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Inversion-Layer Mobility Limited by Coulomb Scattering on Si (100), (110) and (111) n-MOSFETs

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Introduction

Recently, the surface orientation engineering, including hybrid orientation technique (HOT), has been intensively examined to enhance the scaled CMOS performance and to optimize the multi-gate structures [1,2]. Here, the enhancement of the inversion-layer mobility is a key in the surface orientation engineering. It has been reported [3] that the difference in mobility in Si MOSFETs on various surface orientations is basically explainable by that of the conductivity mass (m_c). However, the physical understanding of the surface orientation dependence of mobility is not sufficient. Particularly, the effects of the surface orientation on mobility limited by Coulomb scattering due to interface states and substrate impurities have not been studied yet, in spite of the importance of Coulomb scattering on scaled MOSFETs.

In this paper, the inversion-layer mobility limited by Coulomb scattering due to interface states (μ_{it}) and substrate impurities (μ_{sub}) on (100), (110) and (111) orientations are experimentally evaluated and the physical origins dominating μ_{it} and μ_{sub} are studied.

Devices and Experiment

The devices were conventional n-type MOSFETs with n^+ poly Si gate and 5-nm SiO_2 gate oxide. The electron mobility along the <110> direction was extracted by the split *CV* method. In order to avoid the overestimation of the number of electrons, the oscillation frequency of 1 MHz was used in gate-to-channel capacitance measurement. The gate length was 10 μm to obtain enough response to high frequency *CV* measurement. The gate width was 100 μm.

Fig.1 shows the measurement results of inversion-layer mobility (μ_{eff}), which are in agreement with the previous reports. μ_{it} was extracted by Matthiessen's rule (Fig.2(a)). Interface states were generated by Fowler-Nordheim (FN) injection from inversion-layer to gate oxide. The interface state density (D_{it}) was measured using the charge pumping method with 100 kHz pulse. Similarly, μ_{sub} was extracted by Matthiessen's rule between μ_{eff} with low channel concentration (N_A) and that with N_A of 1×10^{17} cm^{-3} (Fig.2(b)).

Results and Discussion

Figs.3 and 4 show D_{it} increment (ΔD_{it}) dependence of μ_{it} as a parameter of surface carrier densities (N_S). As reported [4], μ_{it} is inversely proportional to ΔD_{it}. The ΔD_{it}^{-1} dependence is confirmed to be independent of the surface orientations. The N_S dependence of μ_{it} with ΔD_{it} of 4×10^{11} cm^{-2}eV^{-1} is plotted in Fig.5. Each curve is confirmed to be proportional to $N_S^{+0.5}$, as previously reported [4]. μ_{it} with low N_A is higher than that with high N_A. In spite of the fact that the carriers in the lowest valley on (100) have the lightest m_c [5], the enhancement of μ_{it} on (100) against those on (110) and (111) is small, even if the N_A difference is taken into consideration. It is also found that the enhancement of μ_{it} on (100) against that on (110) is small under the same N_A of 1×10^{17} cm^{-3} (Fig.6). Fig.7 shows the μ_{it}-m_{c_ave} relationship, where m_{c_ave} was calculated by using the harmonic mean of the valley occupation ratio. Mobility is expressed as $\mu = q\tau/m_c$, where τ is the relaxation time. When τ is supposed to be independent of surface orientation in case of the same N_S and ΔD_{it}, μ_{it} is expected to increase with an increase in $1/m_c$. It is found, however, that μ_{it} on (100) and (110) is the same, in spite of the different values of m_{c_ave}. This result suggests that μ_{it} depends strongly on τ, as well.

One possible origin of this μ_{it} behavior is that the heavier normal mass (m_z) compensates the advantage due to lighter m_c. Since the constant-energy surface of Si conduction band has an ellipsoid-shape, the carriers with lighter m_c have heavier m_z (Fig.8) [5]. The heavier m_z leads to thinner inversion-layer thickness (Z_{ave}). The frequency of Coulomb scattering due to the interface states increases with a decrease in Z_{ave} [6], because the interface states are localized at the MOS interface (Fig.9). Fig.10 illustrates the fact that Z_{ave} is thinner when m_{c_ave} is lighter, meaning that the light/heavy m_c is compensated with the high/low frequency of Coulomb scattering due to thin/thick Z_{ave} with heavy/light m_z. As a result, the surface orientation dependence of μ_{it} can be significantly weakened (Fig.11).

On the other hand, Fig.12 shows that (100) μ_{sub} is higher than (110) μ_{sub}, in contrast to μ_{it} of Fig.6. As reported [7], μ_{sub} is proportional to N_S^{+1}. μ_{sub} does not depend on Z_{ave} because dopant atoms of scattering centers are uniformly distributed in channel regions. The μ_{sub} enhancement ratio (100)/(110) of ~ 1.3 in Fig.12 is smaller than the lowest valley m_c difference in the lowest valley of ~ 1.5 (Fig.8). As shown in Fig. 13, the calculated ratio of m_{c_ave}, weighed effective mass under multi valley occupation, between (110) and (100) is much smaller than the ratio of m_c in the lowest subband and increases with increasing N_S or N_A. As a result, the measured μ_{sub} ratio is almost explained by this m_{c_ave} ratio, meaning that the surface orientation dependence of μ_{sub} is explained by m_{c_ave} under multi subband occupation. Thus, the observed very weak surface orientation dependence of μ_{it} is also attributed to the effect of m_{c_ave}.

