Corrigendum: “Sign of Hall coefficient in nearest-neighbor hopping conduction in heavily Al-doped p-type 4H-SiC” [Jpn. J. Appl. Phys. 59, 051004 (2020)]

Hideharu Matsuura1*, Akinobu Takeshita1, Atsuki Hidaka1, Shiyang Ji2, Kazuma Eto2, Takeshi Mitani2*, Kazutoshi Kojima2, Tomohisa Kato2*, Sadafumi Yoshida2, and Hajime Okumura2

1Department of Electrical and Electronic Engineering, Osaka Electro-Communication University, Osaka 572-8530, Japan
2National Institute of Advanced Industrial Science and Technology, Ibaraki 305-8568, Japan
*E-mail: matsuura@osakac.ac.jp

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In Figs. 1 and 4, the experimental Hall coefficients \([R_H(T)]\) were plotted in m\(^3\)/C, not in cm\(^3\)/C of the vertical axis. In the corrected figures, the experimental \(R_H(T)\) are plotted in cm\(^3\)/C.

![Fig. 1](image1)

**Fig. 1.** \(R_H(T)\) for the 4H-SiC epilayer grown by CVD with \(C_{Al}\) of \(3.4 \times 10^{19}\) cm\(^{-3}\).

![Fig. 4](image2)

**Fig. 4.** (Color online) Arrhenius plots of \(\rho(T)\) and \(R_H(T)\) for the 4H-SiC epilayer grown by CVD with \(C_{Al}\) of \(3.4 \times 10^{19}\) cm\(^{-3}\). Broken and solid lines indicate band and NNH conduction, respectively.

**ORCID iDs**

Hideharu Matsuura https://orcid.org/0000-0001-7190-286X

Takeshi Mitani https://orcid.org/0000-0002-4228-1707

Tomohisa Kato https://orcid.org/0000-0002-9422-6670

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Sign of Hall coefficient in nearest-neighbor hopping conduction in heavily Al-doped p-type 4H-SiC

Hideharu Matsuura1, Akinobu Takeshita1, Atsuki Hidaka1, Shiyang Ji2, Kazuma Eto2, Takeshi Mitani2, Kazutoshi Kojima3, Tomohisa Kato3, Sadafumi Yoshida3, and Hajime Okumura2

1Department of Electronic and Electrical Engineering, Osaka Electro-Communication University, Osaka 572-8530, Japan
2National Institute of Advanced Industrial Science and Technology, Ibaraki 305-8568, Japan
3University of Tokyo, Tokyo 113-8656, Japan

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We have observed negative Hall coefficients [R_H(T)] in a nearest-neighbor hopping (NNH) conduction region in epilayers of heavily Al-doped or Al–N co-doped p-type 4H-SiC grown on n-type 4H-SiC substrates by CVD or in wafers of heavily Al–N co-doped p-type 4H-SiC fabricated by solution growth. We propose a simple physical model to explain the sign of R_H(T) in NNH conduction. According to this model, R_H(T) becomes positive when the Fermi level (E_F) is higher than the Al acceptor level (E_A), that is, the Fermi–Dirac distribution function f(E_F) is greater than 0.5, whereas R_H(T) becomes negative when E_F is lower than E_A, which occurs at low temperatures. Because the dominant conduction mechanism in heavily Al-doped or Al–N co-doped p-type 4H-SiC with Al concentrations on the order of 10^19 cm^-3 is band and NNH conduction at high and low temperatures, respectively, the proposed model can explain why R_H(T) becomes negative at low temperatures.

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1. Introduction

The on-resistance of SiC n-channel insulated-gate bipolar transistors (IGBTs) is considerably lower than that of commercial Si power devices such as Si MOSFETs or IGBTs, which enables the fabrication of SiC power modules with lower on-resistance at high temperatures. The on-resistance of SiC n-channel IGBTs is considerably lower than that of commercial Si power devices such as Si MOSFETs or IGBTs, which enables the fabrication of SiC power modules with lower on-resistance at high temperatures.

