Piezo-Hall effect and fundamental piezo-Hall coefficients of single crystal n-type 3C-SiC(100) with low carrier concentration

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This article reports the results on piezo-Hall effect in single crystal n-type 3C-SiC(100) having low carrier concentration. The effect of crystallographic orientation on the piezo-Hall effect has been investigated by applying stress to the Hall devices fabricated in different crystallographic directions. Single crystal n-type 3C-SiC(100) and 3C-SiC(111) were grown by low pressure chemical vapor deposition (LPCVD) at 1250°C. Fundamental piezo-Hall coefficients were obtained using the piezo-Hall effect measurements as $P_{11} = (-29 \pm 1.3) \times 10^{-11} \text{ Pa}^{-1}$, $P_{12} = (11.06 \pm 0.5) \times 10^{-11} \text{ Pa}^{-1}$ and $P_{44} = (-3.4 \pm 0.7) \times 10^{-11} \text{ Pa}^{-1}$. It has been observed that the piezo-Hall coefficients of n-type 3C-SiC(100) show a completely different behavior as compared to that of p-type 3C-SiC.

Silicon carbide has attracted much attention for electronic applications in harsh environment due to its large bandgap, high thermal conductivity and high saturation velocity. A tremendous progress has been made in recent years on material development of SiC, leading to market availability of 4H-SiC and 6H-SiC¹. Numerous studies on the application of 4H-SiC and 6H-SiC for magnetic field sensing can be found in literature². However, 4H-SiC and 6H-SiC are much more expensive than 3C-SiC. The capability of hetero-epitaxial growth of SiC on large diameter Si wafers combined with its compatibility with the existing process of micro-electro-mechanical systems (MEMS), make it a promising choice for magnetic field sensing in harsh environment application. It can be readily grown over Si substrates of different crystal orientations, e.g. (100), (110) or (111)^{3,4} and can reduce the cost significantly. Additionally, the carrier mobility for 3C-SiC is much larger than the carrier mobilities in 4H-SiC and 6H-SiC which makes it an ultimate choice for magnetic field sensing if the interface defects associated with the growth of 3C-SiC over Si are reduced significantly.

Typical growth temperatures for materials are high and the subsequent cooling to room temperature after growth introduces large amount of stresses in the thin films. These stresses can seriously affect the magnetic field sensitivity of Hall devices. The other factors which can introduce drifts in the magnetic field sensitivity of the Hall devices include a thermal mismatch between mounting material and chip in die attachment, mechanical impact during device operation and packaging of fabricated device⁵⁻⁹. Consequently, these various types of stresses introduced into the device can induce drifts in device parameters, offset voltage, temperature behavior and finally the magnetic field sensitivity⁷. The piezo-Hall effect for Si based Hall devices has been studied for years and a large number of studies on Si can be found

in literature¹⁰⁻¹³. After the measurement of piezo-Hall coefficients for n-type Si, various studies were conducted to compensate for the stress related sensitivity drifts of Si based Hall devices⁵⁻¹³.

The piezo-Hall effect and fundamental piezo-Hall coefficient for single crystal p-type 3C-SiC were reported recently in^{14,15}. But the study on piezo-Hall effect in n-type 3C-SiC is still missing. Therefore, this paper aims to investigate the fundamental piezo-Hall coefficients of single crystal n-type 3C-SiC with low carrier concentration. The effect of crystallographic orientation on the piezo-Hall effect is also investigated using the Hall devices grown by LPCVD in (100) and (111) crystallographic planes. As low doped n-type 3C-SiC is a preferred material for magnetic field sensors, it is very important to investigate the piezo-Hall effect in this material. The results achieved in this study can be useful for designing n-type 3C-SiC Hall devices for magnetic field sensing.

