Experimental Observation of Record-high Electron Mobility of Greater than 1100 cm²V⁻¹s⁻¹ in Unstressed Si MOSFETs and Its Physical Mechanisms

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1. Introduction

Electron mobility (μₑ) of bulk Si with low doping concentration is reported to be approximately 1500 cm²V⁻¹s⁻¹ [1]. However, it is well known that μₑ of bulk unstressed Si MOSFETs with extremely low substrate impurity concentration (universal mobility) never exceeds 1000 cm²V⁻¹s⁻¹ [2], even when MOSFETs are fabricated in perfectly controlled manufacturing facilities. Although one might consider that interface states (Nₛ) could be the origin of the lower μₑ, Nₛ is too low to explain the observed μₑ degradation. Therefore, much worse μₑ of Si MOSFETs has been a big mystery.

In this study, μₑ of greater than 1000 cm²V⁻¹s⁻¹ is demonstrated, for the first time, in unstressed Si MOSFETs, where accumulation-mode, body-channel SOI MOSFETs are used [3-5]. It is revealed that worse μₑ in conventional inversion-mode Si MOSFETs is primarily due to larger Dₑ at Si/SiO₂ interface [6] as well as the larger form factor induced by quantum confinement in 2D electron system.

2. Device structure

Fig. 1(a) shows the schematic of fabricated accumulation-mode, body-channel SOI MOSFETs with the same doping type in channel as that in the source/drain. Since there is no junction, drain current flows through the entire region of SOI layer at voltages around and higher than 𝑉₁/8 (Fig. 1(b)). Phosphorus concentration in SOI layer is 5x10¹⁵ cm⁻³, as is confirmed by SIMS measurement (Fig. 2). 𝑇ₛ𝑂𝐼 is in the range from 13 to 151 nm.

3. Mobility in body-channel SOI MOSFETs

Fig. 3 shows μₑ of 151 nm-thick, body-channel SOI MOSFET as a function of surface carrier concentration (𝑁ᵥ). The maximum μₑ of 1119 cm²V⁻¹s⁻¹ is clearly confirmed. This is the record-high μₑ in unstressed Si MOSFETs. Fig. 4 shows bulk Si μₑ as a function of doping concentration [1, 7]. μₑ of body-channel SOI MOSFET measured in this work is also indicated. It is demonstrated that μₑ of thick body-channel SOI MOSFETs is the same as bulk one.

4. Physical Mechanism of Higher Mobility

A. SOI thicknesses dependence

Fig. 5 shows the μₑ of body-channel SOI MOSFETs for various 𝑇ₛ𝑂𝐼. μₑ degrades gradually as 𝑇ₛ𝑂𝐼 decreases from 71 nm. In Fig. 6, μₑ of body-channel SOI MOSFETs is compared with that of inversion-channel SOI MOSFETs for 𝑇ₛ𝑂𝐼’s of 13 nm and 71 nm. It should be noted that when 𝑇ₛ𝑂𝐼 is approximately 15 nm, μₑ of body-channel MOSFETs is the same as that of inversion-channel MOSFETs. However, when 𝑇ₛ𝑂𝐼 is approximately 70 nm, μₑ of inversion-channel MOSFETs is lower than that of body-channel MOSFETs. These results are explained by the difference in carrier distribution within the channel (Fig. 7). In the 15 nm 𝑇ₛ𝑂𝐼 case, 𝑇ₛ𝑂𝐼 is so thin that electron distributions are the same for both the body- and inversion-channel SOI MOSFETs. On the other hand, in the 71 nm 𝑇ₛ𝑂𝐼 case, electrons populate more closely to the front MOS interface in the inversion-channel SOI MOSFETs; whereas electrons distribute more uniformly within the SOI layers in the body-channel SOI MOSFETs. These calculation results indicate that higher μₑ in thick body-channel SOI is due to the uniform carrier distribution in the thick body. The uniform carrier distribution may 1) decrease the form factor (a decrease in form factor increases μₑ), 2) decrease the impact of increased Dₑ at MOS interface [6], and 3) decrease the effect of Coulomb scattering due to interface states. All these effects contribute to enhance μₑ.

B. Deformation Potential (𝐷ₑ) Contribution in High μₑ

In our previous work [6], we proposed the new Dₑ model where Dₑ increases sharply toward the Si/SiO₂ interface (Fig. 8). Therefore, average Dₑ in body-channel SOI MOSFETs was considered to be lower than that in the inversion-channel SOI MOSFETs.

In order to confirm a decrease in average Dₑ of body-channel MOSFETs, we investigated the strain effects on μₑ for both MOSFETs, since μₑ enhancement ratio (Δμₑ/μₑ) is proportional to Dₑ. We applied uniaxial <110>-tensile stress parallel to the channel and the μₑ enhancement ratio (Δμₑ/μₑ) was compared (Fig. 9). It is shown that the Δμₑ/μₑ is smaller in body-channel SOI MOSFETs, indicating that Dₑ in body-channel SOI MOSFETs is smaller than that in inversion-channel SOI MOSFETs. Fig. 10 shows the Δμₑ/μₑ for various substrate biases (𝑉ₛ) in body-channel SOI MOSFETs. It is shown that Δμₑ/μₑ is increased as the magnitude of negative Vₛ increases. This is because the depletion layer induced by Vₛ reduces the channel thickness, leading to an increase in average Dₑ.