Al-doped or Al co-doped 4H-SiC grown on n-type 4H-SiC substrates by chemical vapor deposition (CVD) is considerably lower than that of commercial Si power devices such as Si MOSFETs or IGBTs, which enables the fabrication of SiC power modules with lower on-resistance at high temperatures. The on-resistance of SiC n-channel IGBTs is considerably lower than that of commercial Si power devices such as Si MOSFETs or IGBTs, which enables the fabrication of SiC power modules with lower on-resistance at high temperatures.

2. Experimental

A 90 µm thick Al-doped 4H-SiC epilayer and a 7.95 µm thick Al-N co-doped 4H-SiC epilayer were grown using a horizontal hot-wall CVD system (VP508 GFR, Aixtron) at between 2.4 × 10^19 and 1.8 × 10^20 cm^-3, grown on n-type 4H-SiC substrates by chemical vapor deposition (CVD). We found that R_H(T) becomes negative not only in the hopping conduction region, but also in the band conduction region, in contrast to the results of Krieger et al. on 6H-SiC.8 Krieger et al.8 considered that negative R_H(T) in NNH conduction might be explained by the models for amorphous semiconductors proposed by Emin18 and Grunewald et al.19 However, Street insisted that the models can be applied to narrow-bandgap materials or materials in which the mobility edge is at the center of the band; however, the conduction in hydrogenated amorphous silicon (a-Si:H) is near the band edge.20 Sign reversal of R_H(T) is observed in a-Si:H, but the correct sign is found in microcrystalline silicon in which the grain size is as small as 3–5 nm.20 These findings suggest that their models cannot be applied to Al-doped p-type SiC. The Hall effect for hopping conduction has been theoretically considered by Holstein, Németh and Mühlchschlegel, and Galperin et al. An impurity Hubbard-band model can be used to describe the complicated behavior of R_H(T) in group-IV elemental semiconductors of p-type Ge, n-type Ge, and n-type Si, as well as in III–V compound semiconductors of n-type GaAs and n-type InP. However, the Hall effect for hopping conduction is not yet well understood and the sign inversion of R_H(T) has been observed in heavily Al-doped p-type SiC at low temperatures, which might arise from a deep Al acceptor level (E_A). In this study, we propose a simple physical model to explain negative R_H(T) in the NNH conduction region at low temperatures in p-type SiC.
approximately 1620 °C on (0001)-oriented 3 inch n-type 4H-
SiC substrates (8° off-orientation toward [1120]). The depletion layer formed by the pn junction electrically isolates the p-type 4H-SiC epilayer from the n-type 4H-SiC substrate, thus enabling measurement of the electrical properties of the heavily Al-doped or Al-N co-doped epilayer. Thick Al-N co-doped 4H-SiC bulk was grown on an on-axis (0001)-oriented 18 mm diameter 4H-SiC substrate at a seed crystal temperature of approximately 2020 °C under a He-N2 atmosphere by solution growth (SG). A 368 μm thick wafer was obtained by slicing the bulk. Because this wafer was free-standing p-type 4H-SiC, we could measure its electrical properties. Four Al/Ti/Al contact dots in the van der Pauw configuration were deposited on the four corners of the 5 × 5 mm samples by electron beam evaporation of Al and Ti, and the samples were annealed at 1000 °C under a N2 atmosphere. The Al-doped sample grown by CVD was obtained with CAl of \(3.4 \times 10^{19}\) cm\(^{-3}\). The CAl and N concentration (CN) values of the Al–N co-doped sample grown by CVD were \(3.9 \times 10^{19}\) and \(8.8 \times 10^{18}\) cm\(^{-3}\), respectively. Here, the values of CAl and CN were determined by secondary-ion mass spectrometry. Using a Hall-effect measurement system (ResiTest8400, TOYO Corporation), the \(\rho(T)\) values of the samples were measured under an AC magnetic field of 0.35 T and 0.05–0.25 Hz, in the temperature range of 60–300 K. The techniques used to obtain reliable \(\rho(T)\) and \(R_H(T)\) values have been described in our previous papers. 

