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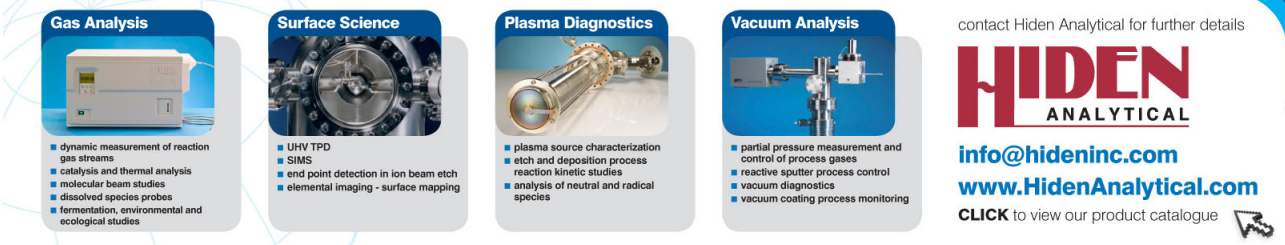

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Effects of electron mass anisotropy on Hall factors in 6H-SiC

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The room temperature Hall factors in 6H-SiC have been measured under different magnetic fields. It is found that the Hall coefficient R_H increases with magnetic field, implying a Hall factor of less than one at zero magnetic field. This behavior has been accounted for by a model based on electron mass anisotropy in 6H-SiC. The Hall factor results show that in 6H-SiC the mass along the *c* direction is a factor of 5 larger than that in the transverse direction and that the electron–phonon scattering time is aobut 1 ps at room temperature, which is consistent with a recent optically detected resonance spectroscopy measurement. Our results indicate that the Hall measurement can be utilized as an effective and simple method for studying scattering mechanisms as well as for determining anisotropic transport properties in SiC and that a correction of the Hall factor is necessary in order to determine the carrier concentration and mobility accurately. © *1996 American Institute of Physics.* [S0003-6951(96)00610-X]

Renewed attention has been given to SiC semiconductors recently because of their promising applications for devices operating under hostile conditions such as high temperatures, high frequencies, and high power.[1] Despite the many research programs conducted on this material, many questions remain unanswered, one of which is the Hall factor in SiC. Hall measurements are the most common and direct methods used to study the electrical properties of semiconductors, including carrier concentrations and mobilities.[2] However, in order to evaluate the impurity concentrations and ionization energies from the Hall data in a correct way, it is necessary to include a correction of the Hall factor.

The Hall factor depends on the magnetic field, the free electron or hole concentration, the scattering mechanism, and the band structure of the semiconductor under investigation. The knowledge of the Hall factor is therefore an important issue. Because the Hall factors are unknown in SiC, they are often set to unity for convenience. Unfortunately, this assumption is strictly valid only for degenerate semiconductors or when the magnetic field is high enough that the magnetic motion dominates the scattering. In most cases, this assumption is not justified. In this letter, we report the results of the first measurements on the Hall factors in 6H-SiC materials at room temperature. We also show from these measurements that when the geometrical factor is carefully taken into account important physical quantities including the mass anisotropic parameter and the scattering times can be obtained from the magnetic field dependence of the Hall factor.

Samples used for this study were nitrogen-doped *n*-type bulk 6H-SiC single crystals obtained from Cree Research, Inc. They were cut from a wafer with carbon terminated surfaces of about $0.8\times0.6\times0.033$ cm^3. Similar results have been obtained for different samples. In this letter, we present the results only for one representative sample. Ohmic contacts for the Hall measurements were achieved by utilizing Pd/In bilayer structure.[2] We first deposited four Pd spots under vacuum followed by a rapid thermal annealing at 950 °C in argon ambient for about 5 min. Indium thin films wer then deposited on the top of Pd contacts following by a subsequent thermal annealing at 450 °C in argon for about 30 min. Gold leads were then attached to the contacts by indium solder for electrical measurements. Ohmic behavior between all four contacts was observed. The Hall coefficient, resistivity, and the electron concentration and mobility were measured by the standard van der Pauw method. The van der Pauw data were corrected for the finite size contact and the geometrical factor (f). When the applied magnetic fields were about 0.2 T, the values of f were larger than 0.90 and the difference in R_1 and R_2 never exceeded 10%, where R_1 and R_2 are the resistances measured in two different configurations. However, it was very difficult to obtain reliable results below 0.2 T. The *c*-axis of the sample was in the direction parallel to the magnetic field.

