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Al doping of 4H-SiC by Laser Irradiation to Coated Film and Its Application to Junction Barrier Schottky Diode

Akihiro Ikeda, Rikuho Sumina, Hiroshi Ikenoue and Tanemasa Asano

[1] Graduate School of Information Science and Electronics, Kyushu University
Moto-oka 744, Nishi-ku, Fukuoka 819-0395, Japan.
Phone: +81-92-802-3732 E-mail: ikeda@ed.kyushu-u.ac.jp

Abstract

We demonstrate the ability of Al doping into 4H-SiC from molten Al produced by pulsed excimer laser irradiation. High concentration (~5×10^{21} /cm^3 at the surface) and deep (~200 nm) Al doping can be achieved by single shot irradiation while keeping the substrate at room temperature. Selective doping can be performed by using SiO_2 mask. The technology is applied to fabrication of junction barrier Schottky (JBS) diode, which demonstrate that the technology can significantly reduce the works.

1. Introduction

Silicon carbide (SiC) is a promising material for next-generation high-power devices because of its higher breakdown field than Si. But, there are issues in process technology to produce SiC devices. One of the issues is local doping. Ion implantation can be applied to the doping of SiC. However, ion implantation of SiC requires hot implantation at 200-700°C followed by high-temperature annealing at about 1700°C. This high-temperature process induces unintentional crystallographic defects in the SiC such as segregation of carbon atoms from the bulk of SiC [1].

We reported previously that phosphorus (P), nitrogen (N) or aluminum (Al) can be doped into 4H-SiC by KrF excimer laser irradiation in phosphoric acid, liquid nitrogen or aluminum chloride solution [2-4]. The p-type doping with Al is particularly interesting for fabrication of devices such as junction barrier Schottky (JBS) diode. However, the doping depth of Al using the aluminium chloride solution is limited to ~40 nm even with increasing the laser fluence or the shot number. This depth is not sufficient to utilize characteristic of pn junction under, in particular, reverse bias.

In this paper, we report that deep Al doping of 4H-SiC can be achieved by irradiating excimer laser to an Al film coated on the 4H-SiC surface. Since the boiling point of Al is very high (~2800 K) at atmospheric pressure while the melting point is low (~930K), the pulsed-laser irradiation may produce a high-temperature molten Al which acts as diffusion source. The application of this new doping technology to fabrication of 4H-SiC JBS is demonstrated.

2. Experimental

Fig. 1 shows a schematic illustration of the doping method. The 4H-SiC sample was composed of a 3.5-μm-thick n-type epitaxial layer (Si-face 4° off, 1.0×1016/cm3 N doped) on n+-type 4H-SiC (0.019 Ω•cm). An Al film was sputter deposited on the n-type 4H-SiC epitaxial layer. The thickness of Al films ranged from 60 nm to 480 nm. A KrF excimer laser (Gigaphoton Inc. wavelength: 248 nm; pulse-duration: 55 ns) was irradiated to the Al film in the air environment. The laser fluence and shot number was 4.0 J/cm^2 and 1 shot. Optical emission spectrum was measured during laser irradiation to monitor the doping process.

3. Results and Discussion

It has been found that there presents an optimum thickness range of Al coating. To investigate change in state of the Al layer after laser irradiation, Auger electron spectroscopy (AES) measurements were performed on the laser irradiation region. Fig. 2 shows spectra taken from two irradiated samples and an unirradiated sample. The laser beam shape was 350×350 μm square. The AES measurement area is 60×60 μm square at the center of the laser irradiation region. For the Al thickness of 60 nm, spectral peak of Al cannot be observed, while it is clearly observed for the 120 nm-thick sample. These results indicates that when Al thickness is thin, Al is evaporated completely by the laser irradiation. Comparison of the 120 nm-thick irradiated sample and the 240 nm-thick unnirradiated sample suggests that the 4H-SiC surface is fully covered with Al for the 120 nm-thick sample even after irradiation. These results were consistent with scanning electron microscopy of the samples.

Fig. 3 shows depth profiles of Al and Si at the laser irradiation region. The profiles were measured after Al removal using wet chemical etching and surface cleaning with CF_4 plasma and O_2 plasma. The surface concentration of Al is ~5×10^{21} /cm^3 for both the 120 nm-thick and 240 nm-thick samples. On the other hand, the 480 nm-thick sample shows less density than the above samples by about one order. We presume that the temperature rise of Al decreases with increasing the thickness due to increase in volume of Al and increase in heat dissipation. Formation of p-type layer has been confirmed for 120 nm-thick and 240 nm-thick samples by Hall effect measurements.

Fig. 4 shows fabrication process of the JBS diode. A circular layout with ring-shaped selective doping areas has been designed. To perform doping in selective area, an SiO_2 mask was used to protect doping. The width of the line and space of the stripe was 6 and 10 μm, respectively. After the laser irradiation, the remained Al film on the sample chip was removed by wet chemical etching. Then, contact hole was opened on the striped doping region by BHF wet etching of the SiO_2 mask. Finally, Ti electrode and Ni electrode was formed on the front- and back-side of the 4H-SiC. To form ohmic and Schottky contacts of the Ni and Ti electrode, 875 and 500 °C annealing in vacuum was performed after the Ni and Ti electrode patterning, respectively.