3. Results and discussion

Figure 1 shows \(R_H(T)\) for the Al-doped 4H-SiC epilayer grown on the n-type 4H-SiC substrate by CVD with CAl of \(3.4 \times 10^{19}\) cm\(^{-3}\). The \(R_H(T)\) values at \(< 95\) K are negative, whereas the values at \(> 95\) K are positive but small. The temperature at which the sign of \(R_H(T)\) changes is referred to as \(T_{\text{inv}}\). The peak of positive \(R_H(T)\) is at approximately 110 K. Figure 2 shows \(R_H(T)\) for the Al–N co-doped 4H-SiC epilayer grown on the n-type 4H-SiC substrate by CVD with CAl and CN values of \(3.9 \times 10^{19}\) and \(8.8 \times 10^{18}\) cm\(^{-3}\), respectively. The value of \(T_{\text{inv}}\) is 135 K, and the peak for positive \(R_H(T)\) is at \(~200\) K. Figure 3 shows \(R_H(T)\) for the Al–N co-doped 4H-SiC wafer grown by SG with CAl and CN values of \(6.7 \times 10^{19}\) and \(8.8 \times 10^{18}\) cm\(^{-3}\), respectively. The value of \(T_{\text{inv}}\) is 167 K, and the peak for positive \(R_H(T)\) is at \(~230\) K.

We observed the negative \(R_H(T)\) values at low temperatures for the Al-doped and Al–N co-doped p-type 4H-SiC epilayers grown on n-type 4H-SiC substrates by CVD as well as for the Al–N co-doped p-type 4H-SiC wafer fabricated by SG, indicating that the appearance of negative \(R_H(T)\) in p-type 4H-SiC, which were also reported in our early papers, originated from p-type 4H-SiC epilayers, not from n-type 4H-SiC substrates, and was independent of N co-doping. Consequently, we could confirm that the depletion layer formed by the pn junction electrically isolated the p-type 4H-SiC epilayer from the n-type 4H-SiC substrate.
Figures 4–6 show Arrhenius plots of $\rho(T)$ and $R_H(T)$ for the 4H-SiC epilayer grown by CVD with $C_{Al} = 3.4 \times 10^{19} \text{ cm}^{-3}$. Broken and solid lines indicate band and NNH conduction, respectively.

Fig. 4. (Color online) Arrhenius plots of $\rho(T)$ and $R_H(T)$ for the 4H-SiC epilayer grown by CVD with $C_{Al} = 3.4 \times 10^{19} \text{ cm}^{-3}$. Broken and solid lines indicate band and NNH conduction, respectively.

The data in $\ln \rho(T) = 1/T$ is approximated by two straight lines (shown as broken and solid lines). The temperature at which the two straight lines cross is referred to as $T_{BH}$.

The common conduction mechanisms in semiconductors include band conduction, NNH conduction, and VRH conduction. Because the currents due to band, NNH, and VRH conduction flow completely in parallel in the valence band, at $E_{Al}$, and around the Fermi level ($E_F$), respectively, $\rho(T)$ can be expressed as

$$\rho(T) = \rho_{Band}(T) + \rho_{NNH}(T) + \rho_{VRH}(T).$$

(1)

$$\rho_{Band}(T) = \rho_{Band0} \exp \left( \frac{\Delta E_{Band}}{k_B T} \right),$$

(2)

$$\rho_{NNH}(T) = \rho_{NNH0} \exp \left( \frac{\Delta E_{NNH}}{k_B T} \right),$$

(3)

and

$$\rho_{VRH}(T) = \rho_{VRH0} \exp \left( \left[ \frac{T}{T_0} \right]^{1/4} \right),$$

(4)

where $\rho_{Band}(T)$, $\rho_{NNH}(T)$, and $\rho_{VRH}(T)$ are $\rho(T)$ for band, NNH, and VRH conduction, respectively; $\rho_{Band0}$, $\rho_{NNH0}$, and $\rho_{VRH0}$ are the pre-exponential factors for band, NNH, and VRH conduction, respectively; $\Delta E_{Band}$ and $\Delta E_{NNH}$ are the activation energies for band and NNH conduction, respectively; $T_0$ is a constant for VRH conduction; and $k_B$ is the Boltzmann constant. From Eq. (1), at a given $T$, the conduction mechanism with the lowest resistivity becomes dominant. In Figs. 4–6, the dominant conduction mechanisms at high and low temperatures are band and NNH conduction, denoted by broken and solid straight lines, respectively.

