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Mobility Enhancement of SOI MOSFETs Due to Subband Modulation in Ultra-Thin SOI Films

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1. Introduction

Low field mobility is still one of the most important physical quantity even for ultra-short channel MOSFETs, because the velocity overshoot effect, which enhances the performance of MOSFETs, is more pronounced with higher mobility in the inversion layer. It is known that inversion-layer electrons on a (100) surface are composed of two kinds of subbands; one is the 2-fold valleys with lighter effective mass perpendicular to the Si/SiO_2 interface and the other is the 4-fold valleys with heavier effective mass. Therefore, an effective strategy to realize higher mobility is to increase the population of the 2-fold valleys, which have higher mobility due to lower conductivity mass.

This paper reports, for the first time, through the theoretical calculation of phonon-limited mobility that, by thinning the SOI layer down to the inversion-layer thickness of bulk MOSFETs, the increase in the occupation of the 2-fold valleys and the resulting higher mobility can be obtained. In such thinner SOI films the subband structure is significantly modulated through the size effect of the SOI thickness itself.

2. Calculation Method

The 2-D subband structure of SOI MOSFETs was determined by applying the method of the self-consistent calculation [1, 2, 3] to the idealistic SOI structure, in which the SOI thickness is uniform and no interface roughness exists. As for the scattering mechanism, only phonon scattering was taken into account, because it dominates the room temperature mobility in Si inversion layer and it is intrinsic scattering mechanism. The mobility was calculated under the relaxation time approximation, using the results of the subband calculations including 20 subbands. Both intra-valley acoustic phonon and inter-valley phonon scattering are included in the same manner as in [2]. It should be noted that the scattering parameters have been carefully chosen [2] so as to fit the experimental mobility in bulk MOSFETs [4]. The substrate impurity concentration of SOI layer was taken to be 5×10^{15} cm^{-3}.

3. Calculated Results

Figs. 1(a), (b) and (c) show the calculated mobility versus the effective normal field, E_{eff}, as a parameter of the thickness of SOI layer, T_{SOI}. The mobility- E_{eff} curve in bulk MOSFETs is also shown for comparison. It is found that mobility has a complicated T_{SOI} dependence, which is summarized as follows; (1) In 20 nm > T_{SOI} > 5 nm, the mobility decreases with a decrease in T_{SOI}. (2) In 5 nm > T_{SOI} > 3 nm, mobility increases with a decrease in T_{SOI}. It is found, in particular, that the SOI mobility with T_{SOI} of around 3 nm becomes higher in higher E_{eff} region than the mobility of bulk MOSFETs. Also, the E_{eff} dependence becomes weaker. (3) In 3 nm > T_{SOI} > 2 nm, mobility decreases with a decrease in T_{SOI}. The mobility with T_{SOI} thinner than 3 nm has almost no E_{eff} dependence.

4. Analysis

The above complicated T_{SOI} dependence of mobility is clearly explained by following two factors; one is the change in the subband occupancy of the 2-fold valleys due to the size effect and the other is the dependence of the inversion-layer thickness on the mobility. Since the 2-fold valleys has lighter conductivity mass than the 4-fold valleys, the increase in the occupation of the 2-fold valleys leads to the increase in the total mobility. On the other hand, the phonon-limited mobility is known to become smaller with a decrease in the inversion-layer thickness [5, 6]. This is because, as electrons are confined more in space, the bandwidth of the frequency of phonons that can couple with 2DEG becomes wider. These two mechanisms competes with each other in terms of the T_{SOI} dependence.

The schematic diagram for explaining the effect of T_{SOI} on the subband structures is shown in Fig.2. In T_{SOI} thicker than 20 nm, the subband structure in SOI MOSFETs is the same as in bulk. As T_{SOI} becomes thinner than 20 nm, the wave function of electrons in the 4-fold valleys is influenced by T_{SOI} and, consequently, the mobility of the 4-fold valleys decreases. Next, when T_{SOI} becomes thinner than 5 nm, the subband energy of the 4-fold is lifted up, because of the size effect of thin T_{SOI}. As a result, the occupancy of the 2-fold valleys and the resultant total mobility increases. However, when T_{SOI} becomes thinner than 3 nm, the mobility of the 2-fold valleys, in which all the electrons exist, are decreased by thinning T_{SOI}.

This interpretation is supported by the subband calculations. Figs. 3, 4 and 5 show the lowