Silicon Carbide Semiconductors for Space Applications

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0. contents

1. Crystallography
2. Physical features
3. Historical background
4. Applications
5. Radiation tolerance
6. Experiments
7. Result and Discussion
8. Summary
9. Other semiconductors
10. epilogue
1. Crystallography

- Crystal structure
  - Silicon-carbon covalent structure
  - Anisotropic and 12 % ionic polarized crystal
  - No-liquid phase in atmospheric pressure

- Silicon carbide crystallizes in numerous different polytypes (more than 200).
  - Wurtzite
    - 2H(hexagonal)-SiC, 4H-SiC, 6H-SiC...
  - Zincblende
    - 3C(cubic)-SiC
  - Trigonal
    - 15R(rhombohedral)-SiC, 21R-SiC...

*Stacking direction*
2. Physical features

- **Special futures**
  - Wide-energy bandgap (~3.2eV)
  - High-thermal conductivity
  - High-saturated electron drift velocity
  - High-breakdown electric field
  - ...and radiation tolerance?

- **Device applications**
  - High temperature
  - High speed
  - High frequency
  - High power
3. Historical background

- 1892  Acheson method [SiO₂+coke]
  - High-hardness (abrasive, structural materials)
- 1907  Mineral cymoscope
  - Luminescence phenomenon
- 1940~  Genesis of semiconductors (Ge, Si, SiC)
  - 1947  Point-contact Ge transistor
- 1955  Lely method (sublimation, high-purity crystal)
  - 1959  First SiC international conference was held.
- 1960~  Progress of Si semiconductor
  - 1970~  Decline of SiC research
- 1980~  SiC blue-LEDs were marketed.
4. Applications

- **Available**
  - Blue- Light Emitting Diode (LED)
    - (displaced by InGaN blue-LED)
  - Schottky Barrier Diode (SBD)
    - Capable reverse voltage; 300~1200 V
    - Average forward current; 1~20 A

- **Expectations**
  - Power devices
    - Unipolar
      - FET (Field Effect Transistor)
        - JFET (Junction FET)
        - MOSFET (Metal-Oxide-Semiconductor FET)
        - MESFET (Metal-Semiconductor FET)
    - Bipolar
      - P-N junction diode
      - Bipolar transistor
      - Thyristor
      - GTO (Gate Turn-Off) thyristor
      - IGBT (Insulated Gate Bipolar Transistor)
  - IC (Integrated Circuit)
5. Radiation tolerance

- Space component requires…
  - High-efficiency for limited power resources,
  - High-reliability for hard-maintenance, and
  - Radiation tolerance.
    - High-energy particles roam in space.
      - Irrecoverable damage (bulk, surface)
      - Single Event Effect (SEE) problems, etc.

- Bulk damage by radiations
  - By α-, β-, γ-ray irradiations
    - It has demonstrated the superiority of SiC, as compared to Si and/or to some other conventional materials.
  - By heavy-ions
    - It is still not clear.
6. Experiments (1)

- I-V characteristics
  - To evaluate the permanent damages due to ions-irradiation.
- Ion Beam Induced Charge Collection (IBICC)
  - To elucidate the damage creations.
- Sample: SiC Schottky barrier diode (SiC SBD)
  - SDP06S60 (Infineon Technologies AG)
    - Commercially available-SiC SBD
    - Maximum forward current: 6A
    - Capable reverse voltage: 600V

Mold removed sample chip.

Carrier density profile obtained by C-V measurement.

Chip size: 1.4 x 1.4 x 0.37 mm
Schottky contact (Ti)
Epitaxial layer: ~6µm
Layout of sample chip.
6. Experiments (2)

- Ions irradiation with ion-specific energies
  - All the ions are able to penetrate through the epitaxial layer.
  - LET and range were derived from the SRIM2003 software.

- Reverse bias dependence
  - It is assumed that the applied-reverse bias voltage is accumulated in the epitaxial layer.
  - Every effect will cause in the epitaxial layer.

- Ion species and the energies used in this study.
  - All the irradiations were held in TIARA (Takasaki Ion Accelerators for Advanced Radiation Application), JAERI (Japan Atomic Energy Research Institute).

<table>
<thead>
<tr>
<th>Ion elements</th>
<th>Energy [MeV]</th>
<th>LET(SiC) [MeV·cm²/mg]</th>
<th>Range(SiC) [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15N³⁺</td>
<td>53.2</td>
<td>3.6</td>
<td>34.3</td>
</tr>
<tr>
<td>26Ne⁴⁺</td>
<td>69.7</td>
<td>6.9</td>
<td>26.4</td>
</tr>
<tr>
<td>40Ar⁶⁺</td>
<td>137</td>
<td>16.7</td>
<td>23.9</td>
</tr>
<tr>
<td>84Kr¹⁷⁺</td>
<td>289</td>
<td>42.7</td>
<td>24.7</td>
</tr>
<tr>
<td>129Xe²⁺</td>
<td>394</td>
<td>73.0</td>
<td>23.1</td>
</tr>
</tbody>
</table>

- An incident ion generates an electron-hole pair.
  - The generation energy is ~9 eV/particle in SiC.
  - Collected charges indicate characteristic spectrum.

