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Femtosecond laser–assisted thermal annealing of Ni electrode on SiC substrate

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Alloying at the metal–semiconductor interface induced by femtosecond laser irradiation associated with thermal annealing was examined to ascertain whether an ohmic contact was formed on silicon carbide (SiC). In general, the electric field of the femtosecond laser beam destroys the crystal structure, but with lower thermal damage around the irradiated areas. In addition to the laser irradiation, we employed thermal annealing to enhance the diffusion of the metal atoms inside the SiC. After these processes, an ohmic contact was successfully formed on the SiC with thermal annealing at a temperature of 900 °C, which is 100 °C lower than with the conventional thermal annealing method. https://doi.org/10.1063/1.5036804

It is widely accepted that annealing at quite high temperatures (above 1000 °C) is necessary to form nickel (Ni) ohmic contact on n-type SiC.[1,2] By employing high-temperature annealing at more than 1000 °C, a contact resistance of $\rho_c = 3 \times 10^{-7}\ \Omega \cdot \mathrm{cm}$ was obtained for n-type 4H-SiC, and a contact resistance of $\rho_c = 10^{-6}\ \Omega \cdot \mathrm{cm}$ was obtained for p-type 4H-SiC.[3] The high annealing temperature causes the melting and/or degradation of contact metals. Thus, barrier metals are often used to avoid this problem.[4] However, the processing of barrier metals is complicated, and a simpler technique for fabricating metal contacts on SiC is required.

The quite high annealing temperature needed for SiC and metal contacts is caused by the strong covalent bonds between the silicon (Si) atoms and the carbon (C) atoms in SiC. This strong bond prevents the migration of Ni atoms into the SiC substrate and alloying between Ni, Si, and C atoms. Here, we proposed using femtosecond laser irradiation to break the bonds between the Si and C atoms. The advantage of the femtosecond laser is that the short optical pulse produces a very strong electric field. This strong electric field easily destroys the crystal structure inside SiC substrates.[5] It has been reported that Ni atoms diffuse into the SiC substrate destroyed by femtosecond laser irradiation with lower temperature.[6] Thus, irradiation by a femtosecond laser at the interface between the Ni contact and the SiC substrate may provide a novel technique for the fabrication of ohmic contacts on SiC. In addition, in the conventional contact formation process, the entire substrate is heated in the furnace. This treatment degrades the devices. The femtosecond laser, on the other hand, is able to locally destroy the crystal structure at the interface between the metal and the semiconductor. Fortunately, this method allocates less thermal energy to the irradiated spot, thereby avoiding damage from thermal degradation around the irradiated areas. The multiphoton absorption process in the femtosecond laser processing also helps to improve the spatial selectivity for the modification area.

In this study, we demonstrated the advantage of femtosecond laser–assisted annealing between the SiC and Ni contacts. The current–voltage (I-V) characteristic between the fabricated contacts is discussed. The contact resistance was measured and Hall measurements were carried out to ascertain the contact resistivity of the contacts and the specific resistivity of the laser–modified SiC.

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We used an n-type 4H-SiC single crystal substrate with the thickness of 340 µm (TankeBlue, $\rho < 0.1\ \Omega\cdot$cm). The surface oxide was removed by 5 min of etching in an 8 vol. % HF solution in distilled water. Before etching, ultrasonic cleaning was carried out in acetone, methanol, and distilled water. As an electrode, Ni with a thickness of 100 nm was deposited on the Si face of the SiC by electron beam evaporation.[7] The dimension of each electrode was 100 µm × 100 µm, and the distance between neighboring electrodes was 50 µm.

A 1-kHz regenerative amplifier based on the chirped pulse amplification system (Spitfire, Spectra-Physics) was used as a light source. The wavelength, pulse duration, and repetition rate of the laser are 800 nm, 130 fs, and 1 kHz, respectively. A femtosecond laser beam was introduced into an inverted optical microscope (Olympus IX70). The magnification of the objective lens (Olympus) used in the microscope was 20. The laser pulses were irradiated normal to the SiC surface and reached to the interface between Ni and SiC through the SiC substrate. The focal point was adjusted to irradiate onto the interface between the Ni and SiC. The irradiation fluence was varied from 1.2 to 10.8 J/cm^2 by using a neutral density filter. The laser spot size at the interface, as evaluated by the D^2 method,[8] was approximately 2.3 µm, and the scanning speed of the sample stage was 50 µm/s. This implies that approximately 50 pulses were irradiated to particular points at the interface. The samples were annealed at 900 °C in an electric furnace. The electrical conductivities between electrodes were characterized by a picoammeter (Keithley, 6487). We also carried out Hall measurements on the samples using the van der Pauw method. We prepared a 2 mm × 2 mm SiC substrate and evaporated Ni electrodes onto the four corners of the substrate. Then, the entire SiC substrate was irradiated by a femtosecond laser with a fluence of 3.6 J/cm^2, which produces ohmic contacts, as discussed later. After that, the sample was thermally annealed at a temperature of 900 °C. The applied magnetic field for the Hall measurements was B = 2500 G. In addition, sheet resistance was investigated by the transmission line model (TLM) method. In order to form an ohmic electrode, femtosecond laser irradiation with a fluence of 3.6 J/cm^2 and thermal annealing at 900 °C were employed. The distance between the ohmic electrodes was varied among 10, 15, 20, and 25 µm. The width of the electrode was 100 µm. The four–probe method was used for evaluation.[9]

