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Estimation of Electron Drift Mobility Along the *c*-Axis in 4H-SiC by Using Vertical Schottky Barrier Diodes

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Abstract. Electron mobility along the *c*-axis is the most important in SiC because the current flows along this direction in vertical SiC devices. However, previous reports on the drift mobility along the *c*-axis are still limited because of the difficulty of sample preparation or analysis. In this study, the authors presented the method to estimate the electron drift mobility of a lightly-doped epitaxial layer by using SiC(0001) vertical Schottky barrier diodes (SBDs). For the analyses, the effects of current spreading and series resistance were carefully considered based on experimental results obtained from SBDs with various device parameters, leading to a more accurate estimation. The mobility along the *c*-axis was obtained as 1070 ± 290 cm^2/Vs for a donor density of 1×10^{15} cm^{-3}, and it was compared with the results by Hall effect measurement.

Introduction

Determination of basic physical properties considering their anisotropy is significant for device fabrication through accurate simulation and optimum designing of devices [1]. In 4H-SiC, mobility has anisotropy [2-7], and that along the *c*-axis ($\mu_{//}$) is the most important because current flows along this direction in typical SiC(0001) vertical devices. However, the determination of the vertical mobility ($\mu_{//}$ in SiC) is not easy in general because the mobility along this direction cannot be obtained through Hall effect measurement in principle, which is the most major method to measure the mobility. This is an inevitable problem caused by the situation where the direction of the current flow for Hall effect measurement (in-plane direction) is different from that for power device operation (vertical direction). There are two possible approaches to determine the vertical mobility:

(i) Hall effect measurement on SiC($11\bar{2}0$) or ($1\bar{1}00$) samples [6]

(ii) Other method than conventional Hall effect measurement on SiC(0001) samples

With the method (i), we can obtain $\mu_{//}$ directly because these faces include the *c*-axis in their in-plane direction while the sample preparation is difficult because the commercially available wafers are exclusively limited to SiC(0001). In addition, there is another problem that we cannot eliminate the effect of Hall scattering factor γ_{H} with this method, which leads to inaccurate determination of the mobility. On the other hand, we can obtain the vertical mobility using available (0001) samples by the methods (ii) without the effect of γ_{H}. However, there is no established method to determine the vertical mobility accurately. While some papers have reported the vertical mobility obtained by using vertical Schottky barrier diodes [8-11], there remain a few problems in the analyses such as neglecting the current spreading and the contribution of series resistance components. Then, the authors attempted to improve this method and to determine the vertical mobility with the analyses using SiC(0001) vertical Schottky barrier diodes with various device parameters. From their electrical characteristics, the mobility of a lightly-doped epitaxial layer was estimated by separating the series resistance components and considering the current spreading inside the SiC drift layer. Finally, the authors obtained the vertical mobility and discussed the accuracy of the present method compared with other ones.

Sample Preparation and Measurement

A 4H-SiC(0001) substrate with an n-type epilayer ($N_D = 1 \times 10^{15}$ cm^{-3}) was prepared, and the thicknesses of epilayer and substrate (d_{epi} and d_{sub}) were varied by polishing as summarized in Table I. After forming an ohmic contact on the bottom side with Ni (100 nm) followed by annealing (950°C, 2 min, vacuum), Au (150 nm)/Al (310 nm)/Ni (130 nm)/SiC SBDs (the radius of Schottky contact r = 100-300 μm) were fabricated on the top side of these samples as illustrated in Fig. 1(a). Here, the Al and Au metals were deposited for ensuring the current uniformity at the Ni/SiC Schottky interface, where the electrodes were thick enough and Ni Schottky contacts were protected from oxidation. To improve the accuracy, the authors prepared SBDs with various device parameters (r ,d_{epi}, and d_{sub}) and performed current-voltage ($I-V$) and capacitance-voltage ($C-V$) measurements for each device. The electron density (n) was obtained from the net donor density determined by $C-V$ measurement, while the resistivity (ρ) was extracted from the series resistance R determined by $I-V$ measurement. Finally, the mobility μ was determined from n and ρ with the relationship of $\mu = 1/en\rho$. The detailed procedures are explained in the next section.

