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Effect of Substrate Heating on Low Contact-Resistance Formation by Excimer Laser Doping for 4H-SiC

Yoshiaki Kakimoto[1,2,a], Takuma Yasunami[1,b], Keita Katayama[1,c], Daisuke Nakamura[1,d], Tetsuya Goto[3,e], Hiroshi Ikenoue[4,f*]

[1]Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan

[2]Department of Gigaphoton Next GLP, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan

[3]New Industry Creation Hatchery Center Tohoku University, 6-6-10 Aramakiaoba, Aoba- ku, Sendai, 980-0845, Japan

[4]Kochi University of Technology, 185 Miyanoguchi, Tosayamadacho, Kami-shi, Kochi, 782-8502, Japan

[a]kakimoto.yoshiaki.124@m.kyushu-u.ac.jp, [b]t.y.0507@icloud.com, [c]katayama.keita.729@m.kyushu-u.ac.jp, [d]nakamura.daisuke.946@m.kyushu-u.ac.jp, [e]tetsuya.goto.b2@tohoku.ac.jp, [f*]ikenoue.hiroshi@kochi-tech.ac.jp

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Abstract. N atoms were doped into SiN_x/4H-SiC substrates by KrF laser irradiation while the substrates were heated. The diffusion depth of nitrogen increased above the solubility limit when the sample heated to 600°C was irradiated by the laser compared to the sample at room temperature. In addition, a clear 4H-SiC pattern was observed in the cross-sectional TEM diffraction image, thereby suggesting that sufficient crystal recovery was achieved even under melt-solidification conditions owing to the effect of substrate heating.

Introduction

Currently, 4H-SiC power devices are being made increasingly thinner to reduce their resistance loss. Contact resistance reduction is required because thinner wafers increase the ratio of contact resistance to substrate resistance loss. A common method for forming contact electrodes is furnace annealing at about 1000°C after Ni deposition, which is incompatible with thinner wafers [1, 2]. Another method is laser annealing, but issues such as carbon segregation remain [3, 4]. In our study, we achieved high-density nitrogen doping on 4H-SiC by depositing SiN_x as a film containing dopants on 4H-SiC and performing excimer laser irradiation at room temperature to achieve contact resistance in the low 10^{-6} Ωcm^2 range [5]. We investigated the change in doping characteristics by laser irradiation of SiN_x/4H-SiC substrates while they were heated.

Experimental Method

The experimental setup is illustrated in Fig. 1. A KrF excimer laser (Gigaphoton Inc., wavelength: 248 nm) was utilized. The SiC wafer to be irradiated was an n-type 4H-SiC (0001) substrate with 350-μm thickness. Employing a chemical vapor deposition method, 100-nm-thick SiN_x films were deposited on the C-face of the 4H-SiC substrate. SiN_x/4H-SiC substrate was heated to 600°C for laser irradiation in a vacuum chamber maintained in an argon gas (1 Pa) atmosphere. The laser irradiation fluence was set to 1.0–4.0 J/cm^2 by attenuator and the irradiation frequency to 1–100 shots/loc. The laser pulse width was extended to 82 ns by OPS (optical pulse stretcher). During laser irradiation, the laser power and beam profile are constantly monitored by the observation system.

After laser irradiation, the SiN_x film was removed with a phosphoric acid solution at 150°C, and O_2 and CF_4 plasma etching was employed to remove C and Si-based products.

