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Low-temperature, high-concentration laser doping of nitrogen to 4H-SiC for low-contact-resistance fabrication

Toshifumi Kikuchi[1,2], Kaname Imokawa[1,2], Akihiro Ikeda[3], Daisuke Nakamura[1]
Tanemasa Asano[1] and Hiroshi Ikenoue[1,2]

[1] Graduate School of Information Science and Electrical Engineering, Kyushu University
[2] Department of Gigaphoton Next GLP, Kyushu University
[1,2] 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
[3] Department of Computer and Information Sciences, Sojo University
[3] 4-22-1 Ikeda, Nishi-ku, Kumamoto 860-0082, Japan
Phone: +81-92-802-3750 E-mail: h.ikenoue.834@m.kyushu-u.ac.jp

Abstract

We propose a method of low-temperature nitrogen doping of 4H-silicon carbide (4H-SiC)(0001) by KrF excimer laser irradiation of a SiNx film. A SiNx film with a thickness of 100 nm was deposited on an n-type 4H-SiC(0001) substrate by chemical vapor deposition. A gas supply nozzle for controlling the ambient environment was installed to avoid oxidation of the SiC surface. Argon gas was used as the ambient gas. High-concentration nitrogen doping (~1 × 10^{21}/cm^3 at the surface) was achieved by laser ablation of the SiN_x film. The contact resistance was measured with Al/Ti electrodes formed on the doped area at low temperatures of 200 °C. The contact resistance was 2.5 × 10^{-5} Ω·cm^2, which is a sufficiently small value for the backside contact resistance of Schottky barrier diodes and PiN diodes.

1. Introduction

4H-silicon carbide (4H-SiC) is a group IV semiconductor with a bandgap energy of 3.26 eV, and it is known as a promising material for high-power devices. It has superior material properties; in particular, 4H-SiC has a high dielectric breakdown field that is about 10 times larger than that of silicon (Si) [1]. Therefore, SiC devices have lower electric power losses than Si.

However, some issues must be resolved in order to fabricate SiC devices. The doping process is one such issue. SiC has a lower electron affinity than Si. Therefore, a larger Schottky barrier is formed, and the contact resistance tends to be larger than that of Si. Thus, heavy doping is necessary to form low-resistance contacts. Nitrogen and phosphorous have been widely studied as n-type dopants of SiC [1]. Hot ion implantation at a high temperature of approximately 600 °C and subsequent annealing at approximately 1700 °C are typically used to dope SiC [1]. However, the concentration limit of the dopants is at the 10^{20}/cm^3 level. In particular, the surface concentration is lower than the bulk concentration because the dopant diffuses very little even at such high temperatures. Therefore, it is difficult to reduce the metal/SiC contact resistance; thus, high-temperature annealing from 800 to 1000 °C is required for electrode formation to reduce the contact resistance due to alloying and defect generation at the interface [1]. These high-temperature processes degrade the crystallinity of the SiC, for example, by segregating C atoms from the SiC bulk. Further, process integration is limited; for example, thinning of the SiC substrate is difficult.

We have investigated a laser doping method for high-concentration, low-temperature doping and reported that heavy N or Al doping of 4H-SiC can be achieved by laser ablation of thin source films (SiN_x or Al) formed on the SiC substrate [2,3]. Recently, we have developed a laser doping method capable of processing the entire SiC wafer with high productivity for a manufacturing system. In this paper, we report the characteristics of N doping of SiC substrates and the contact resistance of a metal/N-doped SiC substrate for low-temperature electrode formation. Finally, we discuss the power loss properties when a backside electrode is formed using this laser doping system.

