons, due to the low concentration of the effective doping.
- As deduced using TDTL, the $V_2^-$, H-related and VO complexes are predominant radiation defects in the p-type CZ Si.
- The TDTL spectroscopy is a reliable tool for tracing of the radiation defect evolution for the range of elevated fluences.
Results on mc-Si irradiated by 8 MeV protons

- Variations of $\tau_R$ appear for ms-Si samples irradiated (synchronously) with the same fluence.

- Variations within fluence dependent $\tau_R$ in mc-Si due to initial material quality (trapping indicates intrinsic defects).
Results on GaN irradiated by 1 MeV neutrons

\[ \sigma(h\nu) \propto \int_0^\infty e^{-\frac{(E+E_d-h\nu)^2}{\Gamma^2}} \frac{\sqrt{EEdE}}{h\nu (E+E_d)^2} \]

\[ \Gamma - \text{the broadening parameter} \]

\[ \Gamma = \Gamma_0 \sqrt{2\coth(h\nu_0/k_BT)} \]

<table>
<thead>
<tr>
<th>Non-irradiated</th>
<th>Irradiated with ( \Phi=10^{16} \text{ cm}^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Photo-activation energy (eV)</td>
</tr>
<tr>
<td>( E_{\text{Mn-1}} )</td>
<td>1.40</td>
</tr>
<tr>
<td>( E_{\text{Mn-2}} )</td>
<td>1.98</td>
</tr>
<tr>
<td>( E_{\text{Mn-3}} )</td>
<td>2.40</td>
</tr>
<tr>
<td>( E_{\text{Mn-4}} )</td>
<td>2.97</td>
</tr>
<tr>
<td>( E_{\text{Mg-1}} )</td>
<td>1.30</td>
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<tr>
<td>( E_{\text{Mg-2}} )</td>
<td>1.70</td>
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<tr>
<td>( E_{\text{Mg-3}} )</td>
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<tr>
<td>( E_{\text{Mg-4}} )</td>
<td>2.39</td>
</tr>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( E_{\text{Mg-5}} )</td>
<td>3.00</td>
</tr>
<tr>
<td>( E_{\text{Mg-6}} )</td>
<td>3.30</td>
</tr>
</tbody>
</table>
GaN LED-based structures for remote dosimetry of 1.6 MeV protons

Evolution of the BELIV current transients for the reverse (a) and forward (b) biased GaN LED ($\tau_{PL} = 45$ $\mu$s). (a) LED irradiated with the proton fluences of 0 (1); $5 \times 10^{14}$ p/cm$^2$ (2); $8 \times 10^{14}$ p/cm$^2$ (3); $1 \times 10^{15}$ p/cm$^2$ (4); $2 \times 10^{15}$ p/cm$^2$ (5); $3 \times 10^{15}$ p/cm$^2$ (6); and $5 \times 10^{15}$ p/cm$^2$ (7), respectively ($U_{P,R} = 6$ V). (b) Pristine LED (1-3) and LED irradiated with the fluence of $5 \times 10^{15}$ p/cm$^2$ (1’-3’) for peak voltage $U_{P,F}$ of 1 V (1 and 1’), 2 V (2 and 2’), and 3 V (3 and 3’).

TCT transients (a) and peak-current (b) as a function of reverse-bias voltage measured on pristine and heavily irradiated LED-based sensor.

E. Gaubas, T. Ceponis, D. Meskauskas, J. Pavlov, A. Zukauskas, V. Kovalevskij, V. Remeikis
Summary

- The non-monotonous variations of trap densities after different anneal steps have been identified in heavily electrons and hadrons irradiated silicon by combining the DLTS and TDTL spectroscopy.

- The similarity between DLTS spectra, obtained for rather low fluence irradiations by protons and pions, indicate that the irradiation with various type penetrative hadrons induce the same defects (the oxygen, vacancy and hydrogen related complexes and TD).

- Contactless TDTL technique allows simultaneous control of interactions among several radiation defects within large fluences irradiated Si structures.

- The AT-GaN material performance showed insignificant changes after neutron irradiation with large fluences (up to $5 \times 10^{16}$ e/cm$^2$).

- GaN LED-based sensors can be used for the synchronous detection of hadron irradiation by recording the optical (B-L) and electrical signals ($I_{SC}$ and TCT transients).
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