We have measured the Hall coefficient R_H at different magnetic fields and found that the values of R_H increase with increasing magnetic field as depicted in Fig. 1. In order to obtain the Hall factor γ, we have to know the Hall coefficient at the magnetic field $B\rightarrow\infty$, $R_H(B\rightarrow\infty)$, which can be obtained by extrapolating the plot of R_H versus $1/B^2$ linearly to $B\rightarrow\infty$.[3] The obtained value of $R_H(B\rightarrow\infty)$ from Fig. 1 is 10.9 cm^3/C. The Hall factor γ is related to the Hall coefficient by

$$\gamma = enR_H, \tag{1}$$

where n is the electron concentration. n should be independent of magnetic field in the region of the measurements. From Eq. (1), we have $\gamma(B)/\gamma(B\rightarrow\infty)=R_H(B)/R_H(B\rightarrow\infty)$. By noting that $\gamma(B\rightarrow\infty)=1$,[3] we obtain the magnetic field dependence of the Hall factor $\gamma(B)$ as,

$$\gamma(B)=R_H(B)/R_H(\infty). \tag{2}$$

By using Eq. (2) and the value of $R_H(\infty)$ as determined from Fig. 1 we have plotted the Hall factor as a function of the magnetic field B, $\gamma(B)$, as shown in Fig. 2. We see that $\gamma(B)$ is less than unity. However, the Hall factor $\gamma(B)$ approaches unity as B approaches to infinity. The insert of Fig. 2 shows the magnetic field dependence of the sample resisitivity. A constant value of 8.2×10^{-2} Ω cm in the measured field region has been obtained, which clearly shows that the

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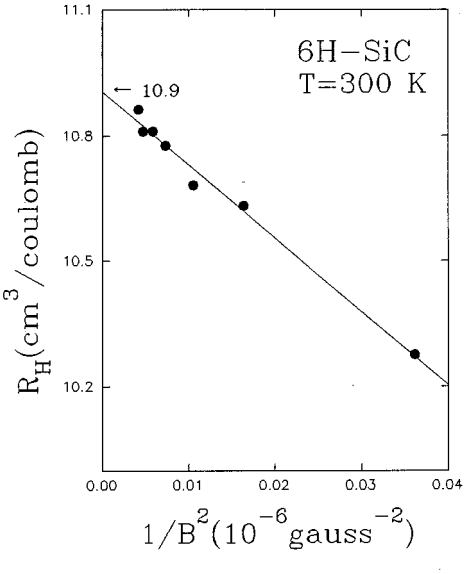

FIG. 1. The plot of Hall coefficient R_H vs $1/B^2$. The solid line is a linear plot, which has been extrapolated to $B\rightarrow\infty$.

behavior of $\gamma(B)$ is not an effect due to magnetoresistance, but is due to the magnetic field dependence of the Hall factor γ. It has been shown that the Hall coefficient, $R_H(B)$, varies with the orientation and magnitude of the magnetic field and the orientation of the applied current.[3–5] These variations depend on both the electron scattering mechanism and the structure of the conduction band.

In the following, we adopt a theory based on the anisotropic electron transport with an energy-independent scattering time developed for the Hall coefficients in *n*-type Ge.[3] The configurations of our experiment are such that the magnetic field is parallel to the *c*-axis, $\mathbf{B}\|c$, and the applied current density is perpendicular to the magnetic field, $j\perp\mathbf{B}$. The

