To be submitted to NIMB.

Ion-Implantation Doping of Silicon Carbide

J. Gardner, A. Edwards, M. V. Rao
George Mason University
Fairfax, VA

N. Papanicolaou, G. Kelner
Naval Research Laboratory
Washington, DC

O. W. Holland
Oak Ridge National Laboratory, Oak Ridge, TN

"The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-96OR22464. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes."

Prepared by the
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
managed by
LOCKHEED MARTIN ENERGY RESEARCH CORP.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-96OR22464

October 1997

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
Ion-Implantation Doping of Silicon Carbide

Jason Gardner, Andrew Edwards, and Mulpuri V. Rao
Department of Electrical and Computer Engineering
George Mason University, Fairfax, Va 22030-4444

N. Papanicolaou and G. Kelner
Naval Research Laboratory, Washington DC 20375

O.W. Holland
Oak Ridge National Laboratory, Oak Ridge, TN 37831

Because of their commercial availability in bulk single crystal form, the 6H- and 4H-polytypes of SiC are gaining importance for high-power, high-temperature, and high-frequency device applications. Selective area doping is a crucial processing step in integrated circuit manufacturing. In Si technology, selective area doping is accomplished by thermal diffusion or ion-implantation. Because of the low diffusion coefficients of most impurities in SiC, ion implantation is indispensable in SiC device manufacturing. In this paper we present our results on donor, acceptor, and compensation implants in 6H-SiC.

All of the implants in this work were performed into p- or n-type epitaxial layers (with carrier concentration ≤2x10^{16} cm^{-3}) grown on Si-faced, 4° off-axis, (100), p or n-type (>10^{18} cm^{-3}) 6H-SiC substrates. Multiple energy implants were performed at RT or at an elevated temperature (700-800 °C). The annealings were performed after encasing the samples in an amorphous SiC susceptor or SiC coated graphite susceptor to minimize Si dissociation from the implanted samples during annealing. To evaluate the thermal stability of the implant, secondary ion mass spectrometry (SIMS) measurements were performed on the annealed samples. Rutherford backscattering (RBS) channeling measurements were conducted to assess the crystal perfection qualitatively. To obtain the electrical activation of the implanted impurities, van der Pauw Hall measurements were performed on the annealed samples. Ohmic contacts to the n- and p-type layers were formed by evaporated Ni and Ti/Al alloyed at 1000 °C and 950 °C for 30s, respectively.

Nitrogen and phosphorous are both useful donors in SiC\textsuperscript{1-6}. At 4 MeV, the N\textsuperscript{+} and P\textsuperscript{+} ions have a range of 2.5 μm and 2.0 μm, respectively. Because of its low atom mass the N implants were performed at both room temperature and elevated temperature (ET) yielding good activation results after annealing. Phosphorous being a heavier atom (atomic mass = 31) does not yield favorable electrical activation if the implants were performed at RT. For 15 keV-280 keV multiple energy N\textsuperscript{+} implants, performed at RT, with a 1.36x10^{15} cm^{-2} total dose, the measured sheet carrier concentration (n\textsubscript{s}) at RT after 1600 °C/15 min annealing is 4.1x10^{14} cm^{-2} with a carrier mobility of 46 cm\textsuperscript{2}/Vs. The N donor has an ionization energy (E\textsubscript{D}) of ~80 meV in 6H-SiC. It is for this reason that the n\textsubscript{s} measured does not represent the substitutional N donor concentration. By increasing the measurement temperature to 473 K we obtained an n\textsubscript{s} of 1.1x10^{15} cm^{-3}. The n\textsubscript{s} seems to increase further at even higher temperatures. For both RT and ET N-implants the RBS yield after annealing
coincided with that of the virgin level indicating a proper lattice recovery. The SIMS measurements did not show any redistribution of \( N \) after annealing.

The 20 keV-550 keV multiple energy RT \( P^+ \)-implanted SiC material with a total dose of \( 1.36 \times 10^{15} \ \text{cm}^{-2} \) gave a \( n_e \) of only \( 6 \times 10^{17} \ \text{cm}^{-2} \) after 1600 \( ^\circ \text{C}/15 \ \text{min} \) annealing. The \( E_D \) value of the \( P \)-donor is \( \sim 85 \ \text{meV} \), which is close to that of \( N \). The poor activation for RT \( P \)-implantation is due to excessive lattice damage. The RBS measurements on annealed material indicated a substantial residual damage in the material. By increasing the implantation temperature to 700 \( ^\circ \text{C} \) we measured an \( n_e \) of \( 7.5 \times 10^{14} \ \text{cm}^{-2} \) and a \( \mu \) of \( 34 \ \text{cm}^2/\text{V.s} \) at RT for \( 2.7 \times 10^{15} \ \text{cm}^{-2} \) \( P \) dose. These values are comparable to that of the \( N \)-implantation. The RBS aligned yield on the annealed material nearly coincided with that of the virgin sample indicating good lattice quality. This means that for \( P \)-implantation an elevated implantation temperature needs to be used. The SIMS measurements did not show any significant redistribution of \( P \) after annealing.

