

Channeling Ion Implantation Technology for Power Devices

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Nissin Ion Equipment Co., Ltd. developed an ion implanter system capable of high-precision channeling for power devices. Channeling implantation is a technique that allows deeper implantation of ions by implanting them along a particular direction of the crystal lattice. This technique not only has the potential to replace parts of the conventional silicon carbide (SiC) power device process that uses a high-energy ion implanter, but also shows promise for significantly improving device characteristics. Our system precisely controls the implantation angle, enabling stable and repeatable channeling ion implantation.

Keywords: silicon carbide power device, channeling implantation

1. Introduction

In recent years, silicon carbide (SiC) power devices have been rapidly growing as key components to achieve carbon neutrality, especially in several strong long-term growth markets such as renewable energy, cloud computing, and electric vehicles. Compared to silicon power devices, SiC power devices exhibit significantly lower power losses, as well as superior heat resistance and higher breakdown voltage. The structure of SiC power devices is shifting from planar to trench type, and the fabrication of advanced devices, such as superjunction structures, requires ion implantation into deep regions.

Conventionally, ion implantation into deep regions has been performed using high-energy ion implanters through a method called random implantation, in which the ion trajectories are independent of the crystal structure, thus necessitating high-energy ion implantation equipment. In contrast, channeling ion implantation (hereafter referred to as “channeling implantation”) injects ions along the crystal lattice axes of the wafer, significantly reducing the

number of collisions with crystal atoms compared to random implantation. This means that ion implantation into deeper regions can be achieved at lower energies during device fabrication, potentially replacing conventional implantation methods that require high-energy equipment. In fact, several advantages of replacing conventional implantation with channeling implantation have been reported.⁽¹⁾ For example, the box-shaped doping profile, which conventionally was achieved by repeatedly changing the acceleration energy after each implantation and performing multiple implantation steps, can be attained with fewer implantations by using channeling implantation.

Furthermore, in random implantation, ions collide with crystal atoms and scatter laterally more as the implantation depth increases. However, channeling implantation minimizes ion spread, enabling accurate dopant profiles with small lateral spread relative to the mask openings. This leads to a reduction of high-resistance components and consequently lowers the on-resistance.⁽²⁾ Additionally, channeling implantation can achieve comparable implanta-

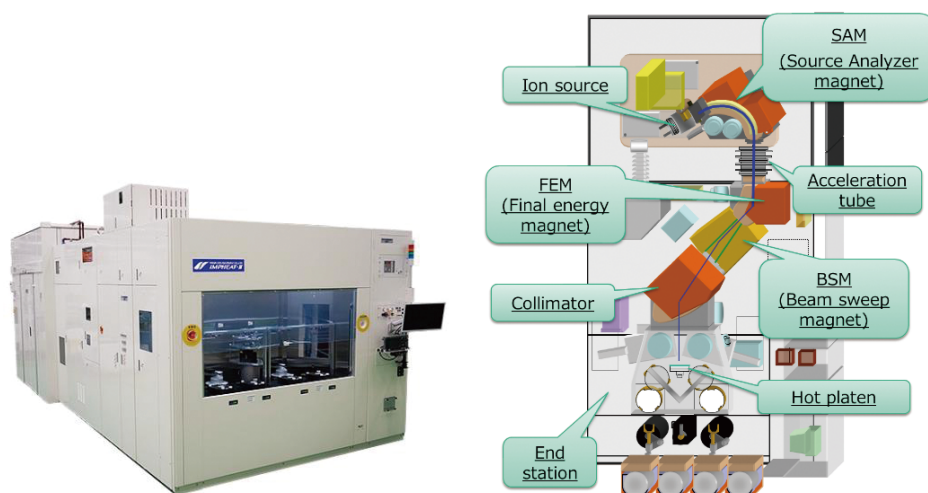


Fig. 1. Appearance and schematic of "IMPHEAT"

tion depths at lower acceleration energies than random implantation, which also offers the advantage of allowing the use of thinner masks.

