Photoinduced transient spectroscopy of epitaxial silicon irradiated with high proton fluences

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Plan of talk:

• Background and motivation
• Experimental details
• Results of HRPITS measurements
• Conclusions
Experimental details

ITME: fabrication of epitaxial layer

1. Starting material: <111>, low resistivity ($\rho<0.02\ \Omega\cdot\text{cm}$)
   300 $\mu$m thick Czochralski (Cz) silicon substrate
doped by Sb donors.
2. Thin (75 $\mu$m) medium resistivity ($\rho=50\ \Omega\cdot\text{cm}$),
   epitaxial silicon layers doped by P donors
   have been grown on the CZ-Si substrates forming
   simple n-n$^+$ structures.

CERN: 24- GeV/c proton irradiation; PS RUN period: P1A-2004

Fluences

- $1.06\times10^{14}\ \text{p/cm}^2$ - sample A
- $5.05\times10^{14}\ \text{p/cm}^2$ - sample B
- $2.17\times10^{15}\ \text{p/cm}^2$ - sample C
- $6.10\times10^{15}\ \text{p/cm}^2$ - sample D

After the irradiation all the samples were stored at -20 $^\circ$C.
Effect of proton fluence on $\mu\tau$ of epitaxial Si
Effect of proton fluence on $E_{TDDC}$ of epitaxial Si
Effect of photon flux on PITS spectral fringes
Epitaxial silicon, proton fluence 1.06x10^{14} p/cm^2 (sample A)

F=1.5x10^{17} cm^{-2}s^{-1}  
F=3.5x10^{15} cm^{-2}s^{-1}
Effect of photon flux on PITS spectral fringes
Epitaxial silicon, proton fluence $2.17\times10^{15}$ p/cm$^2$ (sample C)

$F=1.5\times10^{17}$ cm$^{-2}$s$^{-1}$

$F= 3.5\times10^{15}$ cm$^{-2}$s$^{-1}$
Effect of photon flux on PITS spectral fringes
Epitaxial silicon, proton fluence $6.10 \times 10^{15}$ p/cm$^2$ (sample D)

$F=1.5 \times 10^{17}$ cm$^{-2}$s$^{-1}$

$F=3.5 \times 10^{15}$ cm$^{-2}$s$^{-1}$
Effect of proton fluence on defect structure of epitaxial silicon

Comparison of PITS spectral fringes for $F=1.5 \times 10^{17}$ cm$^{-2}$s$^{-1}$

Sample A $\Phi=1.06 \times 10^{14}$ p/cm$^2$

Sample B $\Phi=5.05 \times 10^{14}$ p/cm$^2$

Sample C $\Phi=2.17 \times 10^{15}$ p/cm$^2$

Sample D $\Phi=6.10 \times 10^{15}$ p/cm$^2$
Parameters of defect centres detected by the PITS method in the samples A, B, C and D of epitaxial silicon subjected to 24 GeV/c proton irradiation

<table>
<thead>
<tr>
<th>Defect centre</th>
<th>Activation energy $E_a$ (meV)</th>
<th>Pre-exponential factor $A$ (s$^{-1}$K$^{-2}$)</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>6</td>
<td>1.5x10$^3$</td>
<td>shallow donor</td>
</tr>
<tr>
<td>T2</td>
<td>17</td>
<td>2.2 x10$^3$</td>
<td>shallow donor</td>
</tr>
<tr>
<td>T3</td>
<td>25</td>
<td>2.4 x10$^3$</td>
<td>shallow donor</td>
</tr>
<tr>
<td>T4</td>
<td>75</td>
<td>1.8 x10$^4$</td>
<td>interstitial related ($I_4$)</td>
</tr>
<tr>
<td>T5</td>
<td>165</td>
<td>3.0 x10$^7$</td>
<td>VO$^{-}$</td>
</tr>
<tr>
<td>T6</td>
<td>200</td>
<td>8.0 x10$^5$</td>
<td>$V_2^{0+}$</td>
</tr>
<tr>
<td>T7</td>
<td>250</td>
<td>1.7 x10$^5$</td>
<td>VOH$^{+/-}$</td>
</tr>
<tr>
<td>T8</td>
<td>360</td>
<td>1.0 x10$^8$</td>
<td>VOH$^{+/-}$</td>
</tr>
<tr>
<td>T9</td>
<td>370</td>
<td>1.5 x10$^7$</td>
<td>$C_{iP_s}$</td>
</tr>
<tr>
<td>T10</td>
<td>400</td>
<td>8.7 x10$^5$</td>
<td>$C_{iO_i}$</td>
</tr>
<tr>
<td>T11</td>
<td>420</td>
<td>1.0 x10$^7$</td>
<td>$V_2^{0/-}$</td>
</tr>
<tr>
<td>T12</td>
<td>470</td>
<td>3.0 x10$^7$</td>
<td>VP</td>
</tr>
<tr>
<td>T13</td>
<td>500</td>
<td>7.6 x10$^8$</td>
<td>hydrogen related ($V_2H$ ?)</td>
</tr>
</tbody>
</table>
Model of trap concentration calculation

