Formation of Low Resistance Contacts to p-type 4H-SiC using Al-Film Source Laser Doping

Kento Okamoto[1], Toshifumi Kikuchi[1], Akihiro Ikeda[2], Hiroshi Ikenoue[1] and Tanemasa Asano[1]
[1]Graduate School of Information Science and Electrical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, Japan
[2]Department of Computer and Information Sciences, Sojo University, 4-22-1 Ikeda, Nishi-ku, Kumamoto, Japan
{okamoto@fed., asano@}ed.kyushu-u.ac.jp

Keywords: 4H-SiC, Ohmic Contact, Laser Doping, Specific Contact Resistance, Aluminum, p-type, Ti/Al.

Abstract: Impact of laser doping on the formation of ohmic contacts to 4H-SiC has been investigated. The laser doping was performed by irradiating pulse-width stretched KrF excimer laser to an Al film coated on the surface of 4H-SiC. Doping and contact formation on the carbon face of 4H-SiC were investigated. The doping was carried out while keeping the sample at room temperature. It is found that the laser doping is able to introduce Al up to a concentration as high as 5×10^{21} cm^{-3}. As a result of heavy doping, the contact made of Ti/Al metallization provides the ohmic contact whose specific contact resistance as low as 4.0×10^{-6} Ωcm^2 without additional heat treatment. The specific contact resistance is lower than that reported for ohmic contacts formed by using ion implantation.

1 INTRODUCTION

The electric power consumption is expected to increase significantly, due to the rise of electric vehicles and artificial intelligence. Development of low-loss power devices is, therefore, highly demanded. Although silicon (Si) power devices have been mainstream, they are facing the physical limit of Si. Wide-gap semiconductors such as silicon carbide (SiC) and gallium nitride are attracting great attention for next-generation power devices.

4H-SiC (hexagonal silicon carbide) has the figure of merit due to its superior physical properties such as high breakdown voltage, excellent thermal conductivity, and high saturation drift-velocity of electrons. Therefore, it is regarded as one of the most promising materials of power devices. Processing technology of 4H-SiC devices has been well advanced as they become of practical use. However, the formation of low resistance contacts to 4H-SiC remains as a challenge. Because the bandgap of 4H-SiC is much wider than that of Si, the potential barrier becomes large at the interface between the metal and the semiconductor and, consequently, the carriers (electrons and holes) hardly flows across the interface. On the other hand, devices made of 4H-SiC such as insulated gate bipolar transistors (IGBTs) are expected to carry a much higher current than those made of Si (Usman and Nawaz, 2014). Therefore, very-low resistance contacts are highly demanded.

To reduce the ohmic contact resistance, reduction of the barrier height at the metal/semiconductor interface and/or an increase in doping concentration near the semiconductor surface is needed. Reduction of barrier height suffers from the constraint of metal work function. p-type heavy-doping of 4H-SiC has remained as one which we should develop since the acceptor energy level is extremely large (0.29 eV for B and 0.18 eV for Al) and, therefore, the activation ratio is small. Ion implantation is widely used as the doping method to form a heavily doped layer at the semiconductor surface (Frazzetto *et al.*, 2011). However, it requires high temperature annealing at about 1700ºC to activate the implanted dopant atoms (Ito, Tsukimoto and Murakami, 2006). This high temperature annealing induces undesirable phenomena such as generation of 3C polytype crystal structure and deterioration in yield. Therefore, low-temperature processing is preferred. Low temperature processing is also mandatory to form ohmic contacts to the back side of the wafer where the device active region has fabricated on the front side.

We have shown that a heavily doped layer can be formed by laser irradiation to an Al film deposited on the 4H-SiC surface. A generation of Al plasma during

Okamoto, K., Kikuchi, T., Ikeda, A., Ikenoue, H. and Asano, T.
Formation of Low Resistance Contacts to p-type 4H-SiC using Al-Film Source Laser Doping.
DOI: 10.5220/0007583002940298
In *Proceedings of the 7th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2019)*, pages 294-298
ISBN: 978-989-758-364-3

laser irradiation was observed by using optical emission spectroscopy (Ikeda *et al.*, 2016). We suppose that high temperature molten Al is formed on the 4H-SiC surface by laser irradiation and it acts as the dopant source and also as the heat reservoir.

In this paper, we show that very-low resistance contacts can be formed by using the laser doping with an Al film, which does not require high temperature annealing. The carbon-face (C-face) of 4H-SiC is used in the investigation since this face composes the back side of conventional MOS-gated devices.

