Real Relationship between Acceptor Density and Hole Concentration in Al-implanted 4H-SiC

H. Matsuura, K. Sugiyama, K. Nishikawa, T. Nagata and N. Fukunaga

Osaka Electro-Communication University
E-mail: matsuura@isc.osakac.ac.jp
Web site: http://www.osakac.ac.jp/labs/matsuura/
Acceptor density in Al-implanted 4H-SiC layer

1. Hall-Effect measurements
Fermi-Dirac (FD) distribution function

\[
f_{FD}(\Delta E_A) = \frac{1}{1 + 4\exp\left(\frac{\Delta E_A - \Delta E_F}{kT}\right)}
\]

Results determined by curve-fitting

\[
N_A = 4.85 \times 10^{19} \text{ cm}^{-3}
\]

\[
\Delta E_A = 157 \text{ meV}
\]

2. TRIM
Concentration of Al atoms in layer is \(\sim 1 \times 10^{19} \text{ cm}^{-3}\)

Is the FD distribution function available for Al acceptor in SiC?
Ground and excited states of Acceptor in SiC

Hydrogenic model

\[ \Delta E_r = 13.6 \frac{m^*}{m_0 \varepsilon_s^2} \frac{1}{r^2} \text{ eV} \]

Acceptor Level (ground state level)  First excited state level

\[ \Delta E_A = \Delta E_1 = 136 \text{ meV} \]
\[ \Delta E_2 = 34 \text{ meV} \]

In the case of p-type SiC

\[ \Delta E_A = 136 \text{ meV} \]
\[ \Delta E_2 = 34 \text{ meV} \]

In the case of B-doped Si

\[ \Delta E_A = 45 \text{ meV} \]

It is necessary to consider a distribution function including the influence of the excited states!!
Conventional distribution function including the influence of excited states

\[
f_{\text{conv}}(\Delta E_A) = \frac{1}{1 + 4 \left\{ \exp \left( \frac{\Delta E_A - \Delta E_F}{kT} \right) + \sum_{r=2} g_r \exp \left( \frac{\Delta E_r - \Delta E_F}{kT} \right) \right\}}
\]

Hardly any holes can be emitted into the valence band, because they are captured at the excited states.

\( N_A \) higher than \( N_A \) obtained by the FD distribution function is required in order to meet \( p(T) \).

Proposed distribution function including the influence

\[
f(\Delta E_A) = \frac{1}{1 + 4 \exp\left(-\frac{E_{\text{ex}}}{kT}\right) \cdot \left\{ \exp\left(\frac{\Delta E_A - \Delta E_F}{kT}\right) + \sum_{r=2} \ g_r \exp\left(\frac{\Delta E_r - \Delta E_F}{kT}\right) \right\}}
\]

This term makes acceptors release holes at high temperatures more easily than \( f_{\text{conv}}(\Delta E_A) \).

Ensemble average of ground and excited state levels

\[
\overline{E_{\text{ex}}} = \frac{\sum (\Delta E_A - \Delta E_r) \ g_r \exp\left(-\frac{\Delta E_A - \Delta E_r}{kT}\right)}{g_1 + \sum_{r=2} \ g_r \exp\left(-\frac{\Delta E_A - \Delta E_r}{kT}\right)}
\]

Average acceptor level: \( \overline{\Delta E_A} = \Delta E_A - \overline{E_{\text{ex}}} \)

Is the real relationship between \( N_A \) and \( p(T) \) necessary to simulate electric characteristics of devices?

When band bending is calculated by Poisson equation:

\[
\frac{d^2 V(x)}{dx^2} = -\frac{q}{\varepsilon_s \varepsilon_0} \left( N_D^+ - N_A^- + p - n \right)
\]

\[
p = N_A \left[ 1 - F(\Delta E_A) \right]
\]

\[
N_A^- = N_A F(\Delta E_A)
\]

Acceptor density \( N_A \)   Distribution function \( F(\Delta E_A) \)

Acceptor density much higher than the real density is required.

Using real acceptor density   Using FD distribution function \( f_{FD}(\Delta E_A) \)

What distribution function is suitable for acceptors?
Experimental

Implantation of Al atoms into 4H-SiC

Implantation energies: 1.0, 1.6, 3.3, 4.4, 5.6 and 7.0 MeV
Average $N_A$ in a box profile: $\sim 1 \times 10^{19}$ cm$^{-3}$

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Implantation temp.</th>
<th>Annealing temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>pSiC(HH)</td>
<td>1000 °C</td>
<td>1575 °C</td>
</tr>
<tr>
<td>pSiC(HL)</td>
<td>1000 °C</td>
<td>1443 °C</td>
</tr>
<tr>
<td>pSiC(LH)</td>
<td>Room temp.</td>
<td>1575 °C</td>
</tr>
<tr>
<td>pSiC(LL)</td>
<td>Room temp.</td>
<td>1443 °C</td>
</tr>
</tbody>
</table>

Hall-effect measurements
Temperatures: 200 K $\sim$ 420 K
Magnetic field: 1.4 T
Free Carrier Concentration Spectroscopy (FCCS)

FCCS signal: 

\[ H(T, E_{\text{ref}}) = \frac{p(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{\text{ref}}}{kT}\right) \]

The FCCS signal has a peak at temperature corresponding to each acceptor.

\[ T_{\text{peak}} \approx \frac{\Delta E_A - E_{\text{ref}}}{k} \]

\[ H(T_{\text{peak}}, E_{\text{ref}}) \approx \frac{N_A}{kT_{\text{peak}}} \exp(-1) \]

Results obtained by FCCS in pSiC(HH)

<table>
<thead>
<tr>
<th>F(ΔE_A)</th>
<th>N_A [cm^{-3}]</th>
<th>ΔE_A [meV]</th>
<th>N_{\text{comp}} [cm^{-3}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>f(ΔE_A)</td>
<td>1.21x10^{19}</td>
<td>177</td>
<td>2.29x10^{17}</td>
</tr>
<tr>
<td>f_{FD}(ΔE_A)</td>
<td>4.85x10^{19}</td>
<td>157</td>
<td>2.45x10^{18}</td>
</tr>
<tr>
<td>f_{\text{conv}}(ΔE_A)</td>
<td>4.69x10^{20}</td>
<td>167</td>
<td>1.62x10^{19}</td>
</tr>
</tbody>
</table>

Rather high N_A is required in f_{FD}(ΔE_A) or f_{\text{conv}}(ΔE_A).
A set of three p(T) simulated using the obtained values

All the simulated p(T) are in good agreement with the experimental p(T).

The curve-fitting procedure of p(T) is not suitable for investigating the influence of the excited states on p(T).
All the peaks of the simulated FCCS signals coincide with the peak of the experimental FCCS signal.

However the solid curve is in better agreement with the experimental FCCS signal than the others.

FCCS is appropriate for investigating the influence of the excited states on $p(T)$. 

\[
H(T,0.231) \times 10^{42} \text{ cm}^{-6} \text{ eV}^{-2.5}
\]

Temperature [K]

Experimental data

Simulation results

- $f(\Delta E_A)$
- $f_{FD}(\Delta E_A)$
- $f_{\text{conv}}(\Delta E_A)$
Obtained results for samples with different $T_{\text{implant}}$ and $T_{\text{anneal}}$

<table>
<thead>
<tr>
<th>Sample number</th>
<th>$N_A$ [cm$^{-3}$]</th>
<th>$\Delta E_A$ [meV]</th>
<th>$N_{\text{comp}}$ [cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>pSiC(HH)</td>
<td>1.21x10$^{19}$</td>
<td>177</td>
<td>2.29x10$^{17}$</td>
</tr>
<tr>
<td>pSiC(HL)</td>
<td>9.49x10$^{18}$</td>
<td>187</td>
<td>1.62x10$^{17}$</td>
</tr>
<tr>
<td>pSiC(LH)</td>
<td>7.14x10$^{18}$</td>
<td>178</td>
<td>6.64x10$^{16}$</td>
</tr>
<tr>
<td>pSiC(LL)</td>
<td>5.44x10$^{18}$</td>
<td>183</td>
<td>1.23x10$^{17}$</td>
</tr>
</tbody>
</table>

Almost all implanted Al atoms in pSiC(HH) behave as an acceptor, while only a half of Al atoms in pSiC(LL) act as an acceptor.

$T_{\text{implant}}$ is effective in forming acceptors in SiC.
Summary

Al-implanted p-type 4H-SiC layers with different $T_{\text{implant}}$ and $T_{\text{anneal}}$ were fabricated. The $p(T)$ in those layers were obtained from Hall-effect measurements.

In order to obtain the reliable acceptor density from $p(T)$, a distribution function including the influence of the excited states of acceptors is found to be required.

In order to investigate the influence of the excited states, FCCS is considered to be more appropriate than the curve fitting procedure of $p(T)$.

When $T_{\text{implant}}=1000^\circ C$ and $T_{\text{anneal}}=1575^\circ C$, almost all implanted Al atoms are found to behave like an acceptor in SiC.