Table I. Thicknesses of epitaxial layers and substrates (d_{epi} and d_{sub}) of samples, which were varied by polishing the surface (epi.) and the bottom (sub.).

Sample	Thickness [μm]	
	epi.	sub.
S-1	45	370
S-2	35	370
S-3	22	370
S-4	15	370
S-5	5	370
S-6	15	300
S-7	15	220

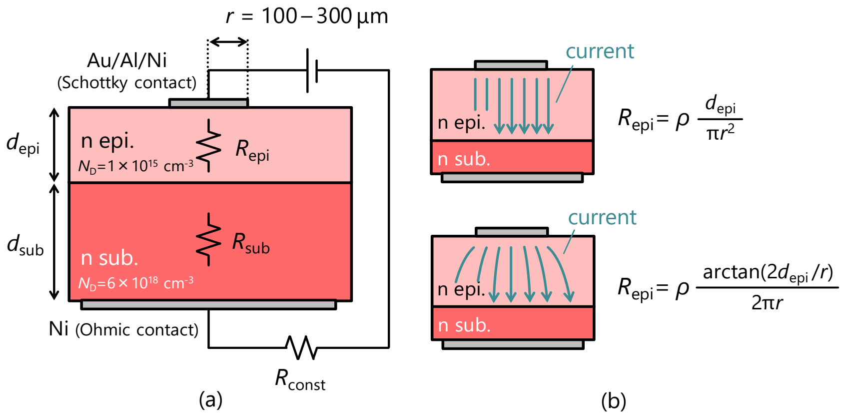

Fig. 1. (a) Cross-sectional diagram of a Ni/SiC Schottky barrier diode and the definition of the components of the series resistance. (b) Schematic illustration of the current flow in a vertical SBD without and with considering the current spreading in the epilayer.

Approach and Data Analyses

(i) Determination of electron density n

Since the donor density of the n-type epilayer is low enough, the ionization ratio of N donors is estimated to be higher than 99%. Therefore, n can be determined from the net donor density $N_D - N_A$, which can be obtained from the $C-V$ measurement on SBDs. The authors performed $C-V$ measurement on the SBDs with different d_{epi} to measure $N_D - N_A$ over a wide depth range. The depth profile of $N_D - N_A$ obtained from the sample S-1 (d_{epi} = 45 μm) is shown in Fig. 2(a) as an example, and the summarized results from various devices are depicted in Fig. 2(b). $N_D - N_A$ was found to be uniform along the depth direction over the whole region of the epilayer, and by averaging these results, n was determined as $n \cong N_D - N_A \cong 9.7 \times 10^{14}$ cm^{-3}.