Fig. 5 shows I-V curve of the JBS diode. I-V curves of pn or

Schottky diode are also plotted for comparison. The pn diode was fabricated by the laser irradiation through a circular SiO_2 mask without the striped pattern. The Schottky diode was fabricated without the laser irradiation (no Al doping). As observed in the I-V curve, the the JBS diode flows larger current than the pn junction diode at the same forward bias, which indicates that the JBS diode shows lower turn-on voltage than the pn diode. On the other hand, the reverse current of the JBS diode is smaller than that of the Schottky diode, indicating that the Schottky junction of the JBS diode is fully pinched-off by the depletion region extended from the pn junction. Under the present design, the Schottky junction is estimated to be pinched-off by the extended depletion regions at ~ -80 V.

4. Conclusion

We have developed a new doping technology of Al into 4H-SiC by using pulsed laser irradiation to Al coated 4H-SiC at room temperature in the ambient air. It produces a p-type layer whose surface concentration is higher and the depth is larger than the previously reported laser doping techniques. The experimental results suggests that doping proceeds thermal diffusion of Al from molten Al. Selective doping using SiO_2 mask can be performed, which can significantly reduce works to fabricate JBS diode.

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We are grateful to Prof. T. Okada for his useful discussion. This work is supported by a Grant-in-Aid for Scientific Research (No. 25289105) and Grant-in-Aid for Scientific Research (No. 26420309) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

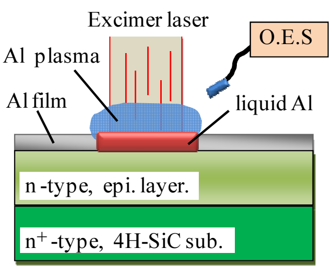

Fig. 1. Illustration of the laser Al doping from liquid Al on the 4H-SiC.

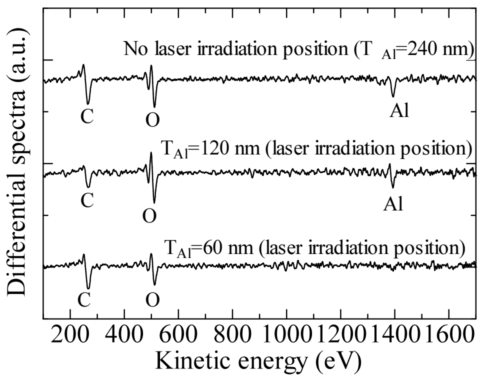

Fig. 2. AES spectra at the laser irradiation regions before the Al removal. AES spectrum without the laser irradiation is also shown.

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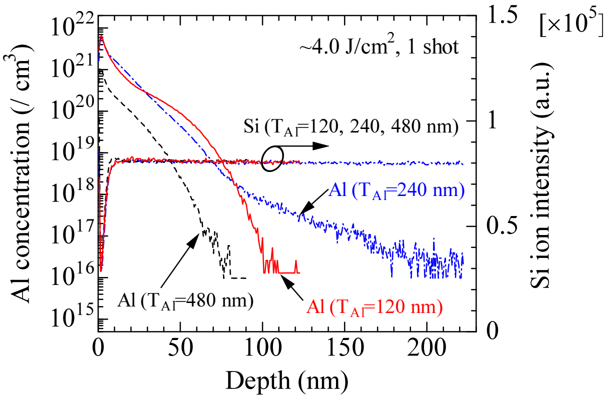

Fig. 3. SIMS depth profile of Al and Si in the 4H-SiC at the laser doping region as a parameter of the Al film thickness.

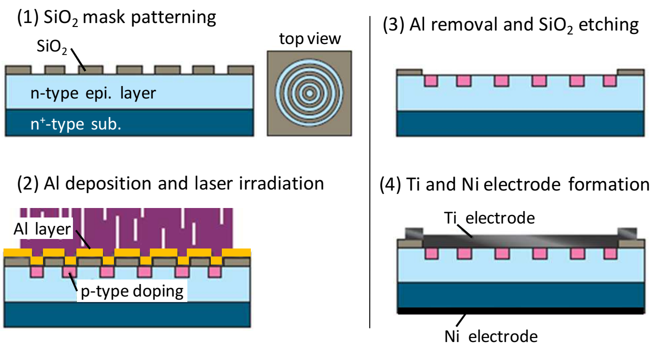

Fig. 4. Fabrication process of the JBS diode by using the Al doping with the laser induced liquid Al.

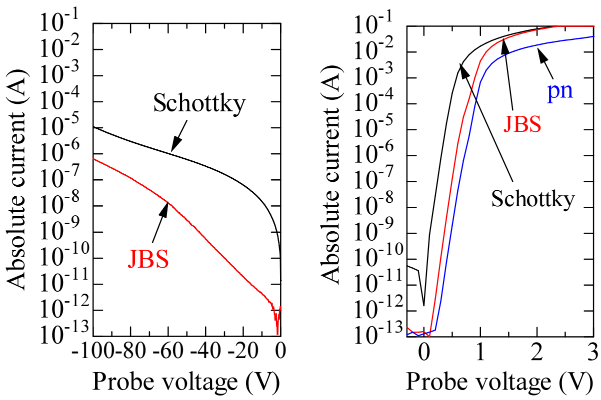

Fig. 5. I-V curve of JBS diode fabricated by the Al doping with the laser induced liquid Al. The I-V curves of pn and Schottky diodes are also shown for comparison to the JBS diode.