Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp213-214

Lateral spreads of Al and P atoms implanted into a high-purity semi-insulating SiC substrate

*Qimin Jin[1], Masashi Nakajima[1], Mitsuaki Kaneko[1] and Tsunenobu Kimoto[1]

[1] Kyoto University, Katsura, Nishikyo, Kyoto, 615-8510, Japan
*E-mail: jin@semicon.kuee.kyoto-u.ac.jp

Abstract

The lateral spreads of Al and P implanted (10 ~ 700 keV) into a high-purity semi-insulating (HPSI) SiC substrate are quantitatively investigated by a threshold-voltage analysis, scanning electron microscope (SEM), and scanning capacitance microscopy (SCM) observations. The lateral spreads are determined to be 0.40 (± 0.05) µm along the $[11\bar{2}0]$ as well as $[1\bar{1}00]$ directions.

1. Introduction

Ion implantation is an essential process to introduce dopants in fabrication of almost all SiC devices. In order to obtain predictable device performances, doped regions formed by ion implantation need to be determined precisely in terms of physical geometries and doping concentration. Practically, implantation profiles change due to the spread of implanted atoms along vertical and lateral directions. However, only a few experimental studies have been reported on the lateral spread of implanted atoms in SiC [1]. In this study, the lateral spreads of Al and P atoms are accurately determined through the channel thickness dependence of threshold voltage in side-gate JFETs [2], SEM, and SCM observations.

2. Experiments

<u>(i) Threshold-voltage analysis:</u> Measured devices are side-gate JFETs as shown in Fig. 1. In a side-gate structure, a gate pn junction is fabricated along the direction orthogonal to ion implantation and therefore, the threshold voltage can be determined by the implantation mask design. Side-gate JFETs were fabricated on a 4°-off-axis high-purity semi-insulating 4H-SiC substrate grown by high-temperature chemical vapor deposition. Al and P ion implantations (10 ~ 700 keV) were performed to form p- and n-regions without samples tilting. Doping concentrations of gate and channel regions are 5×10^{19} cm^{-3}, 1×10^{17} cm^{-3}, respectively. Activation annealing was performed at 1650°C for 10 minutes. Designed channel thickness (a_n) varied from 1.15 µm to 1.5 µm. Gate pn junctions were formed along $[1\bar{1}00]$ or $[11\bar{2}0]$. Figure 2 shows schematic illustrations of gate pn junctions of a side-gate n-JFET. Figure 2 (a) shows pn junctions without the lateral spread, where the channel thickness is equal to the mask opening width a_n. In Fig. 2 (b), the lateral spread of Al atoms in pn junctions ($2\Delta a_\mathrm{n}$) are taken into consideration and therefore, the channel thickness becomes $a_\mathrm{n} - 2\Delta a_\mathrm{n}$.

<u>(ii), (iii) SEM and SCM observations:</u> Figure 3 shows schematic illustrations of a sample for SEM and SCM observations. P ions were implanted into the HPSI substrate without a mask, and subsequently, Al ions were implanted with a SiO_2 mask with a 5-µm-pitch line-and-space pattern. The lateral spread normal to the line opening can be investigated through the line-and-space pattern. Lines were formed along $[1\bar{1}00]$ or $[11\bar{2}0]$ on the same chip. We fabricated this sample under the same condition of doping concentration as the fabrication of side-gate JFETs.

3. Results and Discussion

<u>(i) Threshold-voltage analysis:</u> Lateral spreads of implanted atoms are investigated through threshold voltages of side-gate n- and p-JFETs. When reduction of the channel thickness caused by the lateral spread along one side-gate Δa_n is considered, the following equation can be obtained for n-JFETs [5],

$$\sqrt{\psi_\mathrm{n} - V_\mathrm{th\_n}} = \sqrt{\frac{qN_\mathrm{d}}{8\varepsilon_\mathrm{s}}}(a_\mathrm{n} - 2\Delta a_\mathrm{n}) \quad (1)$$

Where the ψ_n is the built-in potential of the gate p$^+$n junction and $V_\mathrm{th\_n}$ is the threshold voltage of n-JFETs. N_d is the donor concentration in the channel region of n-JFETs. And ε_s is the permittivity of SiC. $V_\mathrm{th\_n}$ and a_n were determined from $I_\mathrm{d} - V_\mathrm{g}$ characteristics of fabricated JFETs and SEM observation, respectively. Then, according to eq. (1) we extracted the lateral spread $2\Delta a_\mathrm{n}$ from the intercept of a $\sqrt{\psi_\mathrm{n} - V_\mathrm{th\_n}}$ - a_n relationship, shown in Figs. 4 (a) and (b). From Fig.4 (a), the lateral spread $2\Delta a_\mathrm{n}$ was determined to be 820 nm along $[11\bar{2}0]$ and 840 nm along $[1\bar{1}00]$ for Al^+ implantation (p-gates in n-JFETs). Similarly, from Fig.4 (b), the lateral spread $2\Delta a_\mathrm{p}$ was determined to be 870 nm along $[11\bar{2}0]$ and 900 nm along $[1\bar{1}00]$ for P^+ implantation (n-gates in p-JFETs).