2 EXPERIMENTAL

A non-doped semi-insulating 4H-SiC substrate was adopted in order to avoid the wraparound current at the time of measurement. The experimental setup used was schematically shown in Fig. 1. An Al thin film (120 nm thick) was deposited on the C-face of the substrate by DC magnetron sputtering. The Al-coated 4H-SiC chip was chucked with a vacuum pump to a computer-controlled mechanical scanning stage and the KrF excimer laser (wavelength: 248 nm) was irradiated while scanning the stage. The laser irradiation condition was as follows; fluence: 2-4 J/cm^2, number of laser pulses: 1-36 shots, and frequency: 100 Hz. The laser spot size was adjusted with a slit to be ~300 µm in the direction perpendicular to the scanning direction while the slit was open along the scanning direction. The original laser pulse was expanded by using an optical pulse stretcher (OPS) to suppress laser ablation of the surface and to increase the heat retention time by laser irradiation (See Fig. 2) (Ikeda *et al.*, 2017). Ar gas blowing to the sample surface was employed to keep the surface unreacted during irradiation. After the laser irradiation, the Al film remained in the irradiated area as well as the unirradiated area was etched with phosphoric acid. The Al etching was followed by CF_4 plasma and O_2 plasma etchings to remove Si and C based materials produced at the surface by the laser irradiation. The CF_4 plasma etching condition was as follows; the pressure was 30 Pa, the etching time was 10 min, and the discharge power was 100 W. The O_2 plasma etching condition was as follows; the pressure was 100 Pa, the etching time was 5 min, and the discharge power was 400 W. Furthermore, the oxide film at the surface was etched with buffered hydrofluoric acid (BHF, 6%). The above cleaning processes by plasma and BHF were repeated several times. A 100 nm-thick Ti film and a 400 nm-thick Al film were sequentially deposited on the treated surface by using a sputtering system to form a metal contact of Al/Ti/p-SiC structure. The Ti/Al electrode is one of the promising contact metals to p-type SiC (Crofton *et al.*, 2002), (Ito, Tsukimoto and Murakami, 2006). The deposited metal electrode was patterned by using photolithography. The electrode size is 400 × 100 µm. Five sets of test patterns whose electrode spacing was modulated were prepared on a test chip.

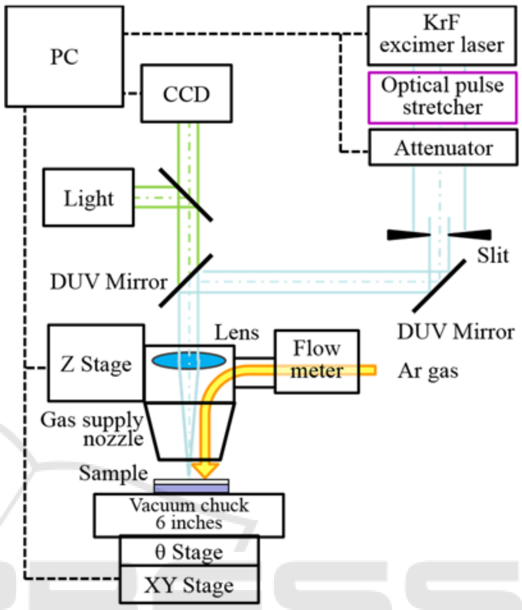

Figure 1: Schematic of the experimental setup.

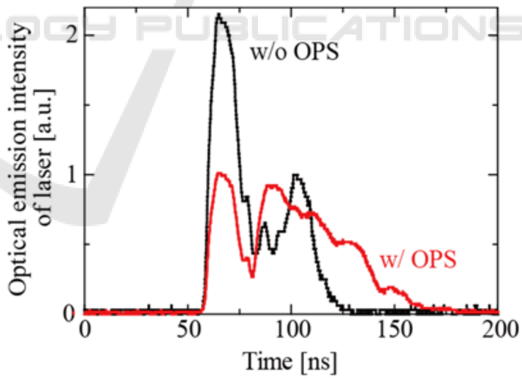

Figure 2: Waveforms of laser pulse intensity produced with and without optical pulse stretcher (OPS).

The sample surface was observed with a scanning electron microscope (SEM). The current-voltage (I-V) characteristic was evaluated by a semiconductor parameter analyzer, Agilent 4156C. The depth profile of aluminum from the doped layer surface was obtained by secondary ion mass spectrometry (SIMS). The specific contact resistance was evaluated by the transfer length method (TLM) based on a transmission line model (Crofton et al., 2002).