2. Experimental

The sample structure was a SiN_x(100 nm)/n-type 4H-SiC(0001) substrate. The SiN_x film was deposited on the C-face of the SiC substrate by chemical vapor deposition. Figure 1 shows a schematic diagram of the laser irradiation system. Laser irradiation was performed by a KrF excimer laser (Gigaphoton Inc., wavelength: 248 nm, pulse duration: 15 ns, full width at half-maximum). Figure 2 shows a schematic diagram of the sample structure and laser doping procedure. Laser irradiation of the sample was performed in Ar ambient by using a gas supply nozzle. The nozzle is very small, approximately 75 mm × 75 mm × 80 mm, and oxidation of the sample surface can be effectively suppressed. The laser beam size on the sample surface was 300 μm × 500 μm. The irradiation fluence ranged from 2.1 to 2.3 J/cm^2. The laser was applied at 100 Hz, and the sample was scanned at rates of 3 to 5 mm/s along the short-axis direction of the laser beam. Scan speeds of 3, 4, and 5 mm/s correspond to 7, 10, and 16 shots/loc., respectively. After irradiation, the non-irradiated area of the SiNx films was removed by a phosphorous acid solution at 150 °C for 25 min.

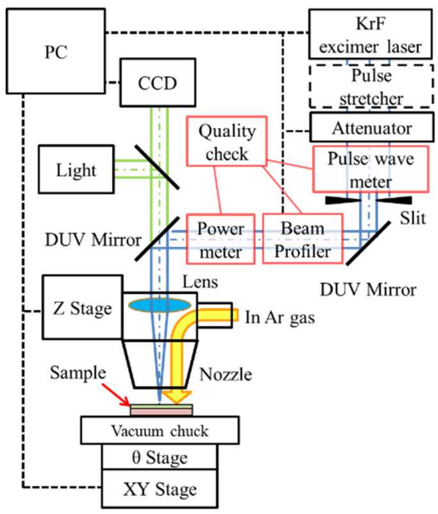

Fig. 1 Schematic diagram of laser irradiation system.

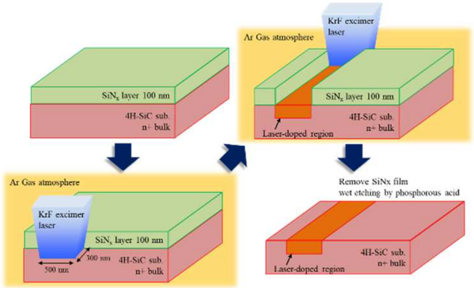

Fig. 2 Sample structure and laser doping procedure.

3. Results and discussion

Figure 3 shows the current–voltage (*I*–*V*) characteristics of the surface after irradiation in Ar ambient and atmosphere. The fluence was 2.2 J/cm^2, and the number of shots was 10. For irradiation in atmosphere, the *I*–*V* curve is nonlinear. On the other hand, for irradiation in Ar ambient, ohmic characteristics with linearity are clearly obtained. Therefore, the developed gas supply nozzle works effectively to avoid oxidation of the SiC surface.

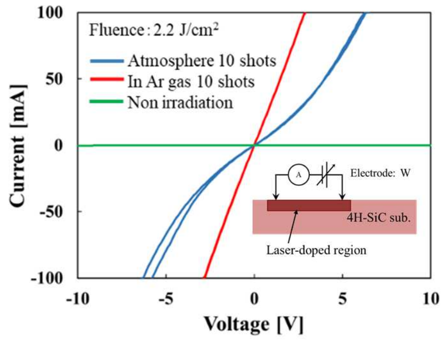

Fig. 3 *I*–*V* characteristics after laser doping in Ar ambient and atmosphere (2.2 J/cm^2, 10 shots).

Figure 4 shows the results of secondary ion mass spectrometry (SIMS) analysis of nitrogen after laser doping in Ar ambient (2.2 J/cm^2, 10 shots). High-concentration nitrogen doping (at the 10^{21}/cm^3 level at the surface) was achieved. In addition, from measurement results of the surface morphology and Raman spectrum, we confirmed that very little laser irradiation damage appeared in the doped region.