According to the multiple parallel conduction model, the Hall coefficient is expressed as

$$R_H(T) = \left[ \frac{\rho(T)}{\rho_{Band}(T)} \right]^2 R_{HBand}(T) + \left[ \frac{\rho(T)}{\rho_{NNH}(T)} \right]^2 R_{HNNH}(T) + \left[ \frac{\rho(T)}{\rho_{VRH}(T)} \right]^2 R_{HVRH}(T),$$

(5)

where $R_{HBand}(T)$, $R_{HNNH}(T)$, and $R_{HVRH}(T)$ are the Hall coefficients corresponding to band, NNH, and VRH conduction, respectively. Because the density of localized states
around $E_F$ is low owing to the high crystalline quality of the epilayers with $C_{Al}$ values of $<2 \times 10^{20} \text{cm}^{-3}$, $\rho_{\text{VRH}}(T)$ is much higher than $\rho_{\text{Band}}(T)$ and $\rho_{\text{NNH}}(T)$, which is consistent with the plots of $\ln \rho(T) = -1/T$ in Figs. 4–6. This indicates that $\rho(T)/\rho_{\text{VRH}}(T)$ in Eq. (5) is negligibly small in these samples. Consequently:

$$R_H(T) = \left[ \frac{\rho(T)}{\rho_{\text{Band}}(T)} \right]^2 R_{\text{Band}}(T) + \left[ \frac{\rho(T)}{\rho_{\text{NNH}}(T)} \right]^2 R_{\text{NNH}}(T).$$

(6)

$R_H(T)$ in Figs. 4–6 reached a peak around $T_{BH}$ and became negative in the NNH conduction region, which can be explained using Eq. (6) if $R_{\text{NNH}}(T)$ is negative. Therefore, we propose and discuss a simple physical model to explain why $R_{\text{NNH}}(T)$ becomes negative at low temperatures.

Figure 7(a) shows an energy band diagram of the hopping of charged carriers (a hole and an electron) at Al acceptor sites in NNH conduction. The current in NNH conduction ($I_{\text{NNH}}$) can be explained not only by the hopping of holes from neutral Al acceptor (Al$^0$) sites to their nearest-neighbor negatively ionized Al acceptor (Al$^-$) sites, but also by the hopping of electrons from Al$^-$ sites to their nearest-neighbor Al$^0$ sites. In other words, $I_{\text{NNH}}$ is proportional to the product of the hole concentration at $E_{Al}$ (i.e. $N_{Al}[1 - f(E_{Al})]$) and the unoccupied probability of holes at their nearest-neighbor Al acceptor sites [i.e. $f(E_{Al})$], or the product of the electron concentration at $E_{Al}$ [i.e. $N_{Al}f(E_{Al})$] and the unoccupied probability of electrons at their nearest-neighbor Al acceptor sites [i.e. $1 - f(E_{Al})$], where $N_{Al}$ is the density of Al acceptors bound to four carbon atoms out of the doped Al atoms and $f(E_{Al})$ is the Fermi–Dirac distribution (i.e. electron occupation probability) at $E_{Al}$. In contrast, $I_{\text{NNH}}$ is inversely proportional to $\rho_{\text{NNH}}(T)$. Therefore, $I_{\text{NNH}}$ is expressed as

$$I_{\text{NNH}} \propto N_{Al} f(E_{Al})[1 - f(E_{Al})] \propto \frac{1}{\rho_{\text{NNH}}(T)}.$$

(7)

Thus, for a force produced by an electric field, it is difficult to distinguish the contribution of holes to $I_{\text{NNH}}$ from the contribution of electrons to $I_{\text{NNH}}$.