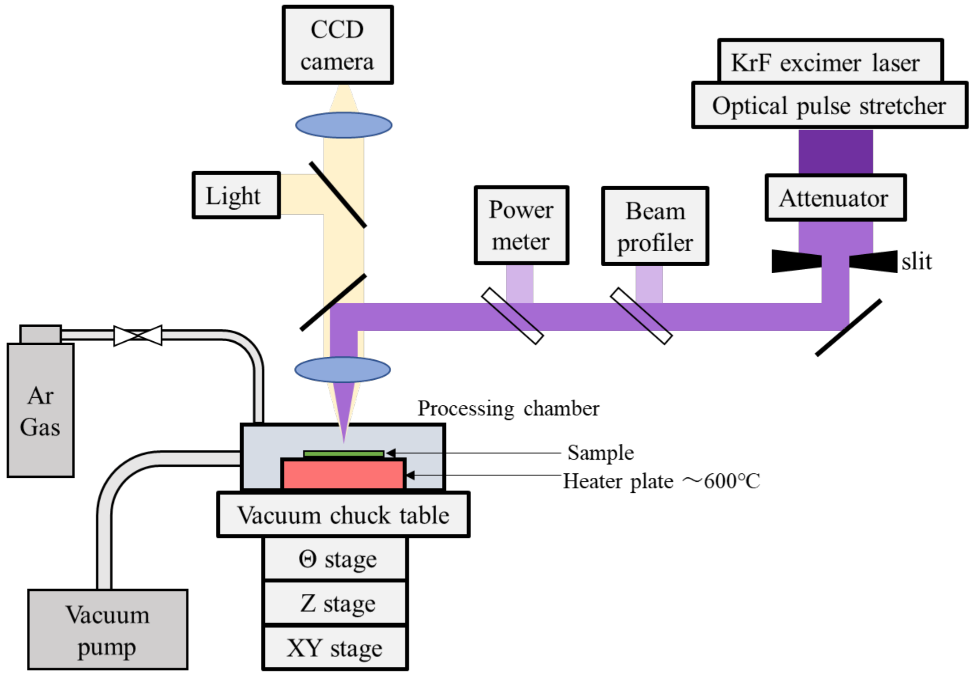

Fig. 1. Schematic of laser irradiation system

Measurement Method of Contact Resistance

Fig. 2 presents a schematic of the sample for contact resistance measurement. In the area highly doped with nitrogen by laser irradiation, a Ti/Al electrode was fabricated after forming a contact hole "*d*" with sizes ranging from 5 × 5 μm to 40 × 40 μm on the SiO_2 insulating film by photolithography. When the electrode dimension *d* was much smaller than the thickness *t* of the SiC substrate, the bulk resistance R_2 and Ni/SiC contact resistance R_3 were considered constant. R_1 is the resistance between the Al/Ti electrode, R_2 is the bulk resistance, and R_3 is the resistance between the Ni electrode, as illustrated in Fig. 2. The total resistance when current is applied R_M is expressed by the following equation.

$$R_M = R_1 + R_2 + R_3. \tag{1}$$

where the ground area of the Al/Ti electrode is *d,* and the contact resistance is ρ_C

$$R_1 = \rho_C / d^2. \tag{2}$$

From Eq. 1 and 2, R_M is given by

$$R_M = \rho_C / d^2 + R_2 + R_3. \tag{3}$$

Because R_2 and R_3 are constant, the contact resistance ρ_C can be obtained by changing the value of *d*, the size of the electrode, and measuring R_M. For example, Fig. 3 illustrates the contact resistance measured by this method at a substrate temperature of 600°C and laser irradiation fluence of 1.4 J/cm^2. As illustrated in Fig. 3, as the electrode size *d* decreases compared to the substrate thickness *t*, the graph can be approximated as a straight line, the slope of which is the contact resistance ρ_C. The contact resistance was calculated to be 4.7 × 10^{-6} Ωcm^2. This method utilizes contact holes as small as *d* = 5–40 μm, making it possible to measure values as low as the 10^{-6} Ωcm^2 range. Fig. 4 presents the I-V characteristics at several measurement points with different contact hole sizes at a substrate temperature of 600°C and laser irradiation fluence of 1.4 J/cm^2.