Single crystal n-type 3C-SiC(100) and 3C-SiC(111) thin films were grown to a thickness of 400 nm on Si(100) and Si(111) substrates by LPCVD process at the temperature of 1250°C. Alternating supply epitaxy (ASE) was employed to grow the single crystal 3C-SiC and the precursors SiH₄ and C₃H₆ were employed as source of Si and C atoms. The grown films exhibited unintentional n-type conductivity. The full details of the growth process can be found in^{16,17}. After the growth process, X-ray diffraction (XRD) analysis of the grown films was carried out to confirm the crystal structure followed by the rocking curve to analyze the crystalline quality. Figure 1(a) shows the XRD pattern of n-type 3C-SiC(100) thin film on Si(100) in conventional θ - 2θ scan mode. It can be observed from Fig. 1(a) that only the peaks corresponding to (100) plane are present, which confirms that single crystal 3C-SiC(100) was grown on Si(100). Figure 1(b) shows the rocking curve of 3C-SiC(100) peak with the observed full width at half maximum (FWHM) value of 0.70°, which shows the good crystalline quality of the grown film. Figure 1(d,e) shows the XRD pattern and rocking curve of n-type 3C-SiC(111), which

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FIG. 1. (a) XRD pattern of single crystal n-type 3C-SiC(100), (b) the rocking curve of 3C-SiC(100), (c) AFM image of n-type 3C-SiC(100), (d) XRD pattern of single crystal n-type 3C-SiC(111), (e) the rocking curve of 3C-SiC(111) and (f) AFM image of n-type 3C-SiC(111).

confirms that the thin film is single crystal and has good crystalline quality. Atomic force microscopy (AFM) was used to measure the roughness of the grown thin films. The AFM images of n-type 3C-SiC(100) and 3C-SiC(111) thin films for a scan area of $5 \mu\text{m} \times 5 \mu\text{m}$ are shown in Fig. 1(c,f). The root mean square (RMS) roughness of n-type 3C-SiC(100) was measured to be $2 \pm 0.5 \text{ nm}$ while that of 3C-SiC(111) was $1.96 \pm 0.5 \text{ nm}$ which shows the excellent surface morphology of the grown films. The conductance type and carrier concentration of the grown thin film were obtained by hot probe measurements and then confirmed by Hall effect measurements. The carrier concentration of n-type single crystalline 3C-SiC(100) and 3C-SiC(111) were found to be $5\text{--}8 \times 10^{16} \text{ cm}^{-3}$. The carrier concentration of the Si substrates was $5 \times 10^{14} \text{ cm}^{-3}$. The electrical resistivity of n-type 3C-SiC(100) was $17.4 \Omega\text{-cm}$ with corresponding hole mobility of $36 \text{ cm}^2/\text{Vs}$. The electrical resistivity of n-type 3C-SiC(111) was $724 \Omega\text{-cm}$ with corresponding hole mobility of $0.86 \text{ cm}^2/\text{Vs}$.

After the growth process, standard photolithography and dry etching processes were used to fabricate the

Greek cross shaped Hall devices (Fig. 2(a)). The Greek cross shape was chosen to investigate the stress-induced piezo-Hall effect because it is the standard device shape for Hall measurements. The devices were designed at different angles in the photolithography mask and the direction of dicing of the beam in particular direction was varied by rotating the mask within the crystal plane. After fabrication of the devices, the wafer was diced into strips with dimensions of $60 \text{ mm} \times 9 \text{ mm} \times 0.675 \text{ mm}$ to apply stress by the bending beam method. Cantilever method was used to apply the stress to the devices in which one end of the beam with the devices was fixed, while a known force was applied to the other end. Consequently stresses from 0 to 343 MPa were induced to n-type 3C-SiC layer to investigate the piezo-Hall effect. The method to numerically calculate the stress-induced into the 3C-SiC layer on Si strip is reported elsewhere¹⁸. The second method to apply the stress along the direction of thickness of the thin film is reported in¹⁴. The Ohmic contacts were confirmed by I - V measurement and horizontal and vertical current leakages from n-type 3C-SiC(100) through to the Si substrate were measured to be less than 2% of the total device current. Therefore, the current leakage is negligible and it does not contribute in the measurements.