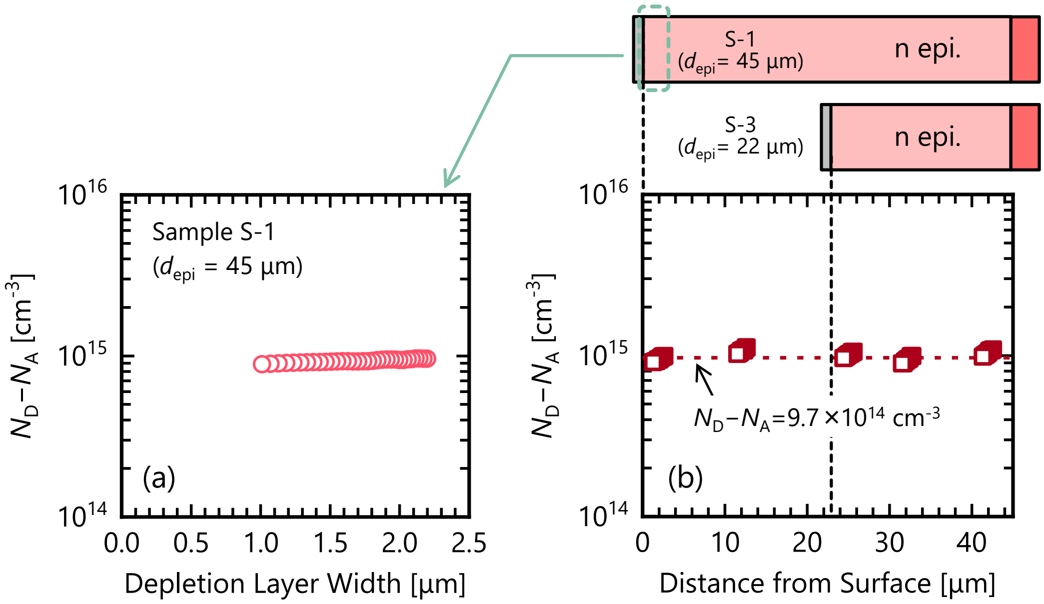

Fig. 2. (a) Depth profile of the net donor density $N_D - N_A$ determined by C–V measurement on a Ni/SiC SBD (d_{epi} = 45 μm, r = 300 μm), and (b) that from the epilayer surface obtained from the SBDs with different d_{epi} (obtained by sequential polishing and C–V measurement).

(ii) Determination of resistivity ρ

The series resistance R was obtained from the forward I–V characteristics for SBDs with various device parameters as shown in Fig. 3. Here, the easiest way to derive the resistivity ρ from the series resistance R is expressed below,

$$R = \rho \frac{d_{epi}}{\pi r^2}, \quad (1)$$

where it is assumed that R is equal to the resistance of the cylindrical region (radius: r and height: d_{epi}) of the epilayer. However, there are two problems with the analysis using Eq. (1). One is that the resistance R should be the total resistance of the epilayer, substrate, probe, and measuring system and they should be separated for an accurate analysis. The other problem is that the current flows with spreading in the epilayer actually while Eq. (1) means the current flows only along the vertical direction without spreading. Here, when considering both the components of series resistance other than the resistance of epilayer R_{epi} and the current spreading, R is expressed by the following equation [12].

$$R = R_{epi}(r, d_{epi}) + R_{sub}(r) + R_{const} = \rho \frac{\arctan(2d_{epi}/r)}{2\pi r} + R_{sub}(r) + R_{const}, \quad (2)$$

where R_{sub} is the substrate resistance and is assumed to be dependent only on r for simplicity, and R_{const} includes the resistance of measuring system and probing, which is independent of r and d_{epi}.

R_{sub} was extracted using SBDs with different d_{sub}. Fig. 4(a) shows the series resistance of SBD (r = 300 μm) as a function of d_{sub}, and R_{sub} was extracted from the linear approximation of the plot. The obtained R_{sub} for various r is summarized in Fig. 4(b). Next, a fitting based on Eq. (2) was performed using $R - R_{sub}$, as shown in Fig. 5, by using ρ and R_{const} as fitting parameters. As a result, these parameters were obtained as $\rho \cong 6.1$ Ωcm and $R_{const} \cong 8.4$ Ω. The fitting results for $R - R_{sub}$ vs. r relationship are depicted by the dashed lines in Fig. 5, which reproduce the experimental results well.

Mobility Extraction and Discussion

The validity of the method to analyze ρ used in this study is discussed in Fig. 6, where ρ obtained by three methods are compared, (a) ignoring both R_{sub} and current spreading, (b) considering R_{sub} and ignoring current spreading, and (c) considering both R_{sub} and current spreading. As can be seen, the result of (c) is more independent of r and d_{epi}, which means the method (c) used in this study is more valid compared with others.

Finally, $\mu_{//}$ was determined from the obtained n and ρ to be $\mu_{//} \cong 1070\ cm^2/Vs$ as depicted in Fig. 7, where $\mu_{//}$ obtained by Hall effect measurement [7] is also plotted. Although $\mu_{//}$ obtained in this study still exhibits a large uncertainty, the average value is close to the Hall mobility. The reason why $\mu_{//}$ in this study is a little lower than the Hall mobility is presumed to be the Hall scattering factor ($\gamma_H > 1$), by which the Hall mobility is slightly overestimated in comparison with the drift mobility.

