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Mobility enhancement by mechanical uniaxial stress on 4H-SiC (0001) lateral metal-oxide-semiconductor field-effect-transistor

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1. Introduction

4H-SiC with a wide bandgap, high breakdown electric field strength, high thermal conductivity, and high electron mobility is an attractive semiconductor for high-power metal-oxide-semiconductor field-effect transistors (MOSFETs). However, the low channel mobility of 4H-SiC MOSFETs owing to the high density of the SiO2/4H-SiC interface states is still a critical issue.1–6 Strain engineering technology is expected in order to enhance the mobility of 4H-SiC MOSFET, while lowering the interface states density in SiO2/4H-SiC interface is also developed. In the state-of-the-art Si-MOSFET technology, strain engineering has been widely studied and employing to enhance the mobility.7–10 Also theoretical studies have quantified the effects of biaxial and uniaxial strain on the electrical properties of SiC.11

On the other hand, there are a few reports of the calculation of strain effect for 4H-SiC. Steel et al. reported the important conductivity mass can be reduced by more than 50% uniaxial tensile strain (>1.5%) from calculation results.12 In addition, uniaxial tensile strain is expected for reducing both intervalley and defect assisted scattering due to the intervalley coupling between the two conduction minima. Also, it is reported from calculation that the energy bandgap of 4H-SiC tends to narrow from bulk SiC case. Also, the strain engineering technology of SiC MOSFET is still limited; the strain direction has been experimentally investigated only for the tensile strain case.

In this work, we fabricated the custom-designed bend-holder to apply not only tensile but also compressive stress to a chip with 4H-SiC MOSFETs. We investigated the effects of mechanical uniaxial strain on the inversion channel mobility in 4H-SiC(0001) n-MOSFET. This work has been partially presented at SSDM 2019 conference.21 Additionally, in extended abstract, we describe the custom-designed bend-holder in detail. The applied stress and strain distribution in the 4H-SiC chip using the custom-designed bend-holder was calculated with general-purpose finite element method (FEM). The calculated stress values was comprehensively compared to that of Raman scattering measurement. Also, the separation method of mobility component was described in detail. Moreover, we deepened the discussion on the relationship between the mobility and stress in 4H-SiC MOSFETs.

2. Experimental methods

We used a conventional lateral n-channel MOSFET prepared on a 4° off p-type 4H-SiC(0001) substrate. The thickness of the gate oxide and the carrier concentration of the p-type well were 100 nm and 3 × 1017 cm−2, respectively. The channel length L and width W were 10 and 80 μm, respectively. 4H-SiC MOSFETs including two channel directions [1120] and [1100] were prepared on the chip (8 × 8 × 0.1 mm3), and set on a custom-designed bend-holder as shown in Fig. 1. An uniaxial stress was applied to the chip using this bend-holder. In order to apply tensile and compressive stresses to the chip, we prepared the convex- and concave-bend-holders with various curvature radii R = 30–100 mm. The stress was applied the chip to work into the top cover with a window for measurement and the basis holder.

We also calculated the distribution of the applied stress and strain in chip by bend-holder using the FEM analysis.
source electrodes, respectively. The characters of G, D, and S mean gate, drain, and source, respectively. The lateral MOSFET in chip. The characters of G, D, and S mean gate, drain, and source, respectively.

2.65 \times 10^{23}$ and the stage variation of the modulus were $0.16$ and $390$ GPa. Figure 3(a) shows a typical perpendicular stress distribution of the device configuration in the lateral MOSFET in chip. The characters of G, D, and S mean gate, drain, and source electrodes, respectively.

First, we numerically calculated the stress and strain in the device due to fabrication processes was evaluated using FEM and Raman spectroscopy, which values were estimated to be $\sim 240$ MPa. Thus, based on these results, our bend-holders can effectively apply a uniaxial stress to MOSFETs fabricated on the chip surface.