In order to evaluate the piezo-Hall effect and calculate the piezo-Hall coefficients, current was applied to the device at terminals 1 and 2, while the change in Hall voltage, corresponding to the change in applied stress, were recorded at terminals 3 and 4 (Fig. 2(a)). In the presence of a constant magnetic field B , when stress is applied to the device at constant input current, the Hall voltage across terminals 3 and 4 will change with the in-

FIG. 2. (a) SEM image of the fabricated Hall device, (b) experimental setup to measure the piezo-Hall coefficients.

FIG. 3. Effect of applied stress on the magnetic field sensitivity of the fabricated Hall device for various angles of rotation within in (100) and (111) planes; (a) Stress along the thickness of the film in (100) plane, (b) in (100) plane for different directions of stress and current, (c) for (111) crystal plane with various angles of rotation, (d) description of angle α between the current flow direction and the longitudinal stress σ . The insets show the directions of current, stress and magnetic field.

crease of applied stress, which is called piezo-Hall effect (Fig. 2(b)). The change in Hall voltage was used to calculate the change in magnetic field sensitivity of the Hall device according to the following relation:

$$\left. \begin{aligned} S &= (V_H/I)/B = R_H(G/t) \\ \Delta S &= (\Delta V_H/I)/B = \Delta R_H(G/t) \end{aligned} \right\} [VA^{-1}T^{-1}] \quad (1)$$

where V_H is the Hall voltage observed at terminals 3 and 4, I is the current flowing through terminals 1 and 2 as shown in (Fig. 2(a)), B is the applied magnetic field, R_H is the Hall coefficient, G is the geometrical correction factor and t is the thickness of the n-type 3C-SiC thin film. Here, ΔS is the change in magnetic field sensitivity of the Hall devices due to change in Hall coefficient ΔR_H and change in Hall voltage ΔV_H . When the stress is applied to the Hall devices it leads to the change in Hall coefficient R_H which changes the Hall voltage, ultimately resulting in change of magnetic field sensitivity of the Hall device. This phenomenon is called piezo-Hall effect. Here, the change in magnetic field sensitivity ΔS of Hall devices from Eq. 1 will be utilized to study the piezo-Hall effect experimentally. Figure 3(a) shows the change in sensitivity of the n-type 3C-SiC Hall devices for

(100) plane when the stress was applied along the thickness of the thin film (into the plane), while the magnetic field was applied out of plane. For this particular configuration it is difficult to apply the stress along the direction of the thickness of the film and the applied stresses are small in magnitude. Due to the small amount of applied stress, the observed Hall voltage at constant stress level showed variation, so a linear fitting was used to obtain the required values. The change in magnetic-field sensitivity is negative for this configuration.

Figure 3(b) shows the change in magnetic field sensitivity of the n-type 3C-SiC Hall devices fabricated in (100) plane at various directions of current and applied stress. The sensitivity of n-type 3C-SiC Hall devices was measured for three different angles (0° , 45° , 90°) between the current flow and the longitudinal stress (Fig. 3(d)). The stress was applied in two different crystal orientations ([100] and [110]) (Fig. 3(b)). It can be observed from Fig. 3(b) that the change in magnetic-field sensitivity shows almost linear behavior against the applied stress. It can also be observed from Fig. 3(b) that the change in magnetic-field sensitivity has the equal magnitude in all the six orientations of the device in (100)

FIG. 4. Spherical plots of piezo-Hall coefficients of single crystal n-type 3C-SiC with low carrier concentration having arbitrary crystal orientation in any wafer plane.

crystal plane with the maximum error being $\pm 5\%$.

Figure 3(c) shows the change in magnetic-field sensitivity of the n-type 3C-SiC Hall device in (111) crystal plane for various directions of applied current and stress. Similar to (100) plane, the change in sensitivity of n-type 3C-SiC Hall devices was measured for three different angles (0° , 45° , 90°) between the current flow and the longitudinal stress. The applied stress was in [110] and [112] directions. The change in sensitivity of the Hall devices in (111) plane for various directions of current and stress was also positive and is almost equal in magnitude within the maximum error of $\pm 5\%$. These results agree with the theoretically analysis of the piezo-Hall effect being independent of the angle of rotation within the crystal plane¹⁹.