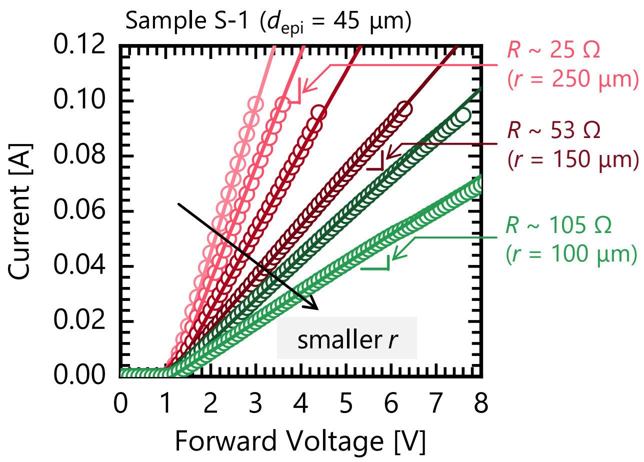

Fig. 3. Forward I–V characteristics of Ni/SiC SBDs with various r (d_{epi} = 45 μm).

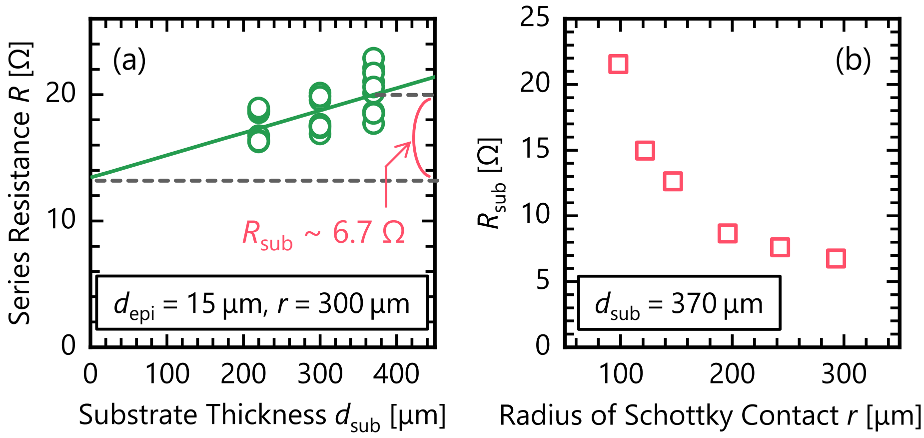

Fig. 4. (a) Series resistance of SBD (r = 300 μm) as a function of d_{sub}, where the substrate resistance R_{sub} is extracted based on linear approximation. (b) R_{sub} (d_{sub} = 370 μm) estimated for SBDs with different r.

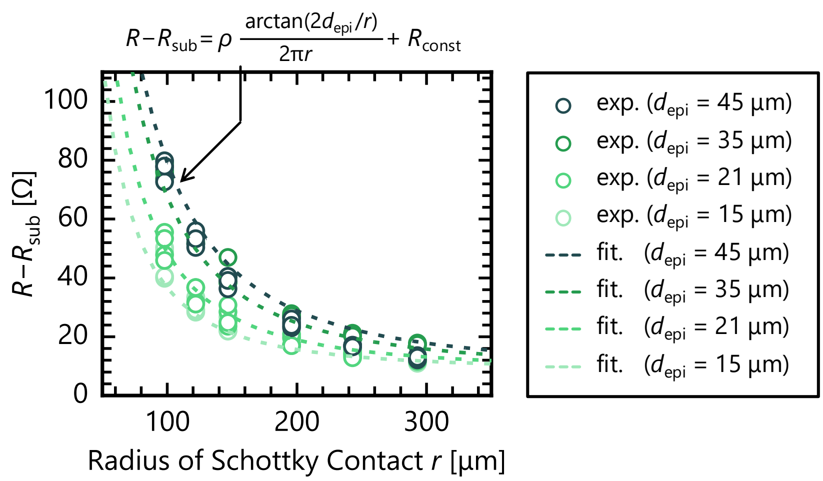

Fig. 5. $R - R_{sub}$ as a function of r obtained from SBDs with various d_{epi}. Dashed lines show the fitting results based on Eq. (2), where the fitting parameters were obtained as $\rho \cong 6.1$ Ωcm and $R_{const} \cong 8.4$ Ω.