Figure 3(c) shows the strain distribution with the convex- and concave-bend-holders of $R = 40$ mm as a function of the distance from the chip surface. The positive and negative values mean tensile and compressive stress, respectively. It is found that the absolute values of maximum strain become the surface and back sides in the $x$ direction. The strain of in the half of the chip thickness becomes to zero. In contrast, in the case of the $y$ direction, the strain values are too small which hardly changes along the depth direction. The strain at surface was estimated to be $\pm 0.13\%$. It found that the convex- and concave-bend-holders can be applied to strain in the 4H-SiC chip approximately $\pm 0.1\%$.

Figure 4(a) shows results of the measured Raman shift of Si–C bond for 4H-SiC MOSFETs strained with the convex-bend-holder for $R = 40$ mm. The quartz line around $430$ cm$^{-1}$ and the $E_2$ mode in 4H-SiC around $776$ cm$^{-1}$ are clearly observed. The insert figure shows the $E_2$ mode with changing the focal point distance which means the different measurement depth along the $z$ direction. We changed the focal point using the change of the stage position. The peak position shifts with the focal point, which means different strain corresponding to the measurement depth. The peak position for the chip strained by various bend-holders with different $R$ as a function of the $z$ position which is defined zero at the surface of the Al electrode are shown in Fig. 4(b). Here, in these holders names, “R30” means the radius of the inside area of hemmed-in yellow dash line indicates the measurement window area. The MOSFET devices in the chip are situated in this area when we measure $I–V$ characteristics. From the simulation result, we can observe that the stress in the measurement window area is uniform.

Figure 3(b) shows the stress values of $x$ and $y$ directions near the center of chip [pointing using circle in the measurement window area shown in Fig. 3(a)] and the results corresponding to Eqs. (1) and (2) as a function of curvature radius in the custom-designed bend-holder. Equations (1) and (2) mean a relationship maximum stress ($\sigma_{max}$) for the curvature radius in the custom-designed bend-holder with $x$ and $y$ directions, respectively.

\[
\sigma_x = \frac{Ed_x}{R}, \quad \sigma_y = \frac{Ed_y}{R},
\]

where $E$, $v$, $d$, and $R$ are the Young’s modulus, the Poisson ratio, the half of the chip thickness, and the curvature radius in the custom-designed bend-holder, respectively. We confirmed that the value of FEM simulation results corresponds to that of Eqs. (1) and (2) as shown in Fig. 3(b). The value of the $x$ direction is an order of magnitude greater than that of the $y$ direction. The stress in the chip increases with decreasing the radius $R$. These results show that the uniformly uniaxial stress can be applied in the measurement window area of the chip using the custom-designed bend-holder. From recent report, a strain in device due to fabrication processes was evaluated using FEM and Raman spectroscopy, which values were estimated to be $\sim 240$ MPa. Thus, based on these results, our bend-holders can effectively apply a uniaxial stress to MOSFETs fabricated on the chip surface.

3. Results and discussion

3.1. Stress and strain evaluation

First, we numerically calculated the stress and strain in the chip by FEM analysis using Poisson ratio and Young’s modulus were 0.16 and 390 GPa. Figure 3(a) shows a typical perpendicular stress distribution of the $x$ direction in the chip with the convex-bend-holder of $R = 40$ mm. $x$, $y$, and $z$ directions were defined parallel- and perpendicular-directions to the bend direction, and a depth direction, respectively. The penetration depth of the 532 nm laser was $\sim 1 \mu m$. The spot size was smaller than 1 $\mu m$. The focal position (FP) from surface is defined parallel- and perpendicular-directions to the bend direction, respectively. The depth resolution was ranging from 1 $\mu m$ to a few $\mu m$. We obtained the quartz line simultaneously to calibrate the thermal fluctuation in the Raman measurement. The electron mobility in MOSFET samples strained with the bend-holder was estimated directly from the drain current-voltage ($I_D–V_G$) characteristics.