The inset in Fig. 7(b) shows the direction of the Lorentz force ($F$) for moving charged carriers in the case of a left-to-right flowing current ($I$) and a magnetic flux density ($B$) directed toward the back of the plane. The Hall effect for hopping conduction is not well understood. Therefore, assuming that hopping holes and electrons in $I_{\text{NNH}}$ are forced into the same direction as the Lorentz force, Fig. 7(b) shows the direction of movement of a hole and an electron in NNH conduction with $B$ directed toward the back of the plane described in a real space. In $I_{\text{NNH}}$, holes as well as electrons are forced to the upper direction under $B$. Therefore, $B$ makes flowing holes hop to upper nearest-neighbor Al$^-$ sites and makes flowing electrons hop to upper nearest-neighbor Al$^0$ sites, indicating that holes and electrons travel in the same direction. For a force produced by a magnetic field, it is possible to distinguish the contribution of holes to the Hall voltage [$V_{\text{NNH}}(T)$] produced by $I_{\text{NNH}}$, from the contribution of electrons to $V_{\text{NNH}}(T)$.

Figure 8(a) shows the van der Pauw configuration of the Hall-effect measurement system, where $W$ is the thickness of the sample, and four electrodes (Electrodes 1–4) are positioned at the four corners of the sample. $I_{\text{NNH}}$ flows from Electrode 1 to Electrode 3, and $V_{\text{NNH}}(T)$ is measured between Electrodes 2 and 4. Analogous to the Hall voltage for band conduction in the van der Pauw configuration, $V_{\text{NNH}}(T)$ is described as

$$V_{\text{NNH}}(T) = R_{\text{NNH}}(T)I_{\text{NNH}}B/W.$$

(8)

Figure 8(b) shows the equivalent circuit for the measured $V_{\text{NNH}}(T)$, where $V_{\text{HN}}(T)$ and $V_{\text{HL}}(T)$ are the Hall voltages due to holes and electrons, respectively, and $r_{\text{NNH}}(T)$ is the resistance between Electrodes 2 and 4 due to NNH conduction, and is described as

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**Fig. 7.** (Color online) Schematics of NNH conduction. (a) Energy band diagram of NNH conduction (hopping of a hole from a Al$^0$ site to its nearest-neighbor Al$^-$ site or hopping of an electron from a Al$^-$ site to its nearest-neighbor Al$^0$ site by an electric field) and (b) hopping of a hole or an electron under a magnetic field directed toward the back of the plane described in a real space. The inset shows the direction of the Lorentz force ($F$) for left-to-right flowing current ($I$) and magnetic flux density ($B$) directed toward the back of the plane.

**Fig. 8.** (Color online) (a) Schematic van der Pauw configuration of the Hall-effect measurement system and (b) equivalent circuit for the Hall voltage produced by $I_{\text{NNH}}$ and $B$. 
\[
{r}_{\text{NNH}}(T) \propto {\rho}_{\text{NNH}}(T) \\
\propto \frac{1}{N_{\text{Al}} f(E_{\text{Al}})[1 - f(E_{\text{Al}})],}
\]
according to Eq. (7).

Assuming that \(I_{\text{NNH}}\) consists entirely of holes or electrons, the Hall voltage \(V_{\text{HH}}(T)\) is defined as
\[
V_{\text{HH}}(T) \equiv R_{\text{HH}}(T)I_{\text{NNH}} \frac{B}{W},
\]
where \(R_{\text{HH}}(T)\) is a parameter. Because the existence probabilities of \(\text{Al}^-\) and \(\text{Al}^{11}\) sites are \(f(E_{\text{Al}})\) and \(1 - f(E_{\text{Al}})\), respectively, the ratio of the amount of holes to the amount of electrons, which are accumulated at Electrode 4 under \(B\), is the ratio of \(f(E_{\text{Al}})\) to \(1 - f(E_{\text{Al}})\). Consequently
\[
V_{\text{HH}}(T) = V_{\text{HH}}(T)/f(E_{\text{Al}}),
\]
and
\[
V_{\text{HH}}(T) = V_{\text{HH}}(T)/[1 - f(E_{\text{Al}})].
\]
From the equivalent circuit shown in Fig. 8(b), \(V_{\text{NNH}}(T)\) can be derived using Eqs. (11) and (12) as
\[
V_{\text{NNH}}(T) = \frac{V_{\text{HH}}(T) - [2f(E_{\text{Al}}) - 1]}{2f(E_{\text{Al}}) - 1}.
\]
Using Eqs. (8), (10), and (13), \(R_{\text{NNH}}(T)\) is obtained as
\[
R_{\text{NNH}}(T) = R_{\text{HH}}(T)/2[2f(E_{\text{Al}}) - 1],
\]
where \(R_{\text{NNH}}(T)\) is positive when \(f(E_{\text{Al}}) > 0.5\) and negative when \(f(E_{\text{Al}}) < 0.5\). In general, \(R_{\text{NNH}}(T)\) is negative at low temperatures because \(E_{\text{F}}\) is located below \(E_{\text{Al}}\), which indicates that \(f(E_{\text{Al}}) < 0.5\), whereas it is positive at high temperatures because \(E_{\text{F}}\) is located above \(E_{\text{Al}}\).

