Defect characterization in boron doped silicon sensors after exposure to protons, neutrons and electrons

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Acceptor removal: reminder

Macroscopic observation in Si detectors:
- mainly as a shift of $V_{fd}$ obtained from CV measurements

$$V_{fd} = \frac{e_0|N_{eff}|d^2}{2\varepsilon_0}$$

AR coefficients reported in literature
- $C_A$ parameter drops with increasing $N_{B0}$ (decreasing resistivity)
- Faster removal for higher resistivity if we take parametrization strict:
  $$N_B = N_{B0} \exp(-C_A \Phi)$$

Assumptions:
- $V_{fd}$ is a valid parameter for evaluation of $N_{eff}$
- $N_{eff} = \text{const}$ throughout the bulk

$$|N_{eff}| = |N_{eff,0}| + g_c \Phi_{eq} - N_c [1 - \exp(-C \Phi_{eq})]$$

Parametrization of $N_{eff}$

Higher resistivity

P. Almeida et al, 32nd RD50 workshop (2018)
Radiation induced removal of B from the substitutional lattice site, its deactivation as a shallow dopant leading to the change of $V_{fd}$ and $N_{eff}$ on the macroscopic level

Originated from $B_iO_i$ complex formation on the microscopic level

- Most typical radiation induced reaction:

$$Si_i + B_s \rightarrow B_i$$

Radiation damage

$$B_i + O_i \rightarrow B_iO_i$$

$B_iO_i$ - donor in the upper part of $E_g$ (contributes with ‘+’ space charge)

For every removed Boron an acceptor is erased and a donor is created (factor of 2! in space charge)
Possible defect kinetics in Si: reminder

Assumption: [O]>>[B],[C]

- Boron can be removed by the reactions:
  \[ V + B_s \rightarrow VB \text{ (anneals out @T-0°C) - no role to play} \]
  \[ I + B_s \rightarrow B_i \rightarrow B_i + O_i \rightarrow B_i O_i \]
  \( B_i \)- highly reactive!

- \( Si_i \) are shared between \( B_s \) & \( C_s \)

Concurrent reaction channel: \( I + C_s \rightarrow C_i \rightarrow C_i + O_i \rightarrow C_i O_i \)
  (Increasing \( C_s \) will protect \( B_s \) from removal)

- \( Vs \): \( V + O_i \rightarrow VO_i \) (remains more \( Si_i \) available)

- Initial Boron removal rate
  (i.e. rate of BiOl formation at low fluence):

  \[ g_B = g_{BiOl} = g_i \left( 1 + \frac{k_{IC}[C_s]}{k_{IB}[B_s]} \right)^{-1} \]

  - Generation of interstitials (outside clusters): \( g_i \approx 1-3 \text{ cm}^{-1} \) (high resistivity silicon)
  - Sharing of interstitials between Bs and Cs: \( k_{IB}/k_{IC} \approx 1-7 \)
  - \([C_s] \approx 1 - 5 \times 10^{15} \text{ cm}^{-3}\)

* EPR studies of the lattice vacancy and low-temperature damage processes in Si by Watkins, G.D.
RD50 Acceptor Removal project

Dedicated defect and material characterization experiment

A large number of identical test structures with known $B_s$ content:
- unify the list of the defects & their impact on sensor properties including introduction rates and annealing behaviour
- different irradiation particle types, materials, initial resistivities, $O_s$ & $C_s$
- underlying reactions?
- is acceptor removal complete? Removal rate?