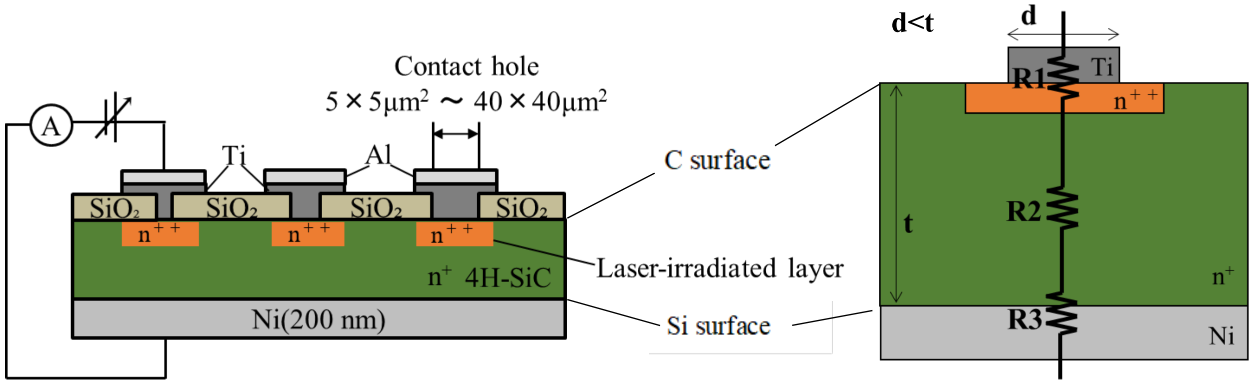

Fig. 2. Structure of test tip for contact resistance measurement

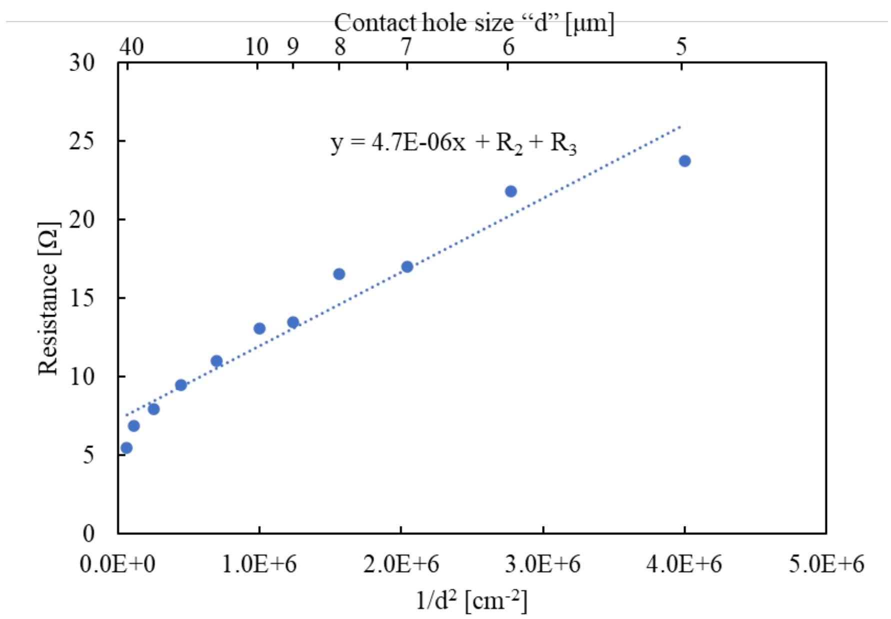

Fig. 3. Measured values of contact resistance (1.4 J/cm^2, 600°C)

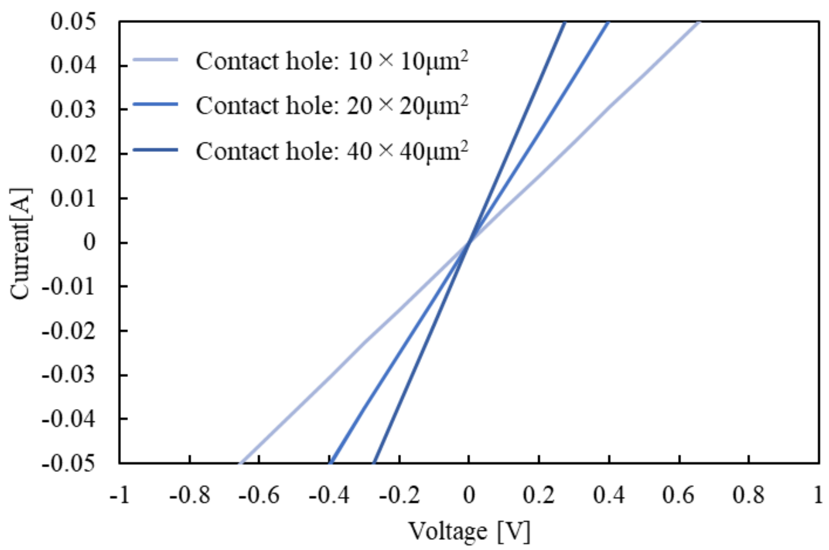

Fig. 4. I-V characteristics of test tip (1.4 J/cm^2, 600°C)

Result and Discussion

Fig. 5 illustrates the contact resistance and surface roughness after laser irradiation at approximately 25°C (room temperature) and 600°C substrate temperature. For irradiation at room temperature, the surface roughness increased at fluences above 2.8 J/cm², and ohmic contacts with contact resistance in the 10^{-6} Ωcm² range were obtained at fluences of 2.5–3.1 J/cm². When irradiated at a substrate temperature of 600°C, the surface roughness increased at fluences above 2.0 J/cm², and ohmic contacts with contact resistances in the 10^{-6} Ωcm² range were obtained at fluences of 1.2–2.0 J/cm². Increasing the substrate temperature decreased the fluence at which surface roughness increased, and ohmic contact was obtained. In the experiment in which the substrate temperature was 600°C, the lowest contact resistance of 2.7×10^{-6} Ωcm² was obtained at laser fluence of 1.8 J/cm², and surface roughness was 7.9 nm.

