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Impact of Mechanical Uniaxial Stress on Mobility Enhancement of 4H-SiC (0001) MOSFET

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Abstract

We investigated the impact of the mechanical uniaxial strain on the inversion channel mobility of 4H-SiC(0001) n-MOSFET. We found that the inversion channel mobility effectively increases with the uniaxial compressive stress mechanically applied with bend holders. From the temperature dependence of mobility, we concluded that the enhancement of mobility is attributed to the reduction of effective mass in 4H-SiC by introduced stress.

1. Introduction

4H-SiC having 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). In the state-of-the-art Si-MOSFET technology, the enhancement of mobility in a strained Si by the band structure modulation has been well established [1]. On the other hand, the strain engineering technology of SiC MOSFET is still limited; recently, the isotropic piezo resistance has been reported for p-type 4H-SiC in (0001) plane [2], although the piezo resistivity of n-type 4H-SiC was only theoretically investigated using the first principle simulation [3]. There is no detail report for the effect of a strain on the mobility in 4H-SiC MOSFET. In this work, we investigated the effects of mechanical uniaxial strain on the inversion channel mobility in 4H-SiC(0001) n-MOSFET.

2. Experimental

We used a conventional n-channel MOSFET on a 4° off p-type 4H-SiC(0001) substrate. The channel length, L and width, W were 10 and 80 μm, respectively. The 4H-SiC MOSFETs with two channel directions $[11\bar{2}0]$ and $[1\bar{1}00]$ were prepared on the chip (8×8×0.1 mm^3). An uniaxial stress was applied to the chip using an custom-designed bend-holder. We prepared the convex- and concave-bend-holders with curvature radials R=30 to 100 mm. In order to apply to stress in the chip, the chip was wedged between the top cover with a window for measurement and the basis holder. First, we confirmed that an uniaxial stress was applied to the sample using the holders. The distribution of the applied stress and strain in chips with bend-holders were calculated using finite element analysis software (ANSYS 19.0). The stress value applied to samples was also experimentally estimated using micro Raman measurement with confocal optical system (λ =532 nm). We simultaneously obtained the quartz line to calibrate the thermal fluctuation in the Raman measurement. The mobility in MOSFET samples strained with the bend holders was estimated directly from the drain current-gate voltage (I_D-V_g) characteristics.

3. Results and discussion

3.1 Stress and strain evaluation

Figure 1 shows results of measured Raman shift for various bend-holders with different radii R. The Raman shift was measured for not only bare SiC substrate but also the chip after the MOSFET fabrication. The stress value was also estimated from the Raman shift using the conversion factor −323 MPa/cm^{-1}[4]. Here, in these holders names, "R30" means the radius of the bend-holder (mm), and "T" and "H" mean the convex and concave of bend-holders, respectively. As shown in Fig. 1, we confirmed that the stress in MOSFET can be controlled depending on the radius of bend-holder. We also found that the stress value of the sample after the MOSFET fabrication almost corresponds to that of bare SiC substrate, which means that the strain induced with the MOSFET fabrication process is enough small to be ignored.

3.2 Electrical characteristic with uniaxial stress

Figure 2 shows g_m-V_g characteristics which was calculated from I_D-V_g characteristics at room temperature for various bend-holders. In the case of the $[11\bar{2}0]$ bend direction, the variation of g_m-V_g characteristics for various bend-holders at the $[1\bar{1}00]$ source-drain (S/D) direction is larger than that

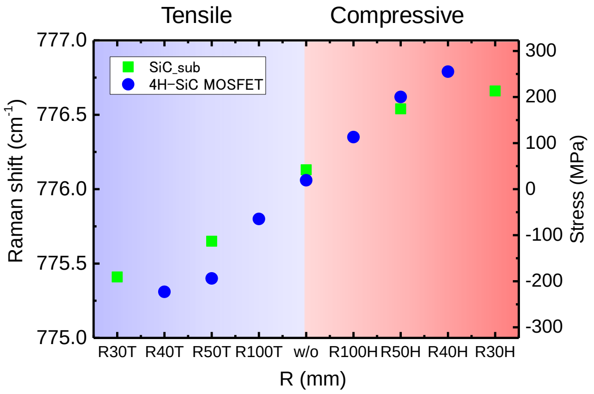

Fig.1 Raman shift of SiC strained with various bend-holders.

at the $[11\bar{2}0]$ S/D direction. In contrast, in the case of the $[1\bar{1}00]$ bend direction, the variation of g_m-V_g characteristics for various bend-holders at the $[11\bar{2}0]$ S/D direction is also large.

The electron field-effect mobility μ_{FE} was estimated from the value of g_{mMax} using eq. (1). The g_{mMax} means maximal value of the g_m.

$$\mu_{FE} = \frac{L}{W} \cdot \frac{g_{mMax}}{C_{ox} \cdot V_D} \quad (1)$$

Here, C_{ox} and V_D are the oxide capacitance and the drain voltage, respectively. Figure 3 shows the field-effect mobility as a function of the stress value estimated from the Raman measurement. In the case of tensile stress, the value of μ_{FE} decreases with increasing the stress. In contrast, in the compressive stress, the value of μ_{FE} increases with the stress. We found that the variation of μ_{FE} for the stress increases at the current direction orthogonal to the bend direction.