Irradiation

Test structure

<table>
<thead>
<tr>
<th></th>
<th>Fz</th>
<th>Cz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity</td>
<td>$&gt;10,000\ \Omega\cdot\text{cm}$</td>
<td>$100\ \Omega\cdot\text{cm}$</td>
</tr>
<tr>
<td>Thickness</td>
<td>100-285 μm</td>
<td>100 or 285 μm</td>
</tr>
</tbody>
</table>

Electron irradiation
- 3.5-5.5 MeV

Neutron irradiation
- Reactor neutrons

Proton irradiation
- Boston General Hospital 230 MeV
- 24 GeV /c

$\gamma$-irradiation
- $^{60}$Co
- 50 kGy, 200 kGy and 1 MGy
- clear signature for identification point and cluster defects

- Identification of main defects responsible of radiation damage in Si and their formation kinetics

EPI
- 10, 50, 250 or 1000 $\Omega\cdot\text{cm}$
- 50 μm active layer

36th RD50 Workshop, June 3-5, 2020, Virtual meeting at CERN, Geneva
Setup for defect characterization

- Closed Cycle liquid Helium Cryocooler with cold head down to 8 K
- Vacuum $\sim 10^{-6}$ mbar.
- Heating coil with temperature regulation for controlled warm-up
- 2 measurement techniques available:
  - TSC: electrometer + Custom LabView DAQ
  - DLTS: Phystech commercial system (hardware, DAQ, analysis software)

Sample holder Version 2020

Work in progress on light injection option
Several new defects are detected in proton irradiated with low fluences (2.4E+13 and 5.4E+13 p/cm²) in low resistivity material

Sensors are not fully depleted, $T_{\text{fill}}$ dependence

Before concentrations were found by integration over TSC peak introducing $T_{\text{threshold}}$ ‘by eye’

$$Q_t = \int dt I_{TSC}(t) \quad n_{t,0} = 2 \frac{Q_t}{q_0 AW}$$

Measured $n_t$ do not explained observed AR (missing factor of 2-4 in $B_iO_i$ concentration)

New fitting procedure is introduced in order to obtain $E_a', \sigma$ and $n_t$ from single TSC scan, works well for single point-like defects
TSC: defect concentrations and introduction rates via fitting

Sensors are not fully depleted

low introduction rate?
TSC: $T_{\text{fill}}$ variation for 0 bias cooling

Example: proton irradiated 50 Ω·cm EPI PiN diode

$0 \text{ bias cooling} \rightarrow$ filling only hole traps with majority carriers

$\Rightarrow X$-defect - hole trap $H(87K)$ (proved by Hamburg group with light injection)

Integration over TSC peak ($V_{\text{bias}}=-100V, T_{\text{fill}}=20K$), Int.rate=$n/\Phi_{\text{eq}}$

<table>
<thead>
<tr>
<th>Fluence</th>
<th>$\Phi_{\text{eq}}$/cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4E+13</td>
<td>1.49E+13</td>
</tr>
<tr>
<td>5.4E+13</td>
<td>3.35E+13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>EPI-04-81, 1.49E+13 n$_{\text{eq}}$/cm$^2$</th>
<th>EPI-05-83, 3.35E+13 n$_{\text{eq}}$/cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H(40K)$</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>$H(87K)$</td>
<td>0.35</td>
<td>0.41</td>
</tr>
<tr>
<td>$H(116K)$</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$C_{\text{i}}O_{\text{i}}$</td>
<td>0.17</td>
<td>0.24</td>
</tr>
<tr>
<td>$H(160K)$</td>
<td>0.02</td>
<td>0.04</td>
</tr>
</tbody>
</table>

~0.4 by fitting
DLTS data on e, p and n irradiated 50 Ω·cm sensors

- holes injection (-10-2 V)

DLTS: $T_w = 200$ ms, $t_p = 1$ ms, $V_R = -10$V, $V_p = 0.6$V

- both carrier types injection (-10+2 V)

DLTS: $T_w = 200$ ms, $t_p = 1$ ms, $V_R = -10$V, $V_p = +2$V

Identification of the defects is ongoing. Further investigations with light injection and isochronal and isothermal annealing are planned in RD50 AR group.

Careful: peak heights do not correspond to $N_T$. 