Fig. 6 presents the depth profiles of nitrogen concentration estimated through a secondary ion mass spectrometry (SIMS) analysis after laser irradiation at fluences of 1.2–2.0 J/cm², substrate temperature of 600°C, and fluence of 2.5 J/cm² at room temperature. The red dashed line in the graph represents the solid solubility limit of nitrogen in 4H-SiC [6]. At a substrate temperature of 600°C, high doping concentrations in the 1.0×10^{21} cm^{-3} range were obtained near the surface at fluences of 1.6 J/cm^2 or higher, exceeding the solid solution limit. In addition, irradiation at a fluence of 1.6 J/cm^2 at a substrate temperature of 600°C produced a nitrogen concentration distribution similar to that at a fluence of 2.5 J/cm^2 at room temperature. At fluences of 1.8 and 2.0 J/cm², the diffusion depth of nitrogen at the melting limit concentration increased. However, at 1.2 J/cm^2, a low contact resistance in the 10^{-6} range was obtained, although the concentration was below the solid solution limit.

Cross-sectional TEM images are presented in Fig. 7. 1.6 J/cm² and 2.0 J/cm² depict the formation of an amorphous layer on the surface layer in the region of approximately 5 nm. No stacking defects were observed in the 4H-SiC crystal at 1.2 J/cm², 1.6 J/cm², and 2.0 J/cm², and a clear 4H-SiC pattern was observed in the cross-sectional TEM diffraction pattern. The contact resistance reduction at 1.2 J/cm² was attributed to the doping achieved without amorphous layers or crystalline defects on the surface layer. The results of 1.6 J/cm² and 2.0 J/cm² suggest that sufficient crystal recovery was achieved even under melt-solidification conditions due to the effect of substrate heating, resulting in low contact resistance.