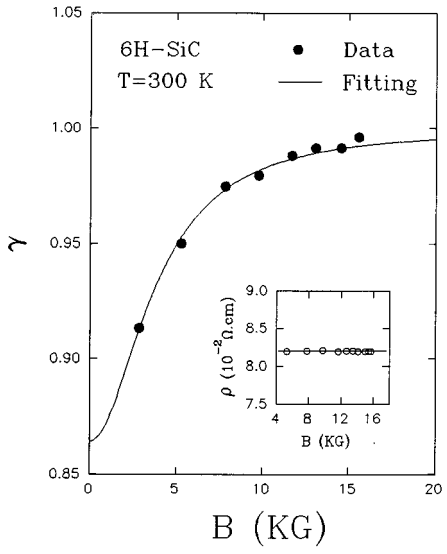

FIG. 2. Hall factor γ of 6H-SiC as a function of the magnetic field measured at room temperature. The solid line is a least squares fit by Eq. (3). The inset is the plot of the sample resistivity as a function of the magnetic field.

expression derived for Ge with the closest experimental configuration compared to ours is[6]

$$\gamma(B)=\frac{(K+2)[3K+(K+2)b^2]}{(2K+1)^2+(K+2)^2b^2}, \tag{3}$$

where $b=\alpha B$ with $\alpha=e\tau/m_t$. m_t is the electron transverse mass and τ is the electron scattering time. K is the mass anisotropic parameter and defines the ratio of the mass along the c direction to that in the transverse direction, i.e., $K=m_l/m_t$. The parameter K also describes the ansiotropic electron transport properties. Equation (3) fits our experimental data quite well as shown in Fig. 2, in which the solid line is the least squares fit of our data by Eq. (3), although the symmetry properties of 6H-SiC are different from those of Ge. Equation (3) satisfies the conditions that $\gamma(\infty)=1$ and that the Hall coefficient must be an even function of B.[4] The fitted values are $\alpha=0.41$ and $K=5.2$, respectively. Thus, at the limit of $B=0$, we obtain the Hall factor $\gamma(0)=3K(K+2)/(2K+1)^2=0.87$.

The above results indicate that in 6H-SiC the electron mass along the c direction is 5.2 times larger than that in the transverse direction. The result is fully consistent with a recent optically detected cyclotron resonance spectroscopy (ODCR) measurement[7] and also with a recent theoretical prediction.[8] The effective masses as determined by ODCR measurements are $m_t=(0.42+0.02)m_0$ and $m_l=(2.0+0.2)m_0$, where m_0 is the free electron mass, implying K=4.8. This value is very close to the mass anisotropy parameter obtained by our Hall measurement ($K=5.2$). Therefore, our results have shown that when the finite size contact and geometrical factor are carefully taken into account, the Hall measurements can indeed be utilized as a simple but effective method for determining the mass anisotropic parameter in SiC.

In addition to the above results, we have also measured electron mobility μ as a function of temperature in the region of 10 K$<T<$550 K as shown in Fig. 3. In the low temperature region, μ increases with increasing temperature following approximately the relation $\mu\sim T^{3/2}$, which suggests that ionized impurity scattering dominates at low temperatures. At temperatures $T>$150 K, the electron–phonon scattering predominantly determines the electron mobility. By considering the electron-acoustic phonon scattering,[9] the mobility μ as a function of temperature in the region of 150 K$<T<$550 K can be written as $\mu=AT^{-3/2}$, where the constant A depends on the elastic modules, the longitudinal and transverse effective masses, and the deformation potential constant. Intervalley scattering is not considered at these temperatures because this scattering mechanism dominates at high temperatures, $T>$550 K.[10] If one includes both the electron-acoustic and electron-optical phonon scattering,[9]then the mobility can be written as $\mu=A'T^{-1.67}$. The constant A' differs from the constant A by including both acoustic and optical phonon scattering. At the present, the physical parameters describing A and A' in SiC are not available. We have used both of these equations to compare with our experimental results and found that $\mu=A'T^{-1.67}$ describes the experimental results better. There-

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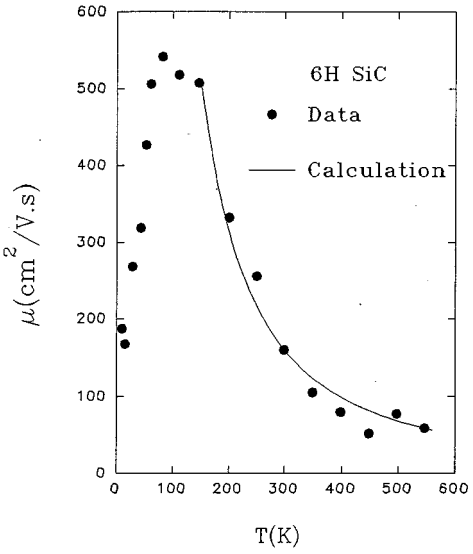