The current–voltage (I-V) characteristics between neighboring contacts before and after annealing at a temperature of 900 °C in nitrogen ambient are shown in Fig. 1. The duration of the annealing was approximately 10 min. The blue line shows the results before annealing, i.e., just after the deposition of Ni onto the SiC surface. The red line shows the result after the annealing, which was applied after the deposition of Ni. Although the current was significantly improved for the sample after annealing, neither characteristic shows ohmic behavior. Here, we should mention that after 10-min annealing at a temperature of 1100 °C, our sample clearly displayed ohmic behavior (not shown). This demonstrates that our deposition process is based on standard deposition procedures.

These results are consistent with a previous report that the Ni ohmic contact on SiC is formed after thermal annealing at a temperature above 1000 °C.[10] To be able to discuss the effect of femtosecond

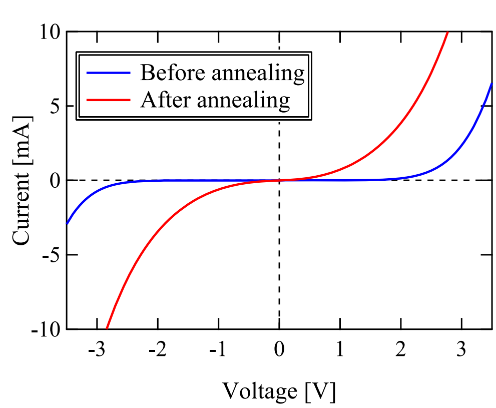

FIG. 1. Current-voltage characteristic between neighboring Ni contacts on SiC. The blue line shows the result before annealing; the red line shows the result after 10 min annealing at a temperature of 900 °C.

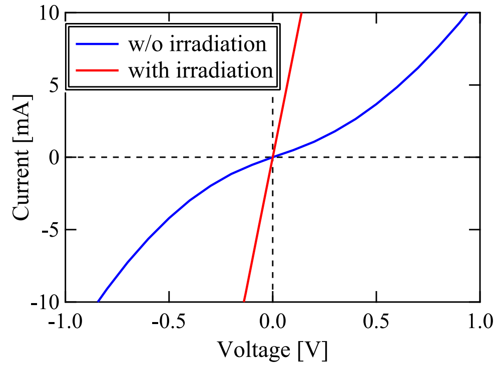

FIG. 2. Current–voltage characteristic between two Ni contacts on SiC. The blue line shows the result of 900 °C annealing without femtosecond laser irradiation; the red line shows the result of 900 °C annealing after femtosecond laser irradiation.

laser irradiation on the formation of Ni ohmic contact on SiC, we carried out thermal annealing after femtosecond laser irradiation. The results of annealing with and without (w/o) femtosecond laser irradiation are shown in Fig. 2. The blue line shows the result of 900 °C annealing without femtosecond laser irradiation; the red line shows the result of 900 °C annealing after femtosecond laser irradiation with a fluence of 3.6 J/cm^2. From this figure, it can be seen that the current between neighboring Ni contacts significantly improved after femtosecond irradiation. It is noteworthy that the current–voltage characteristic of the annealed sample after laser irradiation shows ohmic behavior. This implies that an ohmic contact is formed at an annealing temperature 100 °C lower with the assistance of the femtosecond laser irradiation.

The fluence dependence of the I-V characteristic is shown in Fig. 3. The samples were annealed at 900 °C for 10 min after femtosecond irradiation with various amounts of irradiation fluence. The ohmic characteristic was observed for irradiation fluence of 3.6 J/cm^2 (blue line) and 2.4 J/cm^2 (green line), and ohmic behavior was not observed for irradiation fluence of 1.8 J/cm^2 (orange line) or 1.2 J/cm^2 (red line). The result for the as-deposited sample is also shown (black line). In addition, the Ni contacts were blown out by the femtosecond irradiation when the irradiation fluence exceeded 3.6 J/cm^2. As the fluctuations of the data were less than 1 mA, the tendency of the each data does not change for each measurement. It can be expected that a more systematic investigation of the femtosecond laser irradiation condition will reveal the most suitable irradiation conditions and enable us to form ohmic contacts at lower annealing temperatures.

