Successful n-type Doping of r-GeO_2 Semiconductor by Ion Implantation

A Major Step Forward in Establishing r-GeO_2 Power Device Manufacturing Technology

Patentix Inc. announced that it has successfully imparted n-type conductivity to an insulating crystalline film of rutile-type germanium dioxide (r-GeO_2), a promising next-generation power semiconductor material, using an ion implantation process. Ion implantation allows for high-precision control over the concentration, position, and depth of doping, which will facilitate the fabrication of complex power device structures such as power MOSFETs.

Background

Rutile-type germanium dioxide (r-GeO_2) has garnered attention as a next-generation semiconductor material for high-voltage, high-power, and high-efficiency power devices. It possesses an even larger bandgap (4.68 eV) than silicon carbide (SiC) and gallium nitride (GaN) and is theoretically predicted to allow for control of both p-type and n-type conductivity.

Previously, our company successfully controlled n-type conductivity in r-GeO_2, achieving an electron density of approximately 10^{20} cm^{-3}, by introducing antimony (Sb) as a donor impurity during film growth using our proprietary PhantomSVD method [1]. Applying this in-situ n-type doping technique, we also fabricated the world's first r-GeO_2 Schottky barrier diode (SBD) and successfully demonstrated its diode operation [2].

However, manufacturing power devices with complex structures, such as power MOSFETs, demands a technology that can precisely pattern the donor impurity concentration across the substrate surface. This requirement is difficult to meet with in-situ doping during film growth. Therefore, there has been a strong demand for achieving impurity doping in r-GeO_2 crystals through ion implantation, a technique widely used for conventional semiconductors like silicon (Si) and SiC.

Achievements

We performed Sb ion implantation on an undoped (intentionally not doped) r-GeO_2 thin film grown on a TiO_2 substrate using our proprietary film deposition technology, the Phantom SVD method. Figure 1 shows surface photographs and film thickness measurements at various points across the wafer before and after ion implantation. No significant change in the r-GeO_2 film thickness was observed. Furthermore, X-ray diffraction (XRD) measurements taken before and after the process confirmed that the rutile crystal structure was maintained.

We observed a reduction in sheet resistance in the regions subjected to ion implantation. This indicates that the donor impurities introduced via the ion implantation process were successfully activated, imparting n-type conductivity to the previously insulating r-GeO_2 crystalline film.