Because \(E_{\text{F}}\) is at \(\leq 400\) K in heavily Al-doped 4H-SiC was reported to be located below \(E_{\text{Al}}\) \(48,49\), \(R_{\text{NNH}}(T)\) becomes negative over the entire range of measurement temperatures examined. This indicates that \(R_{\text{NNH}}(T)\) is positive when the dominant conduction mechanism is NNH conduction. Therefore, \(R_{\text{HH}}(T)\) at high temperatures (i.e., in band conduction) is positive because \(R_{\text{HH}}(T)\) is generally positive, and \(R_{\text{HH}}(T)\) at low temperatures (i.e., in NNH conduction) is negative according to our proposed model. According to Eq. (6), \(T_{\text{inv}}\) is the temperature at which
\[
\left[\frac{\rho(T)}{\rho_{\text{Band}}(T)}\right] \propto \left[\frac{\rho_{\text{Band}}(T)}{\rho_{\text{NNH}}(T)}\right]^{2}[R_{\text{NNH}}(T)].
\]
Because \(T_{\text{BH}}\) is the temperature at which
\[
\rho_{\text{Band}}(T) = \rho_{\text{NNH}}(T),
\]
\(T_{\text{inv}}\) is close to \(T_{\text{BH}}\), and the magnitude relation between \(T_{\text{inv}}\) and \(T_{\text{BH}}\) depends on the magnitude relation between \(R_{\text{Band}}(T)\) and \(R_{\text{NNH}}(T)\).

At low temperatures, the occupation probability of holes at \(E_{\text{Al}}\) [i.e., \(1 - f(E_{\text{Al}})\)] for the Al-doped sample is close to 1, and is greater than that for the Al–N co-doped samples because N donors capture holes from Al acceptors.

\section{4. Summary}

In heavily Al-doped or Al–N co-doped p-type 4H-SiC, the Hall coefficient for NNH conduction, in which holes or electrons hop between Al acceptor sites, became negative at low temperatures. The contribution of hopping holes to the Hall voltage could be distinguished from the contribution of hopping electrons. In contrast, the contribution of hopping holes to the current was difficult to distinguish from the contribution of hopping electrons. These results led us to propose a simple physical model that can make the Hall coefficient for NNH conduction negative at low temperatures. In heavily Al-doped or Al–N co-doped p-type 4H-SiC epilayers, our proposed model demonstrated that the temperature-dependent Hall coefficient has a peak and its sign at high temperatures is positive and that at low temperatures is negative. In addition, the resistivity and the Hall coefficient in heavily Al-doped or Al–N co-doped p-type 4H-SiC epilayers on n-type 4H-SiC substrates were confirmed to originate from the p-type 4H-SiC epilayers, not from the n-type 4H-SiC substrates. In other words, we found that the depletion layer formed by the pn junction electrically isolates the heavily Al-doped or Al–N co-doped p-type 4H-SiC epilayer from the n-type 4H-SiC substrate. Furthermore, we showed that the appearance of a negative Hall coefficient in heavily Al-doped or Al–N co-doped 4H-SiC is independent of N co-doping.

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\section{ORCID iDs}

Hideharu Matsuura \(\text{ORCID} 0000-0001-7190-286X\)

Takeshi Mitani \(\text{ORCID} 0000-0002-4228-1707\)

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