Aluminum and boron are the popular acceptor dopants in SiC. At an energy of 1 MeV the Al and B ions have a range of 0.9 \( \mu \text{m} \) and 1.3 \( \mu \text{m} \), respectively. Aluminum is preferred over boron because it is a shallower acceptor. For multiple energy 20 keV-500 keV, 800 \( ^\circ \text{C} \), Al-implantation with a total dose of \( 6.67 \times 10^{15} \ \text{cm}^{-2} \), we measured a RT hole concentration of \( \sim 10^{14} \ \text{cm}^{-2} \) after a 1600 \( ^\circ \text{C}/15 \ \text{min} \) anneal. The carrier mobility measured was 5 \( \text{cm}^2/\text{V.s} \). The low value of the measured sheet hole concentration is due to a high acceptor ionization energy (240 meV) of Al in 6H-SiC. The Al implant is reasonably stable during annealing except for a small degree of out-difusion at the implant tail. The RBS measurements indicated some lattice recovery after annealing, but the scattering yield is higher than that of the virgin level. This means that some residual implant damage remained in the material due to the high atom mass of Al. The Al implants need to be performed at an elevated temperature in order to obtain a satisfactory dopant activation and lattice quality. For RT Al implantation both Al acceptor activation and lattice quality are very poor.

Boron is a lighter atom compared to Al and therefore seems more attractive for ion implantation acceptor doping. It is difficult to obtain a high hole concentration at RT using this dopant due to its higher activation energy (350 meV), compared to that of Al. We could not measure any p-type conduction at RT using B ion-implantation. The B also redistributes during high temperature annealing.

Compensation implants are required to achieve inter-device isolation in planar high-speed integrated circuits made of n- or p-type epitaxial layers. They are also used for junction termination at the wafer surface which helps to increase the junction breakdown voltage. We have used multiple energy iso-electronic C or Si ion bombardment to compensate n-type SiC and deep V ion implantations to compensate p-type SiC.

By performing multiple energy 30 keV-1.3 MeV C\textsuperscript{+} or 30 keV-1.5 MeV Si\textsuperscript{+} bombardments, in n-type 1 \( \Omega \)-cm resistivity SiC, resistivities as high as \( 10^{12} \ \Omega \)-cm were measured over a 1.2 \( \mu \text{m} \) depth. The as-implant resistivity increased with the implant dose at first and then decreased at higher doses due to hopping conduction of the carriers from one trap to another. At high doses, an excessive number of traps are created in the material, exceeding the number required to trap all the
carriers. To optimize the resistivity the excessive trap concentration needs to be decreased by high-temperature treatments. If the wafer needs to be subjected to high-temperature heat-treatments (such as ohmic contact alloying, which is usually done at 900-1000 °C in SiC) after compensation ion bombardment, the ion dose must be selected to give optimum resistivity after the heat-treatment. This means that before heat-treatment the ion bombardment should create more traps than the number of carriers in the material. If the bombardment is designed to give optimum resistivity in the as-implant material then the trap concentration will decrease during the heat-treatment giving a reduced electrical resistivity.

We have used multiple energy (15-200 keV) V-implantations to compensate a 2x10^{16} cm^{-3} carrier concentration p-type epitaxial layer. For 10^{14} cm^{-3} V implant concentration we measured a resistivity of 10^{13} Ω·cm after 1600 °C annealing. Unlike isoelectronic Si or C ion bombardments in n-type SiC the V-implant needs to be annealed in order to introduce compensating deep donor levels in p-type SiC. The V-implant and the compensation it creates is stable only up to 1500-1600 °C. For heat-treatments above 1600 °C the V implant outdiffuses at the surface causing depletion of V and hence a reduction in compensation at the surface region. One of the limitations of V-implantation compensation is its low solid solubility limit (~2x10^{17} cm^{-3}) in SiC. This means that we can compensate p-type material with <2x10^{17} cm^{-3} acceptor concentration using V implantation. We do not have such a limitation in compensating n-type material using isoelectronic ion bombardment. To compensate high donor concentrations we need to introduce more traps by increasing the ion dose.

Acknowledgment

We acknowledge the contributions made by P.H. Chi of NIST, M. Ghezzo and J. Kretchmer of GE, and M.C. Ridgway of ANU. The work at GMU is supported by NSF under Grant # ECS-9711128 and ORNL, managed by Lockheed Martin Energy Research Corp. For the U.S. Department of Energy, under Contract No. DE-AC05-96OR22464.

References


<table>
<thead>
<tr>
<th>Report Number (14)</th>
<th>ORNL/CP-95075</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CONT-971213-__</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Publ. Date (11)</td>
<td>199710</td>
</tr>
<tr>
<td>Sponsor Code (18)</td>
<td>DOE/ER, XF</td>
</tr>
<tr>
<td>JC Category (19)</td>
<td>UC-400, DOE/ER</td>
</tr>
</tbody>
</table>