FIG. 3. Electron mobility μ as a function of temperature for a nitrogen doped 6H-SiC sample. The solid dots are the experimental data and the solid curve above 150 K is the calculation result using $\mu = A' T^{-1.67}$ with $A' = 2.2 \times 10^6$.

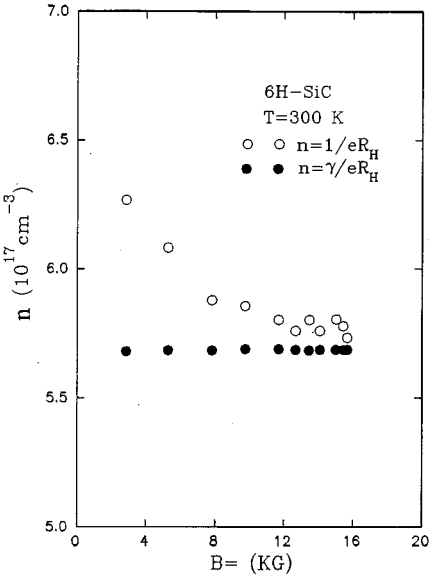

FIG. 4. The electron concentration n as a function of the magnetic field with (●) and without (○) the correction of the magnetic field dependence of the Hall factor γ.

fore, the electron–optical phonon scattering is also important at higher temperatures and cannot be neglected.

The electron–phonon scattering time can also be determined from the magnetic field dependence of the Hall factor by using the fitted value of $\alpha(=e\tau/m_t=0.41)$, which is about 1 ps at room temperature. The electron scattering times of $\tau_{B\perp c}=26$ ps and $\tau_{B\parallel c}=22$ ps at a temperature of 6 K have also been determined by the recent ODCR measurements.[8] The scattering time obtained here is also reasonable, since the electron–phonon (both optical and acoustic) scattering at room temperature is a much faster process than that of the ionized impurity scattering at low temperatures. In fact, the anisotropy of the electron Hall mobility in nitrogen-doped *n*-type bulk 4H, 6H, and 15R SiC has been studied recently by Schadt *et al.*[11] Their results have indicated that the anisotropy of the electron Hall mobility is due to an anisotropy in the electron effective masses and scattering mechanism. Our results are in fact consistent with their conclusions.

The room temperature electron concentration (n) as a function of the magnetic field with and without the correction of the Hall factor is plotted in Fig. 4, which clearly indicates that the electron concentrations measured by Hall measurements have to be corrected with the Hall factor $\gamma(B)$, otherwise the error could be as much as 13% for 6H-SiC. The results obtained here will also be very useful for carrier mobility measurements. It is known that the ratio of the Hall mobility μ_H to the conduction mobility μ_c equals the Hall factor,[12] $\gamma=\mu_H/\mu_c$. On the other hand, the conduction mobility is the one most often calculated by theorists, whereas the low field Hall mobility is the one most often measured experimentally. Thus, knowledge of the Hall factors at different conditions enables one to compare experimental results with calculation directly.

In conclusion, the room temperature Hall factors have been measured in nitrogen-doped 6H-SiC samples. Our results reveal the following two important aspects: (1) in order to determine the carrier concentration and mobility in SiC accurately, one has to include the correction of the Hall factor, which depends strongly on the magnetic field and possibly on the orientations of the magnetic field and applied current; and (2) when the geometrical factor is carefully taken into account the Hall measurements can be utilized as a simple but effective method for studying the scattering mechanism as well as for determining the anisotropic transport properties in SiC. The Hall factors at different temperatures and orientations of the magnetic field and the applied current will be investigated and the corresponding mathematical expressions for the Hall factor γ, such as that of Eq. (3) for 6H-SiC as well as for other polytypes of SiC, will be determined in the near future.

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