- Particle number measurement
  - All the incident ions were counted by
    - IBICC spectrum measurement, and
    - Ion-beam flux density.
7. Result and Discussion (1)

- SiC SBD was damaged by heavy-ions irradiation.
  - I-V characteristics after irradiation.
    - The path has field assisted-emission effect, which suggests high density trap levels were introduced along with the ion-tracks.
  - The defects formed by excess current pass through the device.
    - The excess currents were triggered by the tunneling effects caused by ion incidence.
The leakage current increase was proportional to the number of incident ions.

Each incidence ion creates individual leakage path.

Also the increase was correlated with the bias voltage.

The leakage current increase-rates with each ion irradiation under several bias conditions were examined.

The leakage current increase was forcefully accelerated by the applied bias voltage as for each ion.

The leakage current increase is usually caused by defects in active layer of the device, and the introduction rate of the defects is mostly irrespective of the bias condition...?
7. Result and Discussion (3)

- Bias voltage dependence
  - Each peak was shifted by bias voltage,
  - the peaks were accelerated at higher-voltages, and
  - anomalous large charge collections appeared at higher-voltages.
  - Will they become the predictive feature of damage creation?

- Ion energy dependence
  - Kr- and Ar-ions which have a higher-LET cause permanent damages out of the charge collectable range.
  - The damage creation needs higher-LET.
8. Summary

- Some irradiations for SiC SBD were carried out.
  - Radiation damages could be confirmed by I-V characteristics.
  - The leakage current increase was proportional to the number of incident ions.

- The collected charge spectra were obtained.
  - The anomalously large charge collection was confirmed
  - It is predictive feature for the occurrence of permanent damages.

- A damage creation mechanism was proposed.
  - Higher-LET and higher-bias voltage are more probable conditions, because
  - SiC has a high-breakdown electric field inherently.
  - Schottky barrier narrowing seems to be cause noticeable.

- An important weakness has been revealed.
  - SiC SBDs were unexpectedly susceptible to heavy-ions irradiation.
  - There is problems to be solved for future space applications.
9. Other semiconductors

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>4H-SiC</th>
<th>Si</th>
<th>GaAs</th>
<th>GaN</th>
<th>Diamond</th>
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</thead>
<tbody>
<tr>
<td>Bandgap energy (eV)</td>
<td>3.26</td>
<td>1.12</td>
<td>1.42</td>
<td>3.42</td>
<td>5.47</td>
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<tr>
<td>Electron mobility (cm²/Vs)</td>
<td>1000</td>
<td>1350</td>
<td>8500</td>
<td>1200</td>
<td>2000</td>
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<tr>
<td>Breakdown voltage (MV/cm)</td>
<td>2.8</td>
<td>0.3</td>
<td>0.4</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Saturated drift velocity (cm/s)</td>
<td>2.2x10⁷</td>
<td>1.0x10⁷</td>
<td>1.0x10⁷</td>
<td>2.4x10⁷</td>
<td>2.5x10⁷</td>
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<tr>
<td>Thermal conductivity (W/cmK)</td>
<td>4.9</td>
<td>1.5</td>
<td>0.46</td>
<td>1.3</td>
<td>20</td>
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<td>Johnson’s figure of merits</td>
<td>420</td>
<td>1</td>
<td>1.8</td>
<td>580</td>
<td>4400</td>
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<td>Baliga’s figure of merits</td>
<td>470</td>
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<td>15</td>
<td>680</td>
<td>13000</td>
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<td>p-type controllability</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Δ</td>
<td>Δ</td>
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<tr>
<td>n-type controllability</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>x</td>
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<tr>
<td>Thermal oxidation</td>
<td>O</td>
<td>O</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Low-p wafer</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Δ(SiC)</td>
<td>x</td>
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<tr>
<td>Insulating wafer</td>
<td>O</td>
<td>Δ(SOI)</td>
<td>O</td>
<td>Δ(sapphire)</td>
<td>x</td>
</tr>
<tr>
<td>Hetero junction</td>
<td>x</td>
<td>Δ</td>
<td>O</td>
<td>O</td>
<td>x</td>
</tr>
</tbody>
</table>
10. epilogue

- **WBG semiconductors innovation**
  - GaN, AlN, ZnO, BN...
    - It is evolving further.

- **For space applications**
  - High-efficiency and high-reliability are desired.
  - The evaluation of the radiation tolerance is very important.
    - The examinations must be accomplished adequately.

- **Future work**
  - Clarifying the mechanism for the anomalously large charge collection.
  - Finding a mitigating technique for SEE-like phenomenon.
  - Utilizing the SiC devices with excellent performance for space applications.