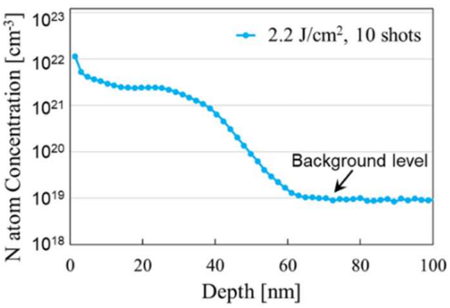

Fig. 4 SIMS analysis of nitrogen (2.2 J/cm^2, 10 shots).

Figure 5 shows the contact resistance measurement method. Al/Ti electrodes with sizes ranging from 5 µm × 5 µm to 50 µm × 50 µm were deposited on the laser-doped region. When the electrode dimension d is much smaller than the SiC substrate thickness t, the bulk resistance *R2* and Ni/SiC contact resistance *R3* are defined as constant. The contact resistance of the (Al/Ti)/SiC substrate can be obtained by measurements of the total resistance, *R* = *R1* + *R2* + *R3*, as a function of the electrode dimension d.

Figure 6 shows the contact resistance measurement results. The Al/Ti electrodes were annealed from 200 to 850 °C for 30 min. All of the *I*–*V* curves exhibited linearity even at room temperature, and the contact resistance was 2.5 × 10^{-5} Ω·cm^3 at an annealing temperature of 200 °C.

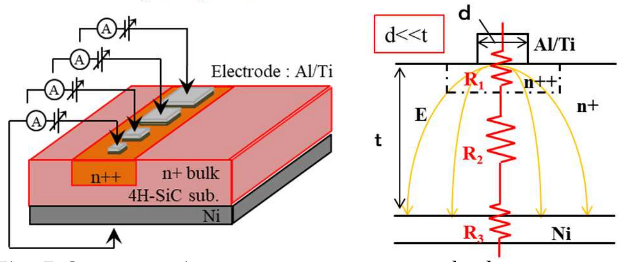

Fig. 5 Contact resistance measurement method.

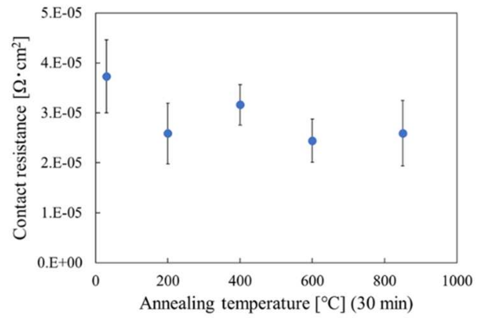

Fig. 6 Contact resistance at the N doping region. The Al/Ti electrodes are formed by annealing for 30 minutes.

4. Conclusions

We proposed a method of low-temperature nitrogen doping of 4H-SiC(0001) induced by KrF excimer laser irradiation of a SiNx film. Laser irradiation was performed using an Ar gas supply nozzle to avoid oxidation of the SiC surface. High-concentration nitrogen doping (at the 10^{21}/cm^3 level at the surface) can be achieved by laser ablation of the SiN_x film. In addition, little degradation of the SiC crystallinity is induced in the nitrogen-doped region. The contact resistance between an Al/Ti electrode and the nitrogen-doped region is 2.5 × 10^{-5} Ω·cm^2 after low-temperature annealing at 200 °C. From this contact resistance result, if a back-side electrode for a Schottky barrier diode (SBD) or PiN diode is fabricated by this method, the power loss ratio of the contact resistance to the bulk resistance can be estimated as 4% and 12.5% at substrate (0.02 Ω·cm) thicknesses of 350 and 100 µm, respectively. Therefore, we can obtain a sufficiently small value for the backside contact resistance of SBD and PiN diodes. From these results, we conclude that low-temperature, high-concentration laser doping can be achieved by laser ablation of a SiNx film on a 4H-SiC substrate.

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