

**DLTS studies on as irradiated PiN diodes of different resistivity**

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Aim

Understand the acceptor removal process in Boron doped silicon and predict ways to control it:

- Detection and electrical characterization of defects induced by irradiation
- Determine the defect generation rate(s)
- Identify in which defects formation B is involved (e.g. $\text{B}_1\text{O}_1$ defect) and evaluate the impact on the acceptor removal rate.
Investigated p-type Samples

PiN pads produced by CiS

50 µm thick P-type substrate:
- EPI, 50 ohm cm (4 samples)
- EPI, 250 ohm cm (4 samples)
- CZ, 100 ohm cm (4 samples)
- EPI, 1000 ohm cm (4 samples)
- FZ high resistivity (4 samples)

Irradiation

23 GeV protons:
(2 samples of each type, 2 fluences)

1MeV neutrons:
(2 samples of each type, 2 fluences)
Investigated p-type, 50 µm thick, PiN Samples

<table>
<thead>
<tr>
<th>Sample (identification No.)</th>
<th>Resistivity (ohm cm)</th>
<th>Irradiation</th>
<th>Fluence (cm²) $\Phi / \Phi_{eq}$</th>
<th>$N_{eff}^{293K}$ (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPI-50-1p (EPI-04-70)</td>
<td>50</td>
<td>23 GeV p</td>
<td>4E12 / 2.48E12</td>
<td>2.61E14</td>
</tr>
<tr>
<td>EPI-50-1n (EPI-04-80)</td>
<td>50</td>
<td>1 MeV n</td>
<td>2.4E12</td>
<td>2.65E14</td>
</tr>
<tr>
<td>EPI-50-2n (EPI-04-83)</td>
<td>50</td>
<td>1MeV n</td>
<td>1.3E13</td>
<td></td>
</tr>
<tr>
<td>EPI-250-1p (EPI-09-105)</td>
<td>250</td>
<td>23 GeV p</td>
<td>4E10 / 2.48E10</td>
<td>4.95E13</td>
</tr>
<tr>
<td>EPI-250-2p (EPI-09-104)</td>
<td>250</td>
<td>23 GeV p</td>
<td>2E11 / 1.24E11</td>
<td>4.85E13</td>
</tr>
<tr>
<td>EPI-250-1n (EPI-09-96)</td>
<td>250</td>
<td>1 MeV n</td>
<td>2.4E10</td>
<td>4.83E13</td>
</tr>
<tr>
<td>EPI-250-2n (EPI-09-99)</td>
<td>250</td>
<td>1 MeV n</td>
<td>1.2E11</td>
<td>4.57E13</td>
</tr>
<tr>
<td>EPI-1000-2p (EPI-15-95)</td>
<td>1000</td>
<td>p</td>
<td>4E10 / 2.48E10</td>
<td>1.05E13</td>
</tr>
<tr>
<td>EPI-1000-2n (EPI-15-92)</td>
<td>1000</td>
<td>n</td>
<td>2.4E10</td>
<td>1.62E13</td>
</tr>
<tr>
<td>CZ-100-1p (CZ-03-78)</td>
<td>100</td>
<td>p</td>
<td>2E12 / 1.24E12</td>
<td>1.56E14</td>
</tr>
<tr>
<td>CZ-100-2p (CZ-03-79)</td>
<td>100</td>
<td>p</td>
<td>1E13 / 6.2E12</td>
<td>1.41E14</td>
</tr>
<tr>
<td>CZ-100-1n (CZ-03-89)</td>
<td>100</td>
<td>n</td>
<td>1.2E12</td>
<td>1.65E14</td>
</tr>
<tr>
<td>CZ-100-2n (CZ-03-88)</td>
<td>100</td>
<td>n</td>
<td>6E12</td>
<td>1.47E14</td>
</tr>
</tbody>
</table>
Typical DLTS spectra

EPI diodes, 50 µm thick diodes

Low resistivity

Medium resistivity

High resistivity

Several yet un-identified defects (traps for holes - H79K, H156K, H223K and H238K)
**Trapping parameters**

**H156K** and **H223K** – well seen in diodes of medium and high resistivity

50 (EPI) and 100 ohm cm (CZ) diodes  
250 ohm cm EPI diodes  
1000 ohm cm EPI diodes

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![Graphs showing trapping parameters for different diodes](image-url)
Trapping parameters

**H156K and H223K** – from **Arrhenius plots** (maxima analyses of DLTS spectra)

EPI-250-1p diode

**H156K:** $E_a = E_v - 0.305$ eV; $\sigma_h = 1.5 \times 10^{-15}$ cm$^2$

**H223K:** $E_a = E_v - 0.435$ eV; $\sigma_h = 6.5 \times 10^{-16}$ cm$^2$
Trapping parameters

**H156K and H223K** – direct analyses of transients at constant temperature

H156K: $\sigma_h = 4.8 \times 10^{-16} \text{ cm}^2$

H223K: $\sigma_h = 1.7 \times 10^{-17} \text{ cm}^2$

$E_a^{H156K} = 0.291 \text{ eV}$

$E_a^{H223K} = 0.363 \text{ eV}$
Trapping parameters

**BiO**

**defect**

Direct measurement of the capture cross sections (errors up to 20%)

- By measuring the amplitude of the emission transient as function of the filling pulse duration at constant temperature