In order to calculate the piezo-Hall coefficients for n-type 3C-SiC(100), the expression for piezo-Hall effect in terms of piezo-Hall coefficients is required. As the crystal structure of 3C-SiC is similar to that of Si, we use the same expression valid for cubic Si¹⁹. Hence, the change in Hall coefficient due to the change in magnetic field sensitivity of the Hall devices upon application of stress is given by:

$$ph = P'_{11}\sigma_1 + P'_{12}\sigma_2 + P'_{13}\sigma_3 + P'_{14}\sigma_4 + P'_{15}\sigma_5 + P'_{16}\sigma_6 \quad (2)$$

where σ_1 is the normal stress orthogonal to the wafer, σ_2 and σ_3 are in plane normal stresses, σ_4 is the in plane shear stress which vanishes at a distance of more than chip thickness from the edge of the chip, and σ_5 and σ_6 are out of plane shear stresses which are normally zero. Note that $P_{12} = P_{13}$ and $P_{14} = P_{15} = P_{16} = 0$ due to the symmetry relations of the cubic crystal system $m\bar{3}m$. Therefore, Eq. 2 reduces to¹⁹:

$$ph = P'_{11}\sigma_1 + P'_{12}\sigma_2 + P'_{13}\sigma_3 \quad (3)$$

where,

$$\left. \begin{aligned} P'_{11} &= P_{11} - 2P_a \sin^2\theta (\cos^2\theta + \sin^2\theta \sin^2\phi \cos^2\phi) \\ P'_{12} &= P_{12} + 2P_a \sin^2\theta \cos^2\theta (1 - \sin^2\phi \cos^2\phi) \\ P'_{13} &= P_{12} + 2P_a \sin^2\theta \sin^2\phi \cos^2\phi \end{aligned} \right\} \quad (4)$$

where $P_a = P_{11} - P_{12} - P_{44}$ and θ and ϕ are the polar and azimuthal angles of spherical coordinate system¹⁴. For n-type 3C-SiC(111), $\theta = 54.7^\circ$ and $\phi = 45^\circ$. In 3C-SiC(100) plane, $\theta = \phi = 0^\circ$ when stress in [100] and $\theta = 0^\circ$, $\phi = 45^\circ$ when stress is in [110] direction. Incorporating these values in Eq. 3 gives the final influence of stress to piezo-Hall effect for (100) and (111) planes in 3C-SiC as follows:

$$\left. \begin{aligned} ph_{(111)} &= \frac{\Delta S}{S} = \frac{P_{11} + 2P_{12} - P_{44}}{3} \sigma_1 + \frac{P_{11} + 2P_{12} - P_{44}}{3} (\sigma_2 + \sigma_3) \\ ph_{(100)} &= \frac{\Delta S}{S} = P_{11}\sigma_1 + P_{12}(\sigma_2 + \sigma_3) \end{aligned} \right\} \quad (5)$$

For the calculation of piezo-Hall coefficient P_{11} , the stress was applied along the thickness of the thin film in (100) crystal planes with $\sigma_2 = \sigma_3 = 0$. Therefore, from Eq. 5 with stress along [100] orientation, the value of P_{11} is determined to be $(-29 \pm 1.3) \times 10^{-11} \text{ Pa}^{-1}$, which is completely different from the piezo-Hall coefficient of p-type 3C-SiC(100)¹⁴. For the calculation of piezo-Hall coefficient P_{12} , uni-axial stress σ_2 is applied and we have $\sigma_1 = \sigma_3 = 0$. Therefore, the corresponding piezo-Hall coefficient measured using Eq. 5 for n-type 3C-SiC(100) was $P_{12} = (11.06 \pm 0.5) \times 10^{-11} \text{ Pa}^{-1}$. For n-type 3C-SiC(111) when stress σ_2 is applied, again we have $\sigma_1 = \sigma_3 = 0$, and the expression $P_{11} - P_{44} = (-32.4 \pm 0.6) \times 10^{-11} \text{ Pa}^{-1}$ can be obtained. Hence, the three independent piezo-Hall coefficients were obtained as: $P_{11} = (-29 \pm 1.3) \times 10^{-11} \text{ Pa}^{-1}$, $P_{12} = (11.06 \pm 0.5) \times 10^{-11} \text{ Pa}^{-1}$, and $P_{44} = (-3.4 \pm 0.7) \times 10^{-11} \text{ Pa}^{-1}$. Using the values of P_{11} , P_{12} and P_{44} , the piezo-Hall coefficients for any arbitrary crystal orientation can be determined using Eq. 4.