Next, we examined to separate mobility components such as Coulomb scattering (μ_C), optical phonon scattering (μ_{OP}), and surface roughness scattering (μ_{SR}) according to the scattering model reported in the previous work [5] using Matthiessen's rule as shown in Figs. 4. The total inversion layer mobility can be described by

$$\frac{1}{\mu_{eff}} = \frac{1}{\mu_C} + \frac{1}{\mu_{OP}} + \frac{1}{\mu_{SR}} \ . \quad (2)$$

From Fig. 4(a), the calculated μ_{eff} curve close to the μ_C curve. We suggest that μ_C act in a dominant factor for μ_{eff} at a low temperature. On the other hand, value of μ_{OP} decreases with increasing measurement temperature. This means that μ_{OP} has an impact on μ_{eff} at a higher temperature. Especially, μ_{OP} becomes a dominant factor at a high temperature and a high effective field.

Then, we investigated effects of the stress and stress direction on μ_{OP} at 500 K and μ_C at 200 K as shown in Figs. 5. μ_{OP} and μ_C at the $[1\bar{1}00]$ S/D direction similarly increase with the stress while μ_{OP} and μ_C at the $[11\bar{2}0]$ S/D direction hardly change with the different stress values. This result indicates that the effective mass of 4H-SiC can be effectively enhanced by the applied stress.

4. Conclusions

We found that the inversion channel mobility of 4H-SiC(0001) MOSFET increases with the uniaxial compressive stress, and the variation of μ_{FE} for the stress increases at the current direction orthogonal to the bend direction. We deduced that the mobility enhancement is attributed to the effective mass decreased by the applied stress.

References

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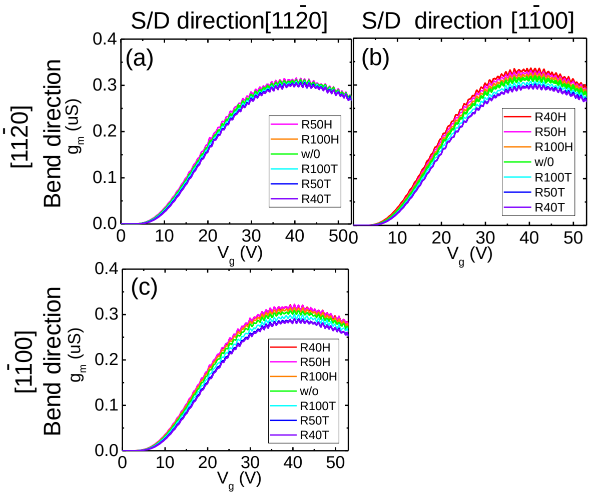

Fig. 2 g_m-V_g characteristics at room temperature with the various bend-holder at V_D=100 mV.

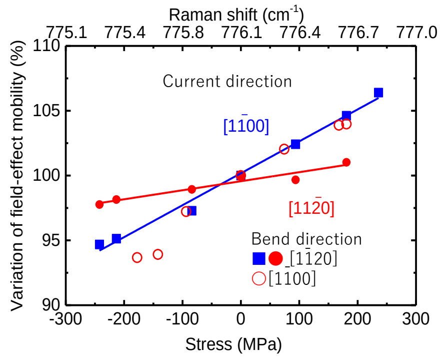

Fig.3 The variation of field effect mobility as a function of the stress.

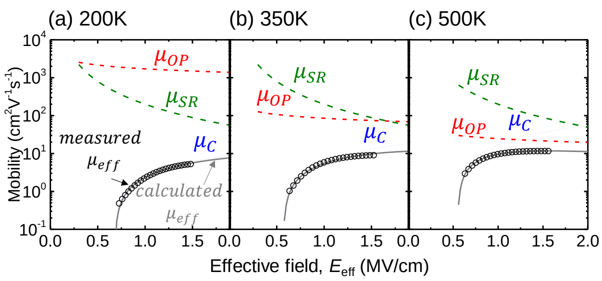

Fig.4 Calculated inversion channel mobility taking into account μ_C, μ_{OP} and μ_{SR}, based on the conventional Si-based model at (a) 200, (b)350 and (c)500K. The experimental data with R50H at the S/D direction and bend direction of $[11\bar{2}0]$ for fabricated MOSFETs are also plotted at each temperature.

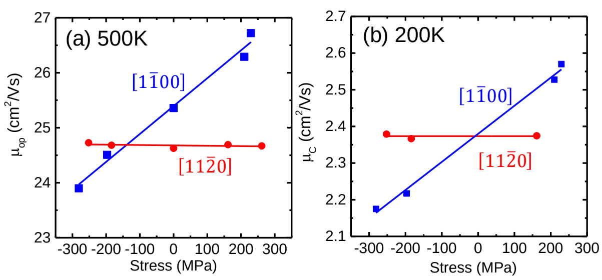

Fig.5 (a) μ_{OP} and (b) μ_C at effective field of 1 MV/cm as a function of the stress.