<u>(ii) SEM observation:</u> Figure 5 shows a SEM image of the line-and-space sample with p$^+$n junctions. In this SEM image, p- and n-regions are observed as bright and dark contrast, respectively. The width of p-region L_p is about 5.4 µm. And a width of mask opening L_mask = 4.5 µm is obtained by recognizing the mask edge, which is shaped by slight over-etching during the formation of an implantation mask. Then, about 0.9 µm of the lateral spread $2\Delta a$ along $[11\bar{2}0]$ was obtained. In a similar way, we also determined the lateral spread along $[1\bar{1}00]$ as 0.9 µm. Almost the same amount of the lateral spread was observed along both the directions.

<u>(iii) SCM observation:</u> Figs. 6 (a) and (b) show cross-sectional SCM images of line-and-space samples with pn junctions along $[11\bar{2}0]$ and $[1\bar{1}00]$, respectively. SCM profiles along white dashed lines in Figs. 6 (a) and (b) are shown in Figs. 7 (a) and (b), respectively. Figs. 7 (a) and (b) show that the maximum width of p-region is 5.4 µm along both the directions. Atomic force microscopy (AFM) profiles of sample's surface are also plotted in Fig. 7. We determined the mask opening width as 4.7 µm using AFM profiles. The lateral spreads $2\Delta a$ along both the directions were determined

to be 0.7 µm by comparing SCM and AFM profiles.

The lateral spreads of Al Δa obtained by different methods are summarized in Table 1. These results show good agreement with each other.

4. Conclusion

The lateral spreads of Al and P atoms in SiC were determined to be 0.40 (± 0.05) µm by three different approaches. These results are important to precisely determine geometries of doped regions, and thereby to design SiC devices.

References

[1] J. Müting et al., Appl. Phys. Lett. **116** (2020) 012101.
[2] M. Nakajima et al., IEEE EDL **40** (2020) 866.
[3] S. M. Sze and K. K. Ng., *Physics of Semiconductor Devices, Third Edition* (2007).

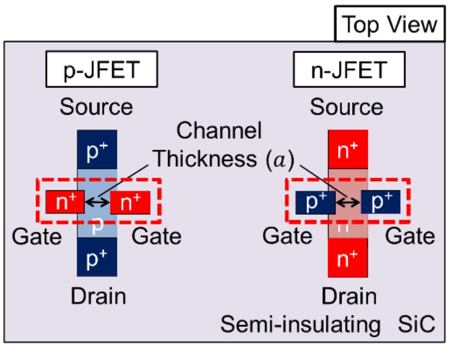

Fig. 1 Schematic illustraion of the side-gate p- and n-JFETs.

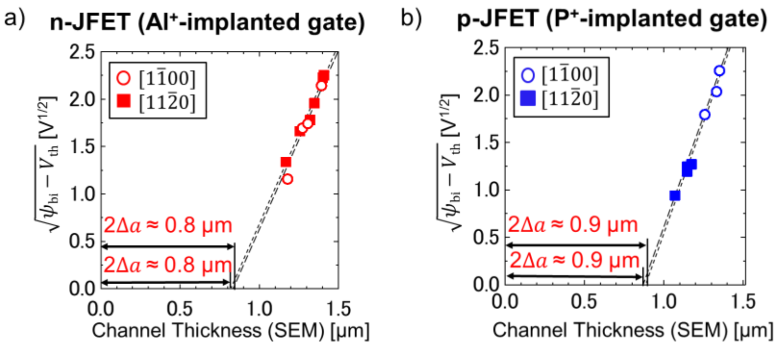

Fig. 4. $\sqrt{\psi - V_{th}} - a$ relationships in fabricated (a) n- and (b) p-JFETs. Threshold voltages were determined from $I_d - V_g$ characteristics of fabricated JFETs. The channel thickness was measured by SEM.