3 RESULTS AND DISCUSSION

3.1 Al Doping

Figures 3(a) and 3(b) show the SEM images of the sample surfaces irradiated without and with the Al film, respectively. The laser scanned area of the sample irradiated with the Al film (Fig. 3(b)) shows a brighter contrast than the other areas, while the laser scanned area in the sample without the Al films (Fig. 3(a)) shows a similar brightness to the other areas. Since the potential increase due to p-type formation results in the enhanced emission of secondary electrons in SEM, these results indicate that p-type doping of 4H-SiC can be performed by the laser irradiation to an Al film deposited on the 4H-SiC substrate.

In order to verify the doping of Al, the presence of Al in 4H-SiC and depth distribution were measured by using SIMS. Figure 4 shows the depth profiles of Al concentration obtained by laser doping at 3.4 J/cm^2 with 4 shots. We find that Al as high as 5×10^{21} cm^{-3} in concentration is introduced by the laser doping. In the figure, the depth profile of Al ion-implanted at 40 keV to a dose of 5.0×10^{14} cm^{-2} was also plotted as a reference. The profile of implanted Al well agrees with the theoretical prediction, which indicates that the SIMS measurement gives accurate concentration and profile of Al. We find from a comparison of the two profiles shown in Fig. 4 that the laser doping produces a highly Al-doped layer particularly in the vicinity of the surface.

3.2 Electrical Characteristics

Figure 5 shows the change in I-V characteristic between two electrodes formed on the samples with and without laser irradiation. The gap spacing between the electrodes was about 30 µm. The probe voltage was swept from -2 to 2 V. In the sample without laser irradiation, the current hardly flows. The current value was several pA at the maximum. On the other hand, in the sample with laser irradiation using the Al thin film, current up to several mA flows, which indicates that the resistance markedly decreased in the laser irradiated region. Besides, the I-V curve shows a good linear relation, suggesting that a highly doped p-type layer was formed by the laser doping.

Figure 6 shows the total resistance (R_T) between two electrodes as a function of the spacing length (L) between the two electrodes. R_T was calculated from the slope of the I-V characteristic from which a linear relation was obtained. In order to accurately derive the specific contact resistance, TLM characteristic shown in Fig. 6 was adopted. From the TLM characteristics, an effective transfer length (L_T) and contact resistance (R_C) can be obtained from the x-, y-intercept of straight line approximated from the plot, respectively. L_T corresponds to the distance at which the voltage or current attenuates to $1/e$. The specific contact resistance (ρ_C) is derived by multiplying R_C, L_T, and the width (W) of the doping region:

$$\rho_C = R_C L_T W. \tag{1}$$

From the experimental results, ρ_C is evaluated to be approximately 4.0×10^{-6} Ωcm^2. This value is significantly lower than the value of the contact resistance obtained by the ion implantation method as follows. In case of Ti/Al contacts to p-type 4H-SiC doped to a concentration of $\sim10^{19}$ cm^{-3}, $\rho_C=2\times10^{-3}$-8×10^{-4} Ωcm^2 (Ito, Tsukimoto and Murakami, 2006). In case of Ti/Al/Ni contact to p-type 4H-SiC doped to a concentration of 10^{20} cm^{-3}, $\rho_C=2.3\times10^{-4}$ Ωcm^2 (Vivona *et al.*, 2017). In case of Ni/Al contacts to p-type 4H-SiC doped to a concentration of 10^{19} cm^{-3}, $\rho_C= 3\times10^{-5}$-8×10^{-6} Ωcm^2 (Vang *et al.*, 2006). In addition, high-temperature post-deposition annealing (PDA) at about 1000°C is usually required to form a good ohmic contact on 4H-SiC. The PDA causes chemical reactions between 4H-SiC and the metals at the interface to form silicide and carbide alloys.

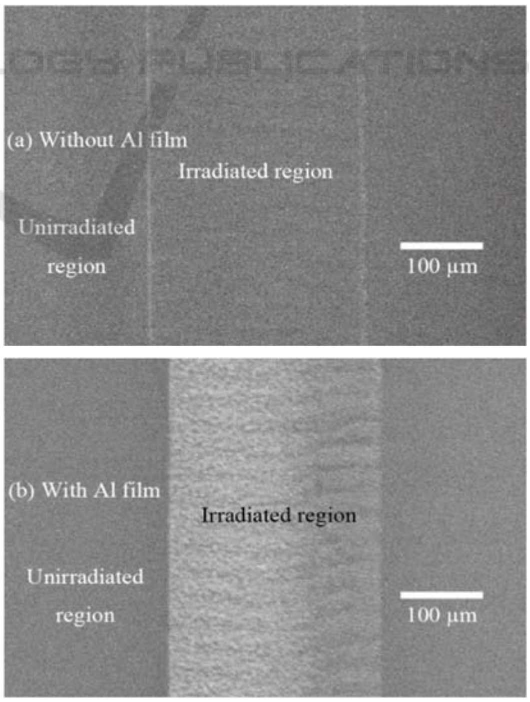

Figure 3: SEM images of the surfaces of SiC samples (a) irradiated without the Al film and (b) irradiated with the Al film.