\[ S(T) = \frac{I(t_1) - I(t_2)}{I_0 - I_\alpha} \]

\[ I(t_1) = Ke_n \exp(-e_n t_1) \quad K = qn_T V \]

\[ I(t_2) = Ke_n \exp(-e_n t_2) \quad V = \frac{wl}{\alpha} \]

\[ n_T = \frac{S(T_m)I_0 \alpha}{qwle_n G_A [\exp(-t_1 e_n) - \exp(-t_2 e_n)]} \]

\[ n_T(0) = \frac{(nc_n + e_p^o + e_p)N_T}{nc_n + pce_p + e_n^o + e_n + e_p^o + e_p} \]

\[ n_T(\infty) = \frac{N_T}{1 + \frac{e_n}{e_p}} \]

- \( I_0 = I(0) \) - the photocurrent at the moment of switching off the illumination pulse
- \( I_\alpha = \lim_{t \to \infty}[I(t)] \) - the photocurrent at the moment of switching on the next illumination pulse
- \( n_T \) - the concentration of the traps filled with electrons
- \( V \) - the volume of the active region
- \( K \) - the electric charge released by the thermal emission
- \( \alpha \) - the absorption coefficient
- \( w \) - the distance between the ohmic contacts
- \( l \) - the ohmic contact width
- \( G_A \) - the current amplifier gain
- \( N_T \) - the trap concentration
The effect of proton fluence on trap concentrations

<table>
<thead>
<tr>
<th>Defect centre</th>
<th>Activation energy $E_a$ (meV)</th>
<th>Pre- exponential factor $A$ (s$^{-1}$K$^{-2}$)</th>
<th>Trap concentration (x10$^{15}$ cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sample C</td>
</tr>
<tr>
<td>T9</td>
<td>370 ($C_1 P_3$)</td>
<td>1.5x10$^7$</td>
<td>0.14</td>
</tr>
<tr>
<td>T10</td>
<td>400 ($C_i O_2$)</td>
<td>8.7x10$^5$</td>
<td>3.7</td>
</tr>
<tr>
<td>T11</td>
<td>420 ($V_2^{0-}$)</td>
<td>1.0x10$^7$</td>
<td>9.9</td>
</tr>
<tr>
<td>T13</td>
<td>470 (VP)</td>
<td>3.0x10$^7$</td>
<td>7.9</td>
</tr>
</tbody>
</table>

Concentration of shallow donors in sample A ($\Phi=1.06x10^{14}$ p/cm$^2$):
- T1 (6 meV) - 5.0x10$^{12}$ cm$^{-3}$,
- T2 (25 meV) - 2.3x10$^{13}$ cm$^{-3}$ and

concentration of interstitial related defect
T4 (75 meV) - 2.1x10$^{14}$ cm$^{-3}$
Conclusions

• Photoinduced Transient Spectroscopy with implementation of two-dimensional analysis of photocurrent decays has been used to investigation irradiation centres produced by high-energy proton irradiation in epitaxial silicon.

• It has been shown that the irradiation with proton fluences of 1.06x10^{14}, 5.05x10^{14}, 2.17x10^{15} and 6.10x10^{15} p/cm^2 results in shifting the Fermi-level position to 0.40, 0.44, 0.57 and 0.59 eV, respectively.

• Apart from typical radiation-induced point defects in Si such as: shallow donors, VO^{-/0}, V_2^{0/+}, C_i P_s, C_i O_i, V_2^{0/-} and VP, some hydrogen related defects as well as an interstitial related defect have been found.

• With increasing the fluence from 2.17x10^{15} to 6.17x10^{15} p/cm^2 the concentrations of V_2^{0/-} and VP rise from 1.0x10^{16} to 2.12x10^{16} cm^{-3} and from 8.0x10^{15} to 2.17x10^{16} cm^{-3}, respectively.

• The concentrations of C_i P_s and C_i O_i are of the order 1.0x10^{14} and 3.0x10^{15}, respectively, and not affected by the increase of proton fluence from 2.17x10^{15} to 6.17x10^{15} p/cm^2.
Acknowledgement

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