Figure 1 shows the appearance and schematic diagram of the high-temperature ion implanter “IMPHEAT” series (maximum energy: 960 keV) developed by Nissin Ion Equipment Co., Ltd. for power semiconductor manufacturing.⁽³⁾ This implanter is capable of implanting various ion species. The implanted aluminum ions and phosphorus ions achieve depths approximately three times and twice, respectively, compared to those implanted with random implantation when channeling implantation is employed. The difference in implantation depth among ion species is caused by variations in electronic stopping power (Se) affecting energy loss during penetration into SiC.⁽⁴⁾ Channeling implantation requires precise control of the implantation angle, and the “IMPHEAT” series offers functions to precisely control the average beam implantation angles in both the vertical and horizontal directions.⁽⁵⁾

Figure 2 presents a schematic diagram of the beam angle measurement and correction system. The vertical beam angle is measured by adjusting the movable front Faraday^{*1} cup, which is positioned in front of the platen,^{*2} and the shutter installed before the back Faraday cup, which is placed behind the platen, while controlling the wafer tilt angle held by an electrostatic chuck and a mechanical clamp on the platen. Horizontal beam angle is controlled by adjusting the magnetic field of the collimator magnet based on measurements from the two multi-point front and back Faraday cups. The “IMPHEAT” series demonstrates excellent angle controllability suitable for channeling implantation, with a control accuracy of ± 0.1 degrees in both the vertical and horizontal directions.⁽⁶⁾

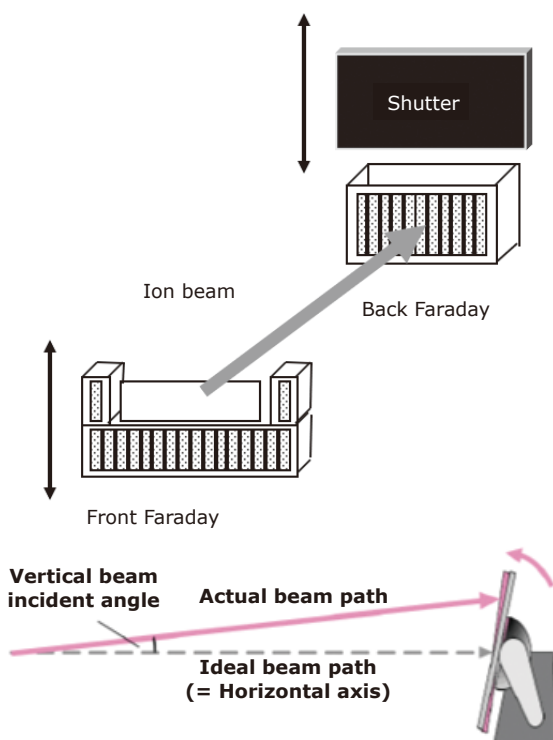


Fig. 2. Beam measurement and angle correction system

2. Channeling Implantation Technology

A major concern for the feasibility and mass production implementation of channeling implantation technology is the reliability and variation of the off-axis angle^{*3} for each wafer. The critical angle at which channeling implantation is possible depends on the acceleration energy, and at the maximum energy of 960 keV for “IMPHEAT” series, implantation angle control within ± 0.2 degrees is required.⁽¹⁾ Measuring the off-axis angle of each wafer in advance and adjusting the ion beam angle during implantation to match the off-axis angle are required to achieve precise channeling implantation.

In response, Nissin Ion Equipment Co., Ltd. developed a system that measures the off-axis angle of each wafer and applies feedforward control of the platen angle for each ion implantation. Figure 3 shows the installation of the X-ray diffraction (XRD) system and its measurement results. Since the X-ray irradiation system is located above the aligner^{*4} and near the operator’s workspace, an interlock is installed on the wafer cassette loading door to prevent X-ray exposure. The X-ray irradiation system irradiates the wafer with X-rays of continuous wavelengths. When the Bragg condition is satisfied for each crystal plane, the X-rays are diffracted in specific directions, creating diffraction patterns known as Laue spots.⁽⁷⁾ The positions of these Laue spots are related to the lattice constants and the arrangement of the crystal planes. By providing information on the angle and distance of the incident X-rays on the wafer, the off-axis angle of the wafer can be measured.

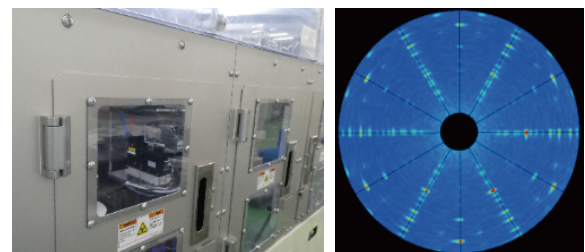


Fig. 3. XRD system installation and XRD measurement results

Furthermore, although SiC wafers used in power devices tend to deform easily, the system holds the wafer flat within a measurement range of $\phi 0.8$ mm using the aligner’s vacuum chuck. Even when applied to deformed wafers, the system enables uniform channeling implantation by holding the entire wafer surface with an electrostatic chuck manufactured to guarantee flatness within 50 μm . This approach avoids the effect of wafer distortion on the accurate angle control during implantation.