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bend-holder (mm), and "T" and "H" mean the convex and concave of bend-holders, respectively. The Raman shift of E_2 mode in 4H-SiC was measured for not only the chip after the MOSFET fabrication but also a bare SiC chip for comparison. In the Raman shift of the chip after the MOSFET and the bare SiC chip without the bend-holder, the peak position of E_2 mode hardly shifts with different focal point. This means that the peak shift of E_2 mode in the chip does not occur under the no strain condition. On the other hand, the peak position of E_2 mode in the chip strained with the concave-bend-holder decreases with increasing the z position. In contrast, in the case of the convex-bend-holder, the Raman shift increases with the z position. In all bend-holder conditions, the peak positions of E_2 mode at the z position around 18 μm correspond with that of the no strain case. It indicates that this position means the center of chip. The behavior of the Raman shift with a focal point is corresponding to the FEM simulation results as shown in Fig. 3(c). It notes that the z position is different from the actual moving distance in the chip of focal point. This result indicates that Raman measurement could be performed from the surface to back side in the chip using the change of z position. Here, we
picked up these vales of the Raman shift at the surface position which is the z position at 0 μm since the mobility was estimated using lateral MOSFET.

The stress value was also estimated from the Raman shift at the surface using the conversion factor $-323 \text{ MPa}/\text{cm}^2$. Figure 5 shows the Raman shift and stress in the bare 4H-SiC substrate, 4H-SiC MOSFET, and the calculated value using Eqs. (1) and (2) with various bend-holders. We found that the stress value of the chip after MOSFET fabrication almost corresponds to that of bare SiC substrate, which means that the strain induced during the MOSFET fabrication process is enough small to be ignored. These stress values are intermediate values calculated results using between Eqs. (1) and (2). It has been reported that the Young’s modulus of SiC is ranging from 300 to 500 GPa. The Young’s modulus of 4H-SiC was characterized using three-point bending experimental, which is reported to be 503.7 GPa. We calculated using the Young’s modulus 390 GPa, which is not too large value. E2 mode are non-polar, and there is no dependency on the propagation angle. Thus, we suggested that the difference of measurement vales from calculated vales is due to average of x, y, and z directions with a few μm region since we used green laser with a wavelength of $\lambda = 532$ nm. From these results, we confirmed that the stress in MOSFET can be controlled by the radius of bend-holder. It is noted that the measurement value is an underestimation of the practical stress value.

3.2. Electrical characteristic with uniaxial stress

Figure 6 shows $g_m$–$V_g$ characteristics which was estimated from $I_D$–$V_D$ characteristics at room temperature for various stressed samples. The stress values shown in Fig. 6 was estimated from the Raman shift. In the case of the [1120] bend direction, the variation of $g_m$ for various stress values at the [1100] current direction is larger than those at the [1120] current direction. In contrast, in the case of the [1100] bend direction, the variation of $g_m$ for various stress values at the [1120] current direction is also large. The $g_m_{\text{max}}$ which is the maximum value of $g_m$ increases with the uniaxial compressive stress, when the stress increases at the current direction perpendicular to the bend direction. The electron field-effect mobility $\mu_{\text{FE}}$ was estimated from the value of $g_m_{\text{max}}$ using Eq. (3)

$$\mu_{\text{FE}} = \frac{L}{W} \frac{g_m_{\text{Max}}}{C_{\text{ox}} \cdot V_D},$$

where $C_{\text{ox}}$ and $V_D$ are the oxide capacitance and the drain voltage, respectively. Figure 7 shows the field-effect mobility with two bend directions the [1100] and [1120] as a function of the stress value. In the case of tensile stress, the value of $\mu_{\text{FE}}$ decreases with increasing the stress. In contrast, in the compressive stress, the value of $\mu_{\text{FE}}$ increases with the stress. We found that the variation of $\mu_{\text{FE}}$ for the stress increases at the current direction perpendicular to the bend direction.

Here, we make a comparison between these results and a behavior of piezoresistance in n-type 4H-SiC. The piezoresistance in 4H-SiC has been reported from experimental and calculated results. Akiyama et al. reported the piezoresistance characteristic in n-type 4H-SiC using piezoresistors with p–n junction of cantilever beam structure at room temperature. Their results were obtained positive (negative) values of the gage factor (GF) with the current direction perpendicular (parallel) to the tensile strain. The positive (negative) values of GF indicate that the conductivity of the SiC piezoresistors decreases (increases) with increasing the stress. Also, a similar tendency has been reported from calculation study. Nakamura et al. reported the GF calculation of a 1% uniaxial tensile strain along the [1100] direction on the 4H-SiC(0001) nanosheet model. The GF also exhibits positive (negative) values with current flow perpendicular (parallel). This behavior is explained by that the valley bottoms at the M point are split into two energy levels ($M_1$, $M_2$) owing to the [1100] strain. Accordingly, the carrier distribution is biased toward the $M_1$ valleys.