TABLE I. Fundamental piezo-Hall coefficients of n-type 3C-SiC and p-type 3C-SiC¹⁴

type of	P_{11}	P_{12}	P_{44}
	$\times 10^{-11} \text{ Pa}^{-1}$	$\times 10^{-11} \text{ Pa}^{-1}$	$\times 10^{-11} \text{ Pa}^{-1}$
*n-type	(-29 ± 1.3)	(11 ± 0.5)	(-3.4 ± 0.7)
p-type	(-2.6 ± 0.6)	(5.3 ± 0.4)	(11.42 ± 0.6)

* present study

Figure 4 shows the directional dependence of all piezo-Hall coefficients of n-type 3C-SiC(100) with low carrier concentration in arbitrary crystallographic orientation using the spherical plots. The directional dependence is shown in three crystallographic orientations $\langle 100 \rangle$, $\langle 010 \rangle$ and $\langle 001 \rangle$. The complete description of the spherical coordinate system used and how to obtain the spherical plots is given in^{14,19}. It can be observed from the spherical plots of Fig. 4 that the piezo-Hall coefficient P_{11} , P_{12} and P_{13} are maximum for $\{100\}$ family of planes and are minimum for $\{111\}$ family of planes (Fig. 4(a,b,c)). The influence of shear stress vanishes for $\{111\}$, $\{110\}$ and 100 planes (Fig. 4(d,e,f)). This behavior of piezo-Hall coefficients is completely different from that of p-type 3C-SiC¹⁴. Table I shows the fundamental piezo-Hall coefficients on n-type 3C-SiC obtained in this study and the fundamental piezo-Hall coefficients of p-type 3C-SiC, which have been reported elsewhere¹⁴.

The different behaviour of piezo-Hall effect and different values of the fundamental piezo-Hall coefficients in n-type and p-type 3C-SiC can be attributed to different conduction mechanisms in these semiconductors. For example, in case of p-type 3C-SiC the conduction is due to holes distributed in light and heavy hole sub-bands in the valence band. When stress is applied to p-type 3C-SiC, the light hole and heavy hole bands split and hole re-distribution occurs, leading to change in conductance mechanism and ultimately the Hall coefficient R_H . In case of n-type 3C-SiC, the electrons are distributed in 6 equivalent energy valleys. When stress is applied, the electrons repopulate due to energy level shifts, leading to change in electron effective mass and mobility which ultimately results in change of Hall coefficient R_H . Therefore, the conduction mechanism is completely different in these two semiconductor types, resulting in different behaviour of piezo-Hall effect. These results have been explained by taking into account the crystal symmetry of 3C-SiC to Si^{20,21}. Piezo-Hall effect also depends upon the level of carrier concentration but at present it is difficult to control the carrier concentration as the doping in our thin films is unintentional doping.

In conclusion, the piezo-Hall effect for single crystal n-type 3C-SiC with low carrier concentration has been investigated for different crystallographic orientations. It has been found that the piezo-Hall coefficients in n-type

3C-SiC with low carrier concentration show a completely different behavior as compared to p-type 3C-SiC(100) and are much larger in value. The piezo-Hall effect is isotropic in n-type 3C-SiC for (100) and (111) planes. After measurement of the fundamental piezo-Hall coefficients, the piezo-Hall coefficients for any arbitrary crystallographic orientation can be obtained using the results presented in this study. As single crystal n-type 3C-SiC with low carrier concentration is a promising candidate for Hall effect devices for harsh environment, the results of this study can be very useful to understand the stress related magnetic field sensitivity drifts in these devices.

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