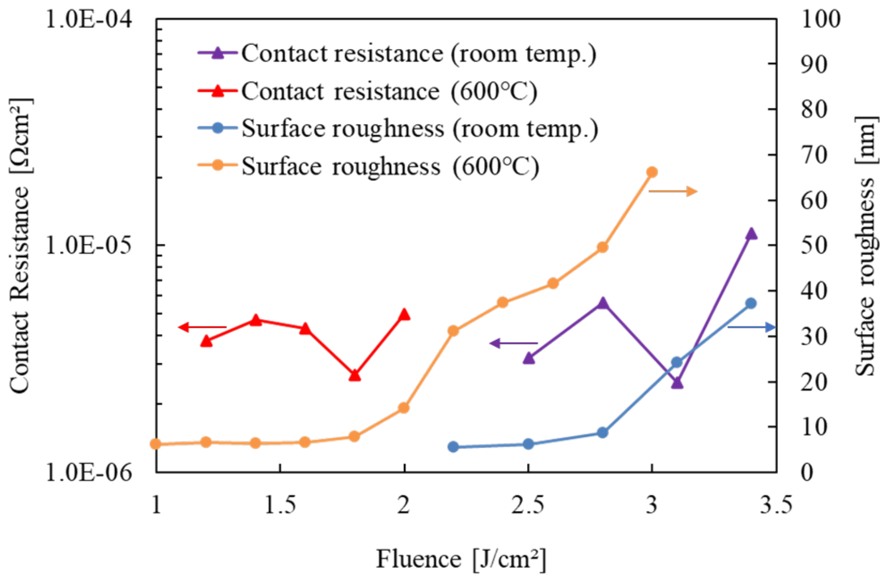

Fig. 5. Measured values of contact resistance and surface roughness

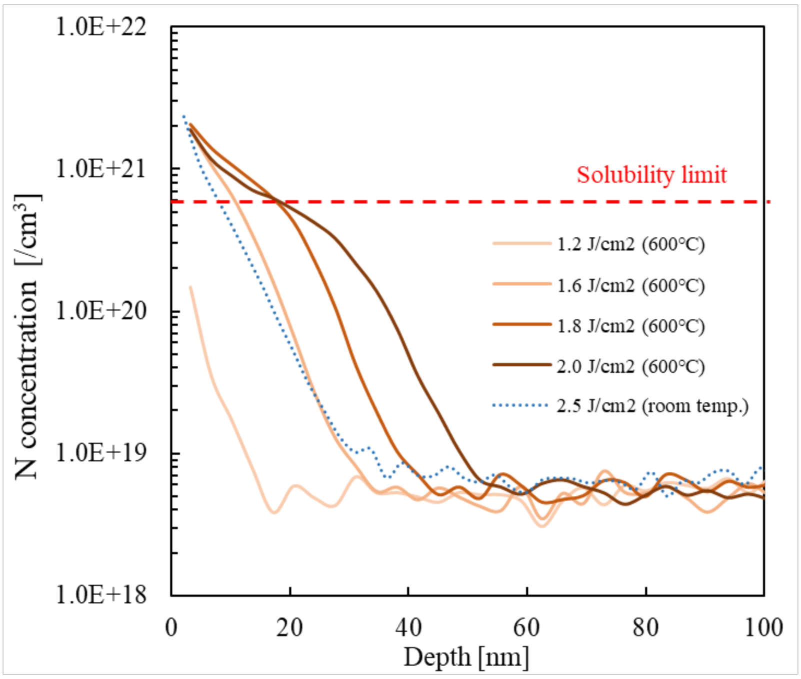

Fig. 6. Nitrogen concentration of 4H-SiC after laser irradiation estimated through SIMS analysis

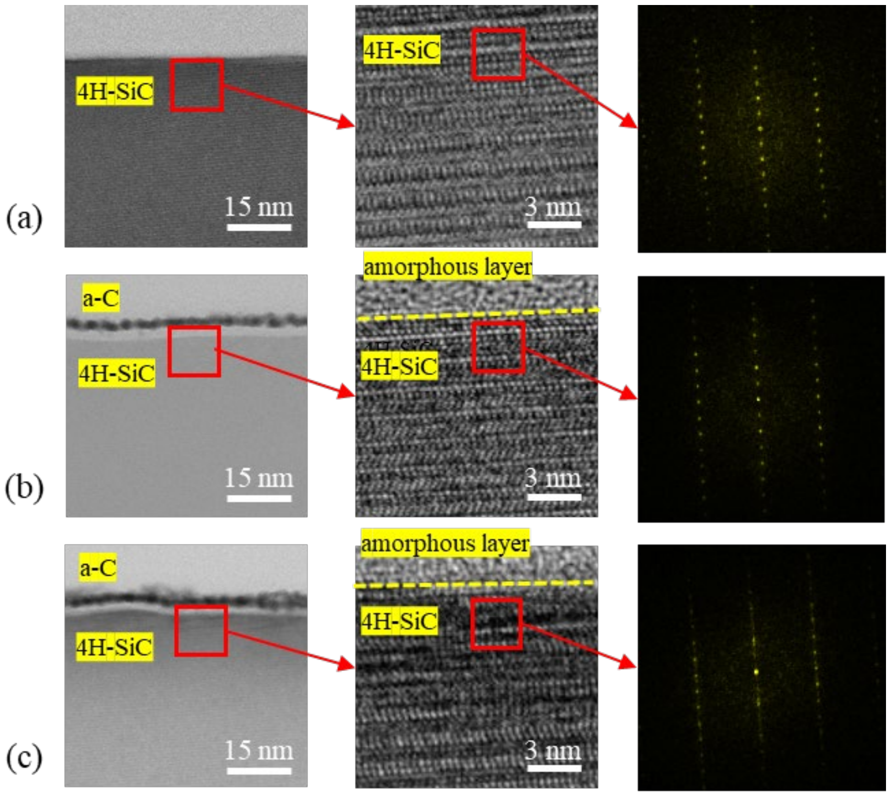

Fig.7. Cross-sectional TEM image (left and middle panels) and electron diffraction pattern (right panel) after laser irradiation at substrate temperature of 600°C
(a) 1.2 J/cm², (b) 1.6 J/cm², (c) 2.0 J/cm²

Conclusion

In conclusion, high-concentration N atom doping can be achieved by excimer laser irradiation of SiN films deposited on 4H-SiC. When the substrate temperature was heated to 600°C in advance, the laser fluence required for doping decreased. When the substrate was heated, contact resistance in the

10^{-6} range was obtained under fluence conditions of melting and solidification, suggesting that substrate heating promoted sufficient crystal recovery.

Acknowledgments

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