In the tensile stress with the perpendicular configuration, the mobility in this study decreases, i.e. increasing resistance, which is the similar tendency of reported results on the perpendicular piezoresistor of n-type 4H-SiC. On the other hand, in the parallel configuration, the variation of mobility with the stress slightly decreases, which is dissimilar to reported piezoresistor results. This indicates that the behavior of piezoresistance of MOSFET is different from the bulk case. Recently, Jaeger et al. reported the piezoresistive coefficients of lateral n-MOSFET on 4H-SiC with a four-point-bending fixture. From the report, the drain currents with both the parallel and perpendicular configuration decrease with increasing the tensile stress. Moreover, the perpendicular responses to stress tend to be larger than those for parallel stress. These results are similar to that in this study. On the other hand, the effect of stress for changing mobility has not been clear.

In the strained Si MOSFET, the strong carrier confinement in inversion layers occur and the strain resolve the sixfold degeneracy of conduction band minima. It suggested two factors of the mobility enhancement associated with strain in Si that the suppression of intervalley phonon scattering due to the strain-induced band splitting, and the decrease in the occupancy of the fourfold valleys which exhibit a lower mobility due to the stronger interaction with intervalley phonons.

In order to investigate effects of scattering on mobility, we examined to separate mobility components such as Coulomb scattering ($\mu_C$), optical phonon scattering ($\mu_{\text{OP}}$), and surface roughness scattering ($\mu_{\text{SR}}$) according to the scattering model reported in the previous work using Matthiessen’s rule as shown in Fig. 8.
Figures 8(a)–8(c) show the effective channel mobility ($\mu_{\text{eff}}$) as a function of the effective field $E_{\text{eff}}$ with measurement temperatures at 200, 350, and 500 K, respectively, with a stress value of 180 MPa and the current flow perpendicular to the bend direction [1120]. The $\mu_{\text{eff}}$ was calculated with the extracted $V_{\text{th}}$ using a conventional equation$^{32}$ and $E_{\text{eff}}$ is defined by$^{33}$

$$E_{\text{eff}} = \frac{q}{\varepsilon_{\text{SiC}}}(N_{\text{dpl}} + \eta N_i),$$

where $g_D$ is the drain conductance, $q$ is the elementally charge, $N_i$ is the surface inversion carrier concentration, $\varepsilon_{\text{SiC}}$ is the permittivity of SiC, $N_{\text{dpl}}$ is the surface concentration of the depletion charge, and $\eta$ is the empirical parameter. The $\mu_{\text{eff}}$ shows a strong dependence not only on the effective field but also on the temperature, which indicates Coulomb scattering and phonon scattering as shown in Fig. 8. Kutsuki et al., reported the carrier scattering model in 4H-SiC trench MOSFETs.$^{31}$ According to the scattering model reported in the previous work, the total inversion layer mobility can be described by

$$\frac{1}{\mu_{\text{eff}}} = \frac{1}{\mu_C} + \frac{1}{\mu_{\text{OP}}} + \frac{1}{\mu_{\text{SR}}},$$

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These \( \mu_C \), \( \mu_{OP} \), and \( \mu_{SR} \) were determined by

\[
\mu_C = \frac{T}{N_T} \left( 1 + \frac{N_s}{N_{str}} \right),
\]

\[
\mu_{OP} = \frac{C}{E_{eff}} \left[ \exp \left( \frac{\hbar \omega_{OP}}{kT} \right) - 1 \right],
\]

\[
\mu_{SR} = \frac{\delta}{E_{eff}},
\]