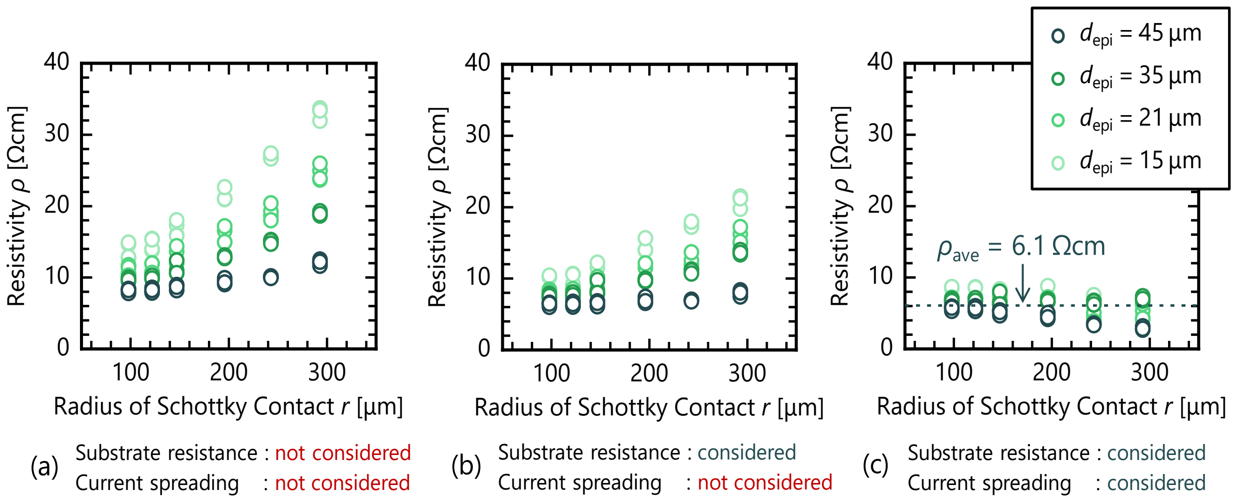

Fig. 6. Resistivity ρ of the epilayer as a function of r obtained by three different analyses, (a) ignoring both R_{sub} and current spreading, (b) considering R_{sub} and ignoring current spreading, and (c) considering both R_{sub} and the current spreading.

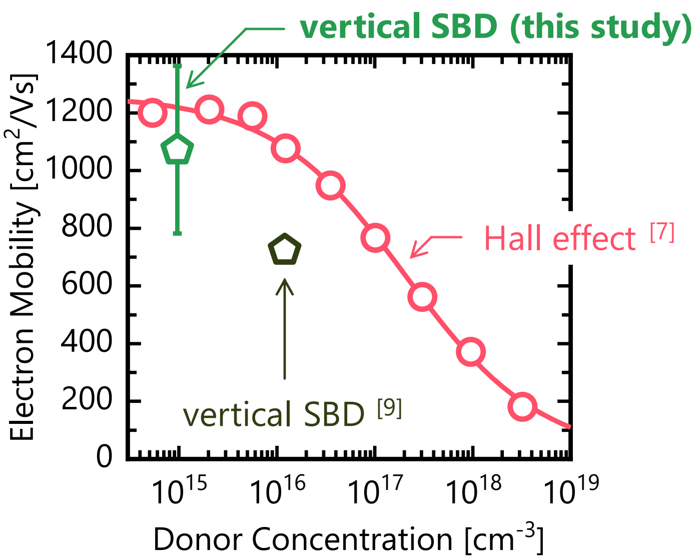

Fig. 7. Comparison between the electron mobility obtained by the present approach using vertical SBDs with that by Hall effect measurement [7]. The error bar indicates the standard deviation.

Summary

The authors presented an approach to estimate the drift mobility of electrons along the *c*-axis ($\mu_{//}$) from $C-V$ and $I-V$ characteristics of vertical SiC(0001) SBDs with various sizes of Schottky contact, epilayer thickness, and substrate thickness. The precision of analysis was improved by separating the series resistance components and considering the current spreading. As a result, $\mu_{//}$ was obtained as 1070 cm^2/Vs for $N_D \cong 9.7 \times 10^{14}$ cm^{-3}. The present approach is effective to estimate the vertical mobility, also for other anisotropic materials.

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