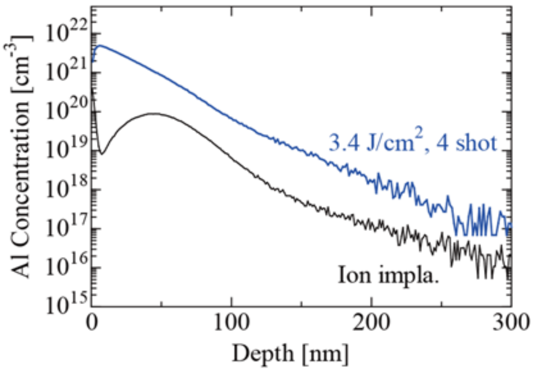

Figure 4: Depth profiles of Al introduced in 4H-SiC by using laser doping and ion implantation.

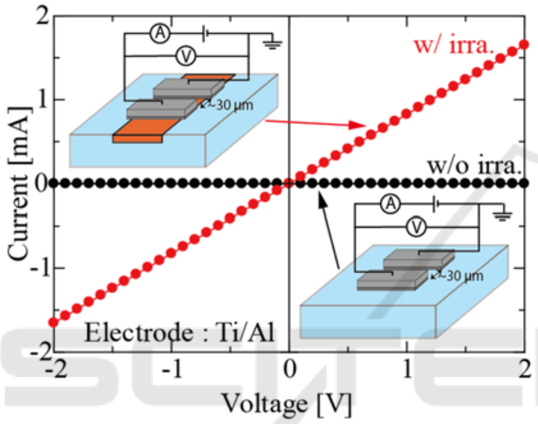

Figure 5: Change in I-V characteristic between the electrodes formed on samples with and without laser irradiation.

3.3 Theoretical Consideration

Specific contact resistance is a function of the potential barrier height at the interface. In addition, it is known that the specific contact resistance strongly depends on the doping concentration and is reduced with the increase of doping concentration. In a contact of very heavily doped semiconductor, the flow of carriers across the interface is dominated by the field emission (FE). That is, for $N_A \geq 10^{19}$ cm^{-3}, ρ_C is dominated by the tunneling process and decrease rapidly with increased doping. Theoretical analysis of FE gives the specific contact resistance described by the following equation: (Sze, 2007)

$$\rho_C = \frac{k}{qA^{**}T} \exp\left(\frac{2\sqrt{\varepsilon_{SiC} m_{lh}^*}}{\hbar} \frac{\varphi_{Bp}}{\sqrt{N_A}} \right) \tag{2}$$

where k is the Boltzmann constant, q is the elementary charge, A^{**} is the effective Richardson constant, T is the absolute temperature, $\boldsymbol{\varepsilon_{SiC}}$ is the permittivity of 4H-SiC (Saito et al., 2004), $\boldsymbol{m_{lh}^*}$ is the effective mass of the light hole (Lindefelt, 1998), φ_{Bp} is barrier height, $\hbar$ is the reduced Planck constant, and N_A is the doping concentration of acceptor.

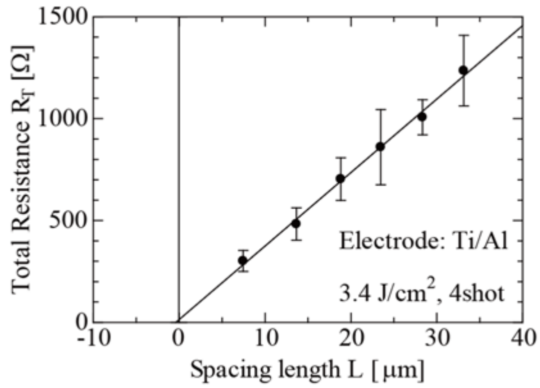

Figure 6: Resistance values of a TLM pattern.