3. Experimental Results

Table 1 compares the off-axis angles of wafers measured by X-ray diffraction rocking curve measurements

with those obtained using the developed system for channeling implantation. The results include measurements from new wafers as well as wafers exhibiting deformation exceeding 200 μm after ion implantation. Since the rocking curve measurement uses the wafer surface as a reference position, the measurements can be performed without being affected by wafer deformation. A comparison of the measurement differences showed variation of 0.06 degrees for new wafers and 0.05 degrees for deformed wafers, demonstrating that the use of the aligner's vacuum chuck enables measurements unaffected by wafer deformation.

Table 1. Summary of measurement results

Sample	XRD measurement of rocking curve	SiC offset angle with our system
New SiC	4.11	4.05
Implanted SiC	4.01	3.96
SiC wafer with 1 μm SiO_2	4.10	4.05
SiC wafer with epi layer	4.12	4.05
Si with resist	0.26	0.25

Furthermore, measurements were conducted on a SiC wafer with a 1 μm thick SiO_2 layer on the surface, a SiC wafer with an epitaxial growth layer, and a Si wafer with a resist film. The differences between the two measurement methods for each wafer type were 0.05 degrees, 0.07 degrees, and 0.01 degrees, respectively, showing no significant discrepancies. These results indicate that measurements using this system are unaffected by the wafer surface condition.

Figure 4 shows the ion distribution during channeling implantation and when the implantation angle is offset from the channeling direction. Implantation was performed

at room temperature using an aluminum ion beam with a maximum energy of 960 keV and a dose of 1×10^{13} ions/ cm^2 . As the material for evaluating the channeling phenomenon, an n-type 4H-SiC (0001) wafer with a 4-degree off-cut in the (11-20) direction was prepared. As a result of feedforward control to adjust the ion beam angle and the wafer off-axis angle relative to the platen tilt angle, the wafer tilt angle held by the electrostatic chuck was controlled to 4.1 degrees during implantation. For comparison, implantation with tilt angle offsets of ± 0.2 degrees and ± 0.4 degrees under the same beam conditions was also performed.

Depth profile measurements by Secondary Ion Mass Spectrometry (SIMS) confirmed that the automated channeling implantation system achieves implantation accuracy within ± 0.2 degrees and produces excellent channeling profiles.

4. Conclusion

Nissin Ion Equipment Co., Ltd. has developed a system that achieves precise implantation angle control necessary for channeling implantation. This system analyzes the wafer's off-axis angle using Laue spots obtained from X-ray measurements and automatically corrects the implantation angle accordingly. To realize this, feedforward control of the platen angle is performed based on the ion beam's implantation angle. The system controls the channeling implantation angle with an accuracy of ± 0.2 degrees and is positioned as a promising alternative to the high-energy implantation process used for channeling implantation in deep regions.

• IMPHEAT is a trademark or registered trademark of Nissin Ion Equipment Co., Ltd.

Technical Terms

- *1 Faraday: A device for measuring the ion beam current.
- *2 Platen: A flat structure for holding the sample.
- *3 Off-axis angle: The angle between the wafer surface and the SiC (0001) crystal plane.
- *4 Aligner: A device placed on the atmospheric side that adjusts the wafer rotation axis.

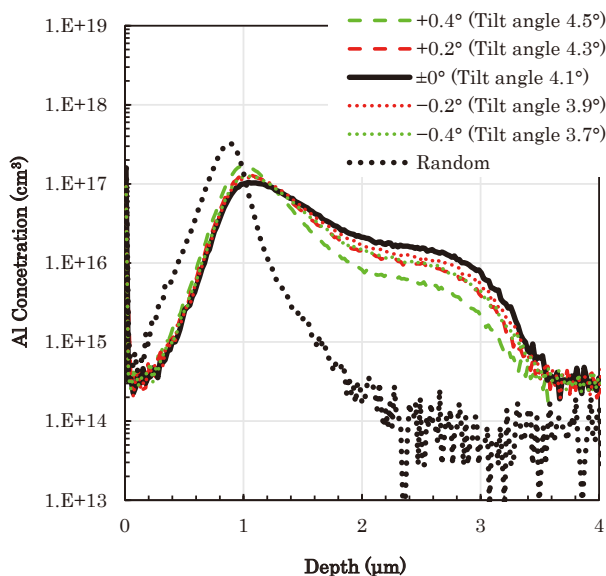


Fig. 4. Ion distribution during channeling implantation and implantation with angle offset from the channeling direction (SIMS evaluation)

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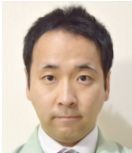
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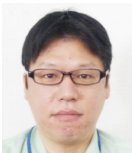
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