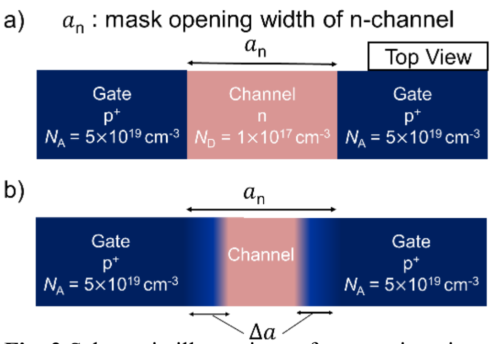

Fig. 2 Schematic illustrations of gate pn junctions (part of a side-gate n-JFET) (a) without and (b) with a lateral spread.

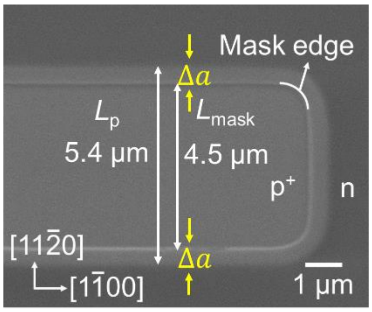

Fig. 5 Plan-view SEM image of a p⁺n junction in a line-and-space sample.

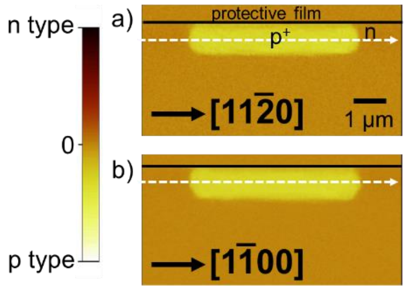

Fig. 6 Cross-sectional SCM images of p⁺n junctions acquired from line-and-space samples. The maximum width of p-region was measured along the white dashed line.

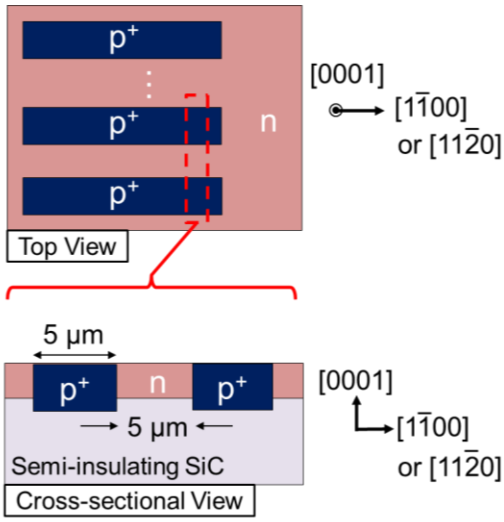

Fig. 3 Schematic illustrations of the line-and-space sample for SEM (plan-view) and SCM (cross-sectional view) observations. A 5-µm-pitch line-and-space pattern is designed.

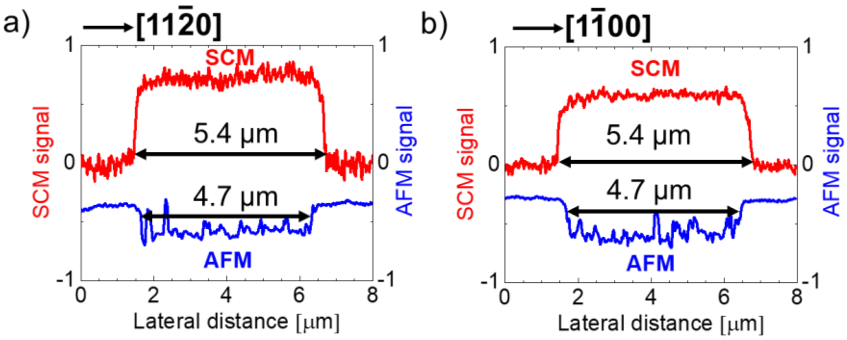

Fig. 7 SCM profiles along white dashed lines in Figs. 6 (a) and (b) and AFM profiles of line-and-space sample's surface along (a) $[11\bar{2}0]$ and (b) $[1\bar{1}00]$.

Table 1 Lateral spreads of Al atoms along $[11\bar{2}0]$ and $[1\bar{1}00]$ investigated through threshold-voltage analysis and SEM, SCM observations.

Lateral spread	Threshold-voltage analysis	SEM observation	SCM observation
$\Delta a_{[11\bar{2}0]}$ [µm]	0.41	0.45	0.35
$\Delta a_{[1\bar{1}00]}$ [µm]	0.42	0.45	0.35