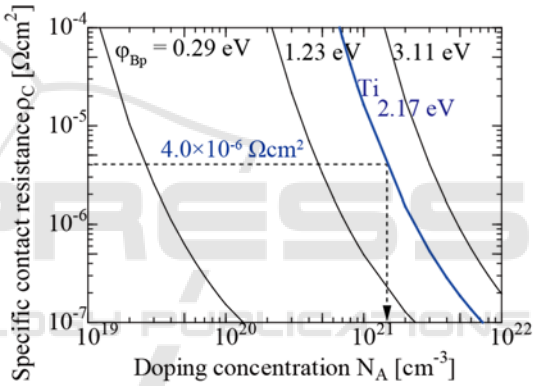

Figure 7: Doping concentration dependence of specific contact resistance calculated for various barrier height.

Figure 7 shows the doping concentration dependence of specific contact resistance calculated from Eq. (2) for various barrier height. The barrier height calculated from the work function of Ti (4.33 eV) (Huang et al., 2012) and the electron affinity of 4H-SiC is 2.17 eV. The specific contact resistance calculated for this value is shown by the solid line in Fig. 7. The theory suggests that doping concentration of about 10^{21} cm^{-3} is required to obtain 4.0×10^{-6} Ωcm^2. This doping concentration agrees with experimental results of SIMS shown in Fig. 4.

4 CONCLUSIONS

We have investigated the formation of low resistance p-type contacts by using laser doping with Al thin film as the source on the C-face of 4H-SiC. Al doping to the concentration as high as 5×10^{21} cm^{-3} can be performed by the irradiation of pulsed excimer laser to the Al film coated 4H-SiC sample kept at room temperature. Owing to the heavy doping, the contact made of Ti/Al metallization provides an ohmic contact whose specific contact resistance as low as 4.0×10^{-6} Ωcm^2 without additional heat treatment. This specific contact resistance is lower than that reported for ohmic contacts formed by using ion implantation. Thus the laser doping with Al thin-film source is a promising candidate to form low resistance ohmic contacts of 4H-SiC power devices.

ACKNOWLEDGEMENTS

This work is supported in part by Grants-in-Aid for Scientific Research, KAKENHI, (No. JP17K06387 and No. JP16H02342) from Japan Society for the Promotion of Science. A part of this work was carried out by using the facility of Department of Gigaphoton Next GLP.

REFERENCES

Crofton, J. et al., 2002. 'Finding the optimum Al–Ti alloy composition for use as an ohmic contact to p-type SiC', *Solid-State Electronics*. Pergamon, 46, pp. 109–113.

Frazzetto, A. et al., 2011. 'Structural and transport properties in alloyed Ti/Al Ohmic contacts formed on p-type Al-implanted 4H-SiC annealed at high temperature', *Journal of Physics D: Applied Physics*, 44.

Huang, L. et al., 2012. 'Low resistance Ti Ohmic contacts to 4H-SiC by reducing barrier heights without high temperature annealing', *Applied Physics Letters*, 100, pp. 1–5.

Ikeda, A. et al., 2017. 'Increased doping depth of Al in wet-chemical laser doping of 4H-SiC by expanding laser pulse', *Materials Science in Semiconductor Processing*. Elsevier Ltd, 70, pp. 193–196.

Ikeda, A. et al., 2016. 'Al doping of 4H-SiC by laser irradiation to coated Al film and its application to junction barrier Schottky diode', *Japanese Journal of Applied Physics*, 55.

Ito, K., Tsukimoto, S. and Murakami, M., 2006. 'Effects of Al ion implantation to 4H-SiC on the specific contact resistance of TiAl-based contact materials', *Science and Technology of Advanced Materials*, 7, pp. 496–501.

Lindefelt, U., 1998. 'Doping-induced band edge displacements and band gap narrowing in 3C–, 4H–, 6H–SiC, and Si', *Journal of Applied Physics*, 84, pp. 2628–2637.

Saito, W. et al., 2004. 'Theoretical limit estimation of lateral wide band-gap semiconductor power-switching device', *Solid-State Electronics*, 48, pp. 1555–1562.

Usman, M. and Nawaz, M., 2014. 'Device design assessment of 4H-SiC n-IGBT - A simulation study', *Solid-State Electronics*. Elsevier Ltd, 92, pp. 5–11.

Vang, H. et al., 2006. 'Ni-Al ohmic contact to p-type 4H-SiC', *Superlattices and Microstructures*, 40, pp. 626–631.

Vivona, M. et al., 2017. 'Electrical and structural properties of surfaces and interfaces in Ti/Al/Ni Ohmic contacts to p-type implanted 4H-SiC', *Applied Surface Science*. Elsevier B.V., 420, pp. 331–335.

Sze, S., 2007. *Physics of Semiconductor Devices*, Jhon Wiley and Sons, Inc., Hoboken, New Jersey, 3rd edition.