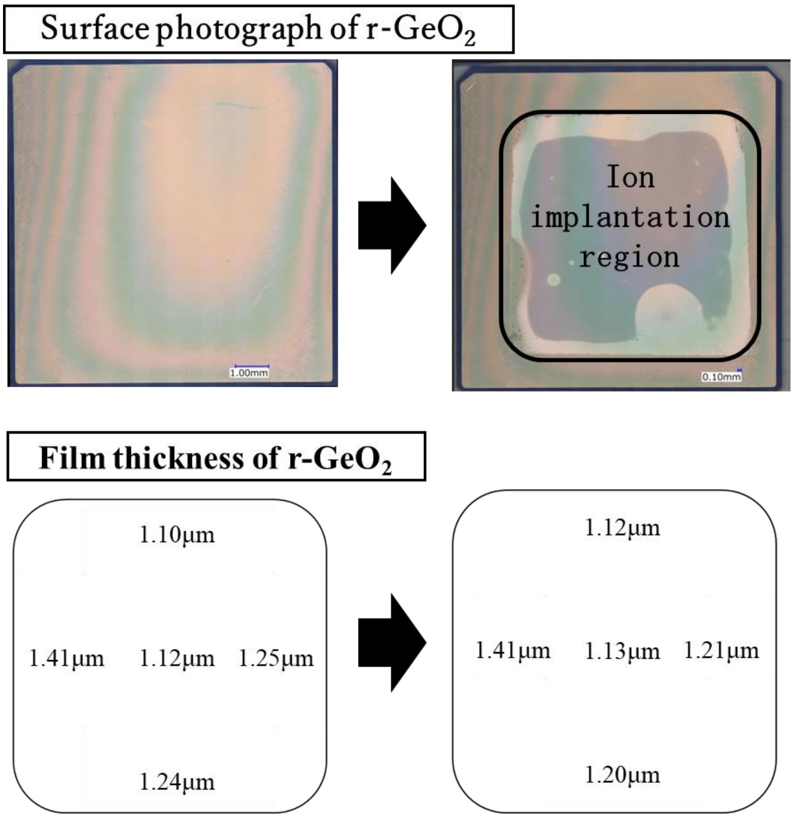

Figure 1: Surface photographs and film thickness maps of the r-GeO_2 thin film before (left) and after (right) ion implantation.

Electrodes were fabricated on the implanted area, and capacitance-voltage (*C*-*V*) measurements confirmed that the region exhibited n-type conductivity. The donor impurity concentration profile, calculated from the *C*-*V* characteristics, is shown in Figure 2. This distribution demonstrates that the donor impurities in this sample were not introduced during film growth but were instead introduced near the film's surface by the ion implantation process.

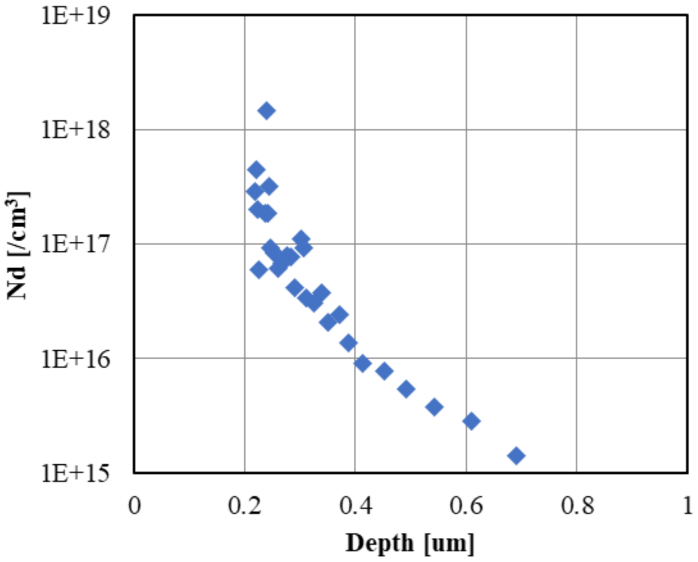

Figure 2: Depth profile of donor impurity concentration in the r-GeO$_2$ thin film within the Sb ion-implanted region, as calculated from C-V characteristics.

However, further verification is required to confirm that the donor impurities introduced by the ion implantation process are indeed Sb. We are currently conducting further analysis, including current-voltage (*I*-*V*) measurements and impurity analysis using secondary-ion mass spectrometry (SIMS), to determine the concentration of Sb introduced into the r-GeO$_2$ film. Detailed results on the structural and electrical properties of the r-GeO$_2$ thin film are scheduled to be reported at the 86th JSAP Autumn Meeting [3].

This successful demonstration of n-type doping via ion implantation is a significant step toward our company's goal of contributing to a decarbonized society with new r-GeO$_2$ semiconductor materials.

Future Outlook

Moving forward, we will focus on optimizing the conditions for impurity doping via ion implantation and will proceed with the fabrication of prototype r-GeO_2 power devices using this process to accelerate their practical application.

References:

[1] Y. Shimizu, et al., “N-type conductivity in single-phase r-GeO_2 thin films.”, 2024 MRS Fall Meeting & Exhibit, SF04.15.08 (2024).
[2] Y. Shimizu et al., "Schottky Barrier Diode Characteristics of Rutile-Structure Germanium Dioxide (r-GeO_2)", The 72nd JSAP Spring Meeting, 15a-K403-11 (2025).
[3] Y. Shimizu et al., "Characterization of Rutile-Structure Germanium Dioxide (r-GeO_2) Using Ion Implantation Process", The 86th JSAP Autumn Meeting (2025) (Submitted).