Conclusions

The μ_{it} and μ_{sub} characteristics on Si (100), (110) and (111) were experimentally examined. The effects of m_{c_ave} and Z_{ave} in the multi valley occupation are found to be the key factors on the very weak surface-orientation dependence of μ_{it}. The difference in μ_{sub} among different surface orientations is explained by m_{c_ave}. These new findings contribute to the comprehensive understanding of the carrier transport in MOSFETs and accurate modeling of the mobility limited by Coulomb scattering on various surface orientations.

Acknowledgements:

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References: [1] K. Uchida et al., IEDM2006, p.1019. [2] M. Saitoh et al., IEDM2007, p.711. [3] T. Satoh et al., Phys. Rev. B4, p.1950, 1971. [4] J. Koga et al., IEDM1994, p.475. [5] F. Stern, Phys. Rev. B, p.4891, 1972. [6] Y. Nakabayashi et al., SSDM2005, p.44. [7] S. Takagi et al., IEDM1988, p.398.

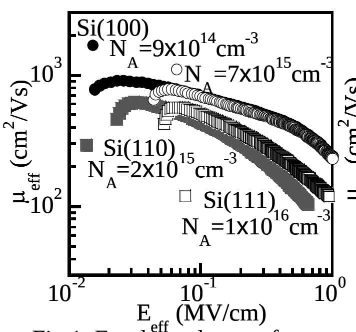


Fig.1 E_{eff} dependence of μ_{eff} on Si (100), (110) and (111). The channel direction is <110>.

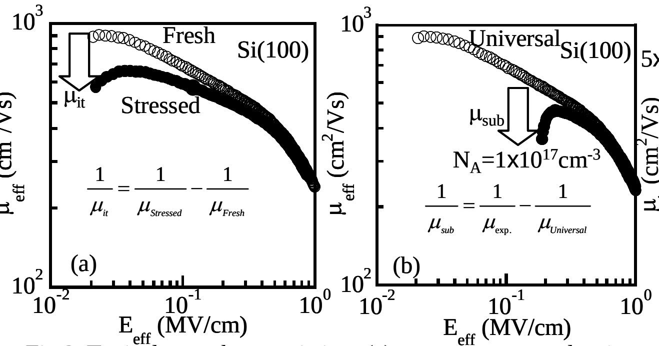


Fig.2 Typical μ_{eff} characteristics. (a) μ_{it} was extracted using Matthiessen's rule between before and after electrical stress. Interface states were generated by FN injection. (b) μ_{sub} was similarly extracted between universal curve and N_A of $1\text{x}10^{17}\text{cm}^{-3}$.

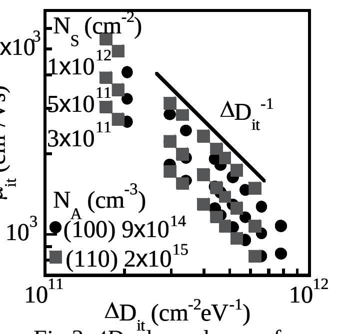


Fig.3 ΔD_{it} dependence of μ_{it} on (100) with N_A of $9\text{x}10^{14}$ cm^{-3} and (110) with N_A of $2\text{x}10^{15}$ cm^{-3}.

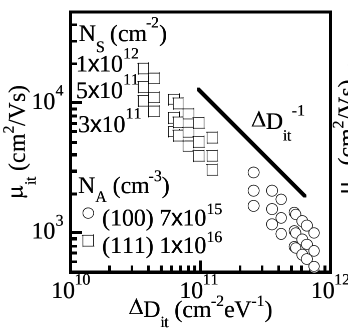


Fig.4 ΔD_{it} dependence of μ_{it} on (100) with N_A of $7\text{x}10^{15}$ cm^{-3} and (111) with N_A of $1\text{x}10^{16}$ cm^{-3}.

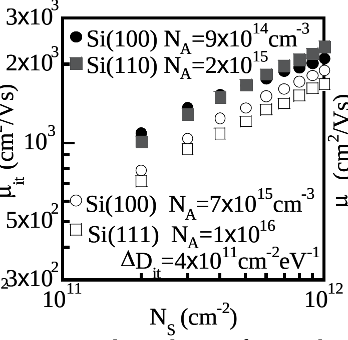


Fig.5 N_S dependence of μ_{it} with ΔD_{it} of $4\text{x}10^{11}$ $\text{cm}^{-2}\text{eV}^{-1}$. (111) μ_{it} is obtained from extrapolation of ΔD_{it}^{-1} dependence.

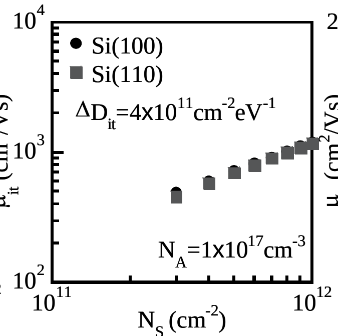


Fig.6 N_S dependences of μ_{it} on Si (100) and (110) with N_A of $1\text{x}10^{17}\text{cm}^{-3}$.

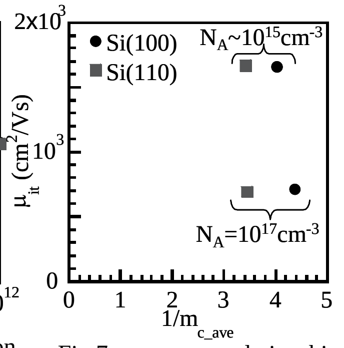
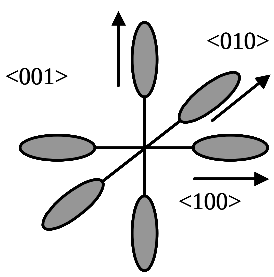


Fig.7 μ_{it}-m_{c_ave} relationship on various orientations at N_S of $5\text{x}10^{11}$ cm^{-2} and ΔD_{it} of $4\text{x}10^{11}$ $\text{cm}^{-2}\text{eV}^{-1}$.



	m_c	m_z
(100)	0.190	0.916
	0.315	0.190
(110)	0.283	0.315
	0.315	0.190
(111)	0.296	0.258

Fig.8 conduction band for electron and effective masses of three surface orientations.

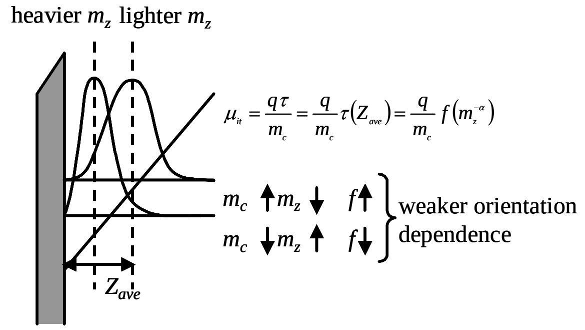


Fig.9 Surface charge distribution on MOS interface. When m_z is heavy, carrier distribution shifts near to interface, i.e., Z_{ave} becomes thin. Since the carriers with the lighter m_c are located closer to the interface, the frequency of Coulomb scattering due to interface states is increased.

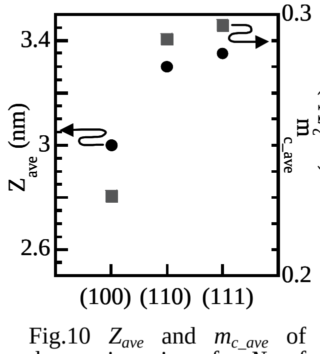


Fig.10 Z_{ave} and m_{c_ave} of three orientations for N_A of 10^{17}cm^{-3}. When m_{c_ave} light, Z_{ave} is thin.

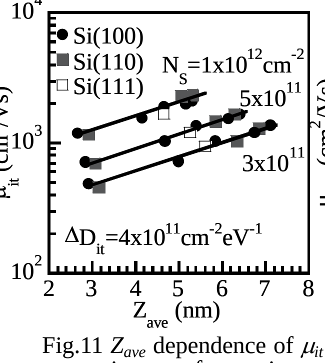


Fig.11 Z_{ave} dependence of μ_{it} on various surface orientations.

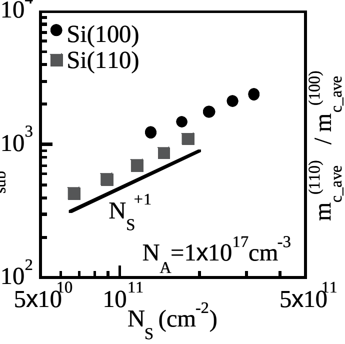


Fig.12 N_S dependences of μ_{sub} on Si (100) and (110) with N_A of $1\text{x}10^{17}\text{cm}^{-3}$. Surface orientation dependence is observed, in contrast to μ_{it}.

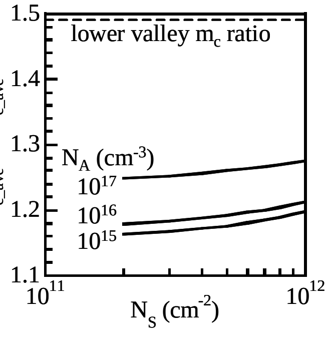


Fig.13 The ratio of m_{c_ave} (110) to (100). The ratio increases with increasing N_S or N_A.