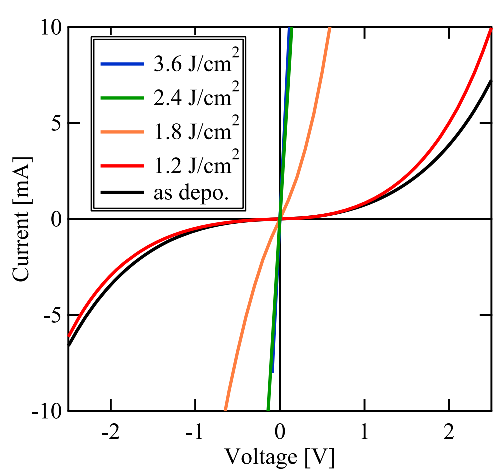

FIG. 3. Fluence dependence of the I-V characteristic of the 900 °C–annealed sample after femtosecond laser irradiation. The results for an irradiation fluence of 3.6 J/cm^2 (blue line), 2.4 J/cm^2 (green line), 1.8 J/cm^2 (orange line), and 1.2 J/cm^2 (red line) are shown. The result for the as-deposited sample is also shown (black line).

Hall measurements on the laser-irradiated sample showed a specific resistance of 1.46×10^{-2} Ω·cm, a carrier density of 1.04×10^{18} cm^{-3}, and a mobility of 410 cm^2/(V·s).[11] However, the values obtained are composed of two components, the conduction path through the laser–modified layer and that through the unmodified SiC underneath the laser–modified layer. In this report, we would like to evaluate the precise values for the laser–modified layer. For this purpose, a two–layer model is employed according to Ref. 12. Equations (1) and (2) give the apparent mobility and the bulk carrier concentration, respectively, for the top layer, the subscripts "l" and "u" denoting the contributions of the laser–modified and the underlying layers, respectively.

$$\mu_u = \frac{\bar{n}\bar{\mu}^2 d + S_q n_l {\mu_l}^2 d_l}{\bar{n}\bar{\mu} d - n_l \mu_l d_l} \tag{1}$$

$$n_u = \frac{1}{d_u} \frac{(\bar{n}\bar{\mu} d - n_l \mu_l d_l)^2}{\bar{n}\bar{\mu}^2 d + S_q n_l {\mu_l}^2 d_l} \tag{2}$$

Here, $\bar{n}$ and $\bar{\mu}$ are the apparent values extracted from the single-carrier single-layer model, d is the total thickness $(d_l + d_u)$, and S_q is the sign of the charge of the carriers of the interfacial layer (+1 for holes and −1 for electrons). n_u and μ_u are the carrier concentration and mobility, respectively, obtained with the 1100 °C annealing without laser irradiation and can be used as fixed parameters that reflect the values for the unmodified layer. The values of n_u and μ_u were 2.25×10^{17} cm^{-3} and 150 cm^2/(V·s), respectively.

By assuming the value of μ_l, the value of n_l can be obtained through Equation (1). The value of n_u is obtained by using μ_l and n_l. Here, we can compare the calculated value of n_u with the one experimentally obtained. By changing the values of μ_l, we can find an appropriate value for μ_l, one for which the calculated and the experimental values coincide, and thus obtain the value of n_l. In this way, we obtained a carrier density (n_l) of 2.73×10^{20} cm^{-3} and a mobility (μ_l) of 432 cm^2/(V·s) for the laser-modified layer. In this estimation, we assumed the thickness of the femtosecond laser–modified layer (d_l) to be 1 µm and d = 300 µm.

To evaluate the contact resistivity, we carried out the TLM measurement. The result is shown in Fig. 4. Linear dependence on the distance between the electrodes can be clearly observed, and the intercept of the ordinate corresponds to twice the contact resistance. The sheet resistance of the ohmic electrode formed by the laser irradiation, as extracted from Fig. 4, is 0.1 Ω/m^2. The contact resistance was 2.95×10^{-3} Ω·cm. From these results, it is revealed that ohmic electrodes with low contact resistivity were successfully fabricated by femtosecond laser irradiation.

In conclusion, thermal annealing with the aid of femtosecond laser irradiation was examined. As in the previous report, the ohmic characteristic was not observed for the 900 °C–annealed sample without femtosecond laser irradiation. In contrast, a clear ohmic characteristic was observed for the 900 °C–annealed samples after femtosecond laser irradiation. The carrier density also increased approximately one order of magnitude after the femtosecond laser irradiation. Finally, a contact

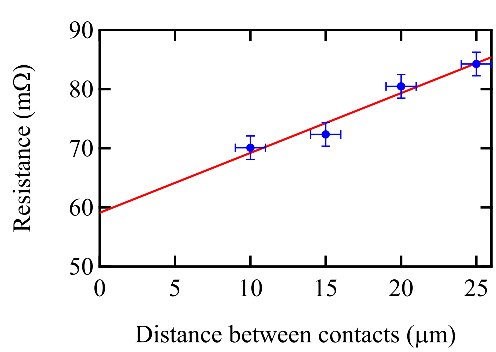

FIG. 4. Evaluation of sheet resistance of the ohmic electrodes by the transmission line model (TLM) method for the femtosecond laser–assisted annealing samples. A linear tendency was observed, and the intercept of the ordinate corresponds to twice the contact resistance.

resistance of 2.95×10^{-3} Ω·cm was obtained for the laser–annealed contact, which can be used for actual devices.

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