<table>
<thead>
<tr>
<th>DLTS signal (pF)</th>
<th>DLTS signal (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>Temperature (K)</td>
</tr>
</tbody>
</table>

[Graphs showing DLTS data with various conditions]
Arrhenius plots using correlator functions

DLTS: $U_R = -10\, \text{V}, \, U_p = -2\, \text{V}, \, T_w = 20\, \text{ms}$

- Peak 1 - $C_{i1}$ or $I_2O_{5/0}^+$
  Stability 225 $^\circ\text{C}$ or 50-100 $^\circ\text{C}$
- Peak 2 - $V_{3}^{15/0}$
- Peak 3 -
- Peak 4 - $V_{2}^{0/0}$...
- Peak 5 - $B_{i}$
- Peak 6 - $C_{i0}^{10/0}$
- Peak 7 - $H_{255}$
- Peak 8 - $H_{220}$

Annealing is planned
### DLTS measurements results:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Resistivity (Ω·cm)</th>
<th>Particle type</th>
<th>Fluence</th>
<th>$\Phi_{\text{neq}/\text{cm}^2}$</th>
<th>Annealing status</th>
<th>$N_{\text{eff}}$ (cm$^{-3}$)</th>
<th>$N_{\text{BIO}}/N_{\text{TBI}}$</th>
<th>Intr. rate $B_{\text{O}}$</th>
<th>NT$<em>{\text{CI/O}}/N</em>{\text{TCl}}$</th>
<th>Intr. rate C$_{\text{O}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPI-04-81</td>
<td>50</td>
<td>p</td>
<td>2.4E+13</td>
<td>1.49E+13</td>
<td>0 min</td>
<td>1.8E+14</td>
<td>2.18E+13/2.82E+13</td>
<td>1.46/1.89</td>
<td>7.83E+12/1.29E+13</td>
<td>0.53/0.87</td>
</tr>
<tr>
<td>EPI-05-83</td>
<td>50</td>
<td>p</td>
<td>5.4E+13</td>
<td>3.35E+13</td>
<td>0 min</td>
<td>1.1E+14</td>
<td>6.58E+13/1.15E+14</td>
<td>1.96/3.43</td>
<td>1.65E+13/2.72E+13</td>
<td>0.49/0.81</td>
</tr>
<tr>
<td>EPI-04-98</td>
<td>50</td>
<td>n</td>
<td>4E+12</td>
<td>4E+12</td>
<td>0 min</td>
<td>1.9E+14</td>
<td>1.15E+12/1.85E+12</td>
<td>0.29/0.46</td>
<td>3.70E+11/6.67E+11</td>
<td>0.09/0.17</td>
</tr>
<tr>
<td>EPI-08-83</td>
<td>250</td>
<td>n</td>
<td>5E+11</td>
<td>5E+11</td>
<td>0 min</td>
<td>3.3E+12</td>
<td>1.79E+10/2.17E+10</td>
<td>0.04/0.04</td>
<td>1.37E+10/2.22E+10</td>
<td>0.03/0.04</td>
</tr>
<tr>
<td>EPI-12-103</td>
<td>1k</td>
<td>n</td>
<td>1E+11</td>
<td>1E+11</td>
<td>0 min</td>
<td>7.5E+11</td>
<td>1.42E+09/1.73E+09</td>
<td>0.014/0.02</td>
<td>4.24E+09/6.69E+09</td>
<td>0.04/0.07</td>
</tr>
<tr>
<td>EPI-02-100</td>
<td>10</td>
<td>ē</td>
<td>5E+14</td>
<td>1.9E+13</td>
<td>RT</td>
<td>1.5E+15</td>
<td>4.34E+13/5.53E+13</td>
<td>2.28/2.91</td>
<td>1.05E+13/1.57E+13</td>
<td>0.81/0.83</td>
</tr>
<tr>
<td>EPI-02-105</td>
<td>10</td>
<td>ē</td>
<td>5E+14</td>
<td>1.9E+13</td>
<td>RT</td>
<td>1.4E+15</td>
<td>4.09E+13/5.21E+13</td>
<td>2.15/2.74</td>
<td>1.53E+13/2.16E+13</td>
<td>0.62/1.14</td>
</tr>
<tr>
<td>EPI-06-88</td>
<td>50</td>
<td>ē</td>
<td>2E+14</td>
<td>7.6E+12</td>
<td>RT</td>
<td>2E+14</td>
<td>1.32E+13/1.57E+13</td>
<td>1.74/2.07</td>
<td>6.44E+12/9.61E+12</td>
<td>0.85/1.26</td>
</tr>
</tbody>
</table>
$B_iO_i$ - Introduction rates