where \( N_T \) is the total number of trapped charges, \( T \) is the absolute temperature, \( \hbar \omega_{OP} \) is the optical phonon energy, \( k \) is the Boltzmann constant, and \( N_{str}, C, \) and \( \delta \) are empirical parameters. The individual contributions of mobility terms \( (\mu_C, \mu_{OP}, \) and \( \mu_{SR}) \) to total effective mobility were calculated at each temperature, as demonstrated in Figs. 8(a)–8(c). In the all measurement temperature, the calculated \( \mu_{eff} \) curves are fitted to the measurement \( \mu_{eff} \) curves using mobility components of \( \mu_C, \mu_{OP}, \) and \( \mu_{SR} \). In the low measurement temperature, the calculated \( \mu_{eff} \) curve almost overlap the \( \mu_C \) curve as shown in Fig. 8(a). And then, in a higher measurement temperature, the \( \mu_C \) also dominant component in the low effective field. We suggest that \( \mu_C \) acts in a dominant factor for \( \mu_{eff} \) at a low temperature and the effective field due to a high doping concentration in the substrate. On the other hand, \( \mu_{OP} \) becomes a dominant factor at a high temperature and a high effective field. Next, we investigated effects of stress on the \( \mu_C \) and \( \mu_{OP} \).

Figures 9(a) and 9(b) show the \( \mu_C \) at 200 K and \( \mu_{OP} \) at 500 K, respectively, with the current flow at the [1100] or [11\overline{2}0] directions to the bend direction [11\overline{2}0] at an effective field of 1 MV cm\(^{-1}\) as a function of the stress. The measurement temperature is picked up that these mobility components became a dominant factor. Both \( \mu_{OP} \) and \( \mu_C \) with the current flow along the [1100] direction, i.e. the perpendicular configuration increases with increasing the stress value. In contrast, in the parallel configuration, the \( \mu_{OP} \) and \( \mu_C \) hardly change for stress values. The variation of both \( \mu_{OP} \) and \( \mu_C \) with the stress of approximately \( \pm300 \) MPa are approximately ten percent. This means that the specific scattering becomes non-dominant by stress. Here, we assumed that the surface inversion carrier concentration with different stress conditions is same. As a result, we considered that the average effective mass of 4H-SiC is changed.

In the Si case, strain induced the mobility enhancement which mainly originates from the reduction of scattering rates, together with the reduction of mean conductivity effective mass through repopulation effects of modulated band structure.\(^{19}\) From the previous calculation report, the M point at the conduction minimum are split into two energy levels owing to the strain and then the carrier distribution occurs.\(^{19}\) Thus, in the one possible reason of mobility enhancement in the 4H-SiC MOSFET, we suggested that the channel mobility to apply the uniaxial stress is changed by changing the average effective mass which occurs by carrier redistribution due to split of the M point. On the other hand, anisotropic characteristics of mobility changing in 4H-SiC MOSFET cannot enough explain the bulk case. It will be necessary to study more the calculation and experimental results in a strained 4H-SiC MOSFET.

4. Conclusions

We first demonstrated changing the inversion channel mobility of lateral n-channel MOSFET on 4H-SiC(0001) with applying mechanical uniaxial compressive and tensile strains using the custom-designed bend-holder. The stress in the chip after MOSFET fabrication was comprehensively estimated by Raman scattering measurement and FEM calculation. We confirmed that amount of stress values in the chip can change the curvature radials in the custom-designed bend-holder. We found that the inversion channel mobility of 4H-SiC(0001) MOSFET increases with the uniaxial compressive stress, and the variation of \( \mu_{eff} \) for the stress increases at the current direction perpendicular to the bend direction. In contrast, with the parallel configuration, the mobility is hardly changed by the applied stress. In order to investigate the effects of scattering for mobility, we separated the components of effective channel mobility \( (\mu_{eff}) \). From the temperature dependence of \( \mu_{eff} \), the Coulomb scattering \( (\mu_C) \) acts in a dominant factor for \( \mu_{eff} \) at a low temperature and the low effective field. On the other hand, the value of phonon scattering \( (\mu_{OP}) \) decreases with increasing measurement temperature. The variation of both \( \mu_{OP} \) and \( \mu_C \) with the stress of approximately \( \pm300 \) MPa are approximately ten percent. This means that the specific scattering becomes non-dominant by stress. Thus, we
deduced that the mobility enhancement is attributed to the effective mass decreased by the applied stress.

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