**σₐ** - trapping of electrons - pulses of forward injection

**σₚ** ~ 1x10⁻¹⁴ cm²

**σₜ** - trapping of holes - use double pulses

(1st to charge the defect with electrons and 2nd for capturing holes)

**σₜ** ~ 2.5x10⁻²⁰ cm²
**Trapping parameters**

**B\textsubscript{i}O\textsubscript{i} defect**

**Activation energy** (errors up to 5%)

- from direct analyses of transients at 120 K and exponential decay fit
- (using as input the $\sigma_e=10^{-14}$ cm$^2$ value measured at the same temperature)

**EPI** – resistivity 250 ohm cm

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\[E_{BiO_i} = 0.248 \text{ eV} \pm 1 \text{ meV}\] 
(from conduction band)

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Same values for activation energy of BiO\textsubscript{i} in samples measured under similar electric fields
Trapping parameters

\( B_{\text{Oi}} \) defect - Dependence of \( E_a \) on the electric field magnitude – Poole Frenkel effect for coulombic centers

Enhanced field emission for \( B_{\text{Oi}} \) defect – still more measurements needed for parametrizing the electric field dependence
B_{i}O_{i} generation rate(s)

EPI diodes

23GeV proton irradiation

Medium resistivity/ fluences in the E10-E11 p/cm² range

Low resistivity/ fluences above E12 p/cm²

- The rate of BiOi defect generation in proton irradiated samples:
  - Increases when the material resistivity is lowered (as expected)
  - ~ constant for medium resistivity and fluences of E10-E11 p/cm²
- H156K defect – may change in another in the E10-E11 cm² fluence range (to be investigated further)
The rate of BiOi defect generation in neutron irradiated samples:
- Increases when the material resistivity is lowered (as expected)
- Decreases with increasing the fluence above $10^{12}$ n/cm$^2$
- H156K defect – may change in another in the E10-E11 cm$^2$ fluence range (to be investigated further)
BiOi generation rate decreases with increasing the fluence (above 10^{12} /cm^2 !?) (with only a small decrease in the generation rate of CiOi)

BiOi generation rate increases with increasing the fluence (with a similar increase in the generation rate of CiOi)
Neutron versus Proton irradiation

Proton irradiation induces more defects than neutron irradiation in low resistivity EPI diodes.
Neutron versus Proton irradiation

Medium resistivity EPI diodes

Proton irradiation induces less defects than neutron irradiation in medium resistivity EPI diodes
Neutron versus Proton irradiation

Low resistivity CZ diodes (with more O and C than EPI diodes)

For same equivalent fluences Proton irradiation induces more defects than neutron irradiation – similar to the case of low resistivity EPI diodes
Dependence on doping

All the experiments done in the same place, with the same set-up/procedures.

- Large differences between proton (open symbols) and neutron irradiation (filled symbols) for the same equivalent irradiation fluence and material (EPI and CZ) for fluences above $10^{12}\,\text{cm}^{-2}$.

- The generation rate is also varying with the fluence (above $10^{12}\,\text{cm}^{-2}$) for the same type of irradiation and material impurity content.
BiOi generation rate – a real puzzle!

Dependence on fluence and type of irradiation

EPI material:

- **Low fluences & low B doping:** Similar generation rates for B$_2$O$_3$ and C$_2$O$_3$ defects for the same type of irradiation (more after neutrons than after protons)

- **Increasing the fluence** (100 times) & B doping (5 times): gBiOi > gCiOi (more after protons than after neutrons) for both type of irradiations
BiOi generation rate – a real puzzle!

Dependence on fluence and type of irradiation

**CZ material** (at least 10 times more C and O in CZ than in EPI), irradiated with ½ fluences used for low resistivity EPI diodes:
- \( g_{\text{BiOi}} < g_{\text{CiO}} \) for both type of irradiations (same equivalent fluence)
- **different fluence dependence** (for fluences \( 10^{12} \) – \( 10^{13} \) cm\(^2\) \( g_{\text{BiOi}} \) decreases after neutron irradiation and increases after proton irradiation) and **different generation rates after n or p irradiation** (larger after proton irradd), possible reason –interstitials trapped in the clusters generated by 1MeV neutron irradiation
BiOi generation rate – a real puzzle!

**Dependence on the material** (different C content in EPI and CZ materials)

- Fluence range $10^{12} – 10^{13}$ cm$^{-2}$

For similar fluences range and B doping – the generation rate of BiOi is larger in EPI than in CZ material (the opposite stands for the CiOi defect) for both types of irradiations – a result of the competition on interstitials between B and C.
Summary and further work

- **Trapping parameters of several defects induced by irradiation**
  - Activation energy and capture cross sections (BiOi, H156K and H223K)
  - Concentrations and generation rates
- **The generation of BiOi defects depends on:**
  - **B doping** – the prime factor in generating the BiOi defect
  - **Impurity content (C and O content)** – Large differences between EPI and CZ of similar B doping
  - **Type of irradiation** - Large differences between p/n irradiation even for the same equivalent fluence (above 10^{12} cm^{-2}) and impurity content (B, C and O) in the material
  - **Irradiation fluence** – Large differences in the defect generation rates even when use the same type of irradiation and material

- More diodes still to be measured in the RD50 Acceptor removal project
- Check the impurity content – is B content fully accounting for Na value or it is partly compensated during the growth process?
- Annealing studies
- Different resistivity diodes (e.g. EPI 100 ohmcm, CZ 50, 250 ohmcm)?!
- LGAD diodes
Thank you for your attention!