Comparison of $B_iO_i$ introduction rate to ‘Acceptor Removal rate’

![Graph showing comparison of $B_iO_i$ introduction rate to Acceptor Removal rate with data points and lines representing different cases.](image-url)
Conclusions

- TSC and DLTS were performed on 5.5 MeV electron, 23 GeV proton and reactor neutron irradiated sensors (10, 50, 250 and 1k Ω・cm)
- Defects observed after ė-irradiation have been also detected after proton and neutron irradiation with additional cluster-related ones
- Identification of defects ongoing, new defects are detected after low fluence proton irradiation in TSC
- Analysis on introduction rates is ongoing (table+see talk of Ioana)
- \( g_{B_iO_i}(n) < g_{B_iO_i}(p) < g_{B_iO_i}(e) \), \( \Omega \)- and \( \Phi \)-dependent
- Additional annealing study and optical injection are planned

Microscopic understanding of acceptor removal remains incomplete, but we did several big steps forward
Spare slides
• All EPI wafers are produced in the same facility/process on same substrate (low resistivity CZ p-type Si) differing only in Boron content = resistivity of EPI layer
• All samples were irradiated together for each type of particles

Characterization on processed devices: SR (Spreading Resistance) and SIMS (Secondary Ion Emission Spectroscopy)
Displacement damage in Si

for actual use of this tabulation, please refer to:
A. Vasilescu and G. Lindstroem
Displacement damage in Silicon
on-line compilation: http://sesam.desy.de/~gunnar/Si-dfunc

electron induced displacement damage in silicon
listed for kinetic energies between 300 keV and 200 MeV:
The only reliable data are from:
G.P.Summers et al., IEEE NS 40, No 6 (1993), 1372

<table>
<thead>
<tr>
<th>$E_{el}$ (MeV)</th>
<th>NIEL (MeVcm²/g)</th>
<th>NIEL (MeVmb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>6.21E-06</td>
<td>2.897E-01</td>
</tr>
<tr>
<td>0.5</td>
<td>1.54E-05</td>
<td>7.183E-01</td>
</tr>
<tr>
<td>0.7</td>
<td>2.19E-05</td>
<td>1.022E+00</td>
</tr>
<tr>
<td>1</td>
<td>2.97E-05</td>
<td>1.385E+00</td>
</tr>
<tr>
<td>2</td>
<td>4.81E-05</td>
<td>2.244E+00</td>
</tr>
<tr>
<td>3</td>
<td>6.06E-05</td>
<td>2.827E+00</td>
</tr>
<tr>
<td>5</td>
<td>7.76E-05</td>
<td>3.620E+00</td>
</tr>
</tbody>
</table>

/95=0.038


Extraction results: 88.79%
Laplace: 5.5 MeV electron irradiated 50 Ω·cm EPI PiN diode

\[ N_{eff,0} = \sim 2E+14 \text{ at/cm}^3 \]

Results of transient measurements close to \( T_{peak} \)
+ direct evaluation of the data (by DLTFS method)
+ Laplace DLTS with variation of \( V_p \) and \( t_p \)

At least 2 levels are detected overlapping in DLTS spectra at 60K, 120K, 190K with majority carrier injection; several electron traps besides B\(_{Oi}\) are found around 50K and 70K. Identification is not clear at the moment.

Further investigation with the light (minority carrier) injection, in low T region and annealing studies are planned.