Finally, the effects of position dependent Dₑ, and wider wavefunction are more quantitatively studied by self-consistent calculations. The position dependent Dₑ (Fig. 11), which is slightly modified from our previous report [6], is used to calculate μₑ of body-channel SOI MOSFETs (Fig. 12). It is shown that μₑ of body-channel SOI MOSFET is well reproduced by the model. By using the same Dₑ model, we also reproduce the μₑ of inversion-channel SOI MOSFETs (Fig. 13). Fig. 14 illustrates experimental and theoretical μₑ as a function of 𝑇ₛ𝑂𝐼 in inversion-channel SOI MOSFETs [8], showing a good agreement. These results indicate the validity of our Dₑ model. In other words, the observed record-high μₑ is due to a smaller average Dₑ and smaller form factor in body-channel SOI MOSFETs.

5. Conclusions

We fabricated the body-channel SOI MOSFETs and observed the record-high μₑ of 1119 cm²V⁻¹s⁻¹ in 151-nm-thick devices. This is due to a unique electron distribution in the body-channel SOI MOSFETs; electron distribution within the entire SOI layer, which leads to a smaller form factor, a smaller average deformation potential (Dₑ), and less mobility degradation due to Coulomb scattering by Nₛ. From the stress effect on μₑ and the theoretical calculation of μₑ, the above model is confirmed (Fig. 15).
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References

Fig. 1: (a) Schematic of accumulation-mode, body-channel SOI MOSFETs. The channel doping type is the same as the source/drain ones. (b) Current components in the device. At a voltage higher than \( V_{FB} \), current flows in both the accumulation layer and body channel.

Fig. 2: Phosphorus SIMS profile in a 150 nm-thick body channel SOI MOSFET. Phosphorus concentration in SOI layer is determined to be \( 5 \times 10^{19} \text{cm}^{-3} \).

Fig. 3: Electron mobility (\( \mu_e \)) of 151-nm-thick accumulation-mode, body-channel SOI MOSFETs. The observed \( \mu_e \) of \( 1119 \text{cm}^2\text{V}^{-1}\text{s}^{-1} \) is the highest value among the values reported in unstressed Si MOSFETs.

Fig. 4: Electron mobility (\( \mu_e \)) as a function of donor concentration (\( N_D \)) in bulk Si. It is firstly demonstrated that \( \mu_e \) of thick body-channel SOI MOSFET is the same as that of bulk Si.

Fig. 5: Electronic mobility (\( \mu_e \)) for body-channel SOI MOSFETs in comparison with conventional inversion-channel SOI MOSFETs. The difference between two cases is obvious in thicker 70 nm-thick SOI MOSFETs.

Fig. 6: Mobility enhancement ratio (\( \Delta \mu/\mu \)) induced by uniaxial tensile stress for body- and inversion-channel SOI MOSFETs. The smaller \( \Delta \mu/\mu \) in body-channel SOI MOSFETs suggests that \( \Delta \mu \) in body-channel SOI MOSFETs is smaller than that in inversion-channel SOI MOSFETs.

Fig. 8: Position-dependent deformation potential (\( \Delta \mu \)) model proposed in Ref. 6. In bulk Si, \( \Delta \mu \) takes the position-independent value of 9 eV. On the other hand, in MOS structures, \( \Delta \mu \) increases sharply at Si/SiO\(_2\) interface. In MOSFETs, electrons are concentrated more at the MOS interface, which leads to an increase in the average \( \Delta \mu \) for electrons in MOSFETs.

Fig. 9: Mobility enhancement ratio (\( \Delta \mu/\mu \)) induced by uniaxial tensile stress for body- and inversion-channel SOI MOSFETs. The smaller \( \Delta \mu/\mu \) in body-channel SOI MOSFETs suggests that \( \Delta \mu \) in body-channel SOI MOSFETs is smaller than that in inversion-channel SOI MOSFETs.

Fig. 10: Mobility enhancement ratio (\( \Delta \mu/\mu \)) induced by uniaxial tensile stress in body-channel SOI MOSFETs for various substrate biases (\( V_s \)). It is shown that \( \Delta \mu/\mu \) increases as the magnitude of negative \( V_s \) increases.

Fig. 12: Mobility (\( \mu_e \)) versus surface carrier concentration (\( N_S \)) characteristics in body-channel SOI MOSFET. By using our position-dependent \( \Delta \mu \) model, calculated \( \mu_e \) agrees well with experimental data.

Fig. 13: Mobility (\( \mu_e \)) versus surface carrier concentration (\( N_S \)) characteristics in inversion-channel SOI MOSFET. The good agreement between calculation and experiment is also confirmed in conventional, inversion-channel SOI MOSFETs.

Fig. 15: The origin of mobility difference. In body-channel SOI MOSFETs, higher mobility is observed because of 1) smaller electron density in larger deformation potential region, 2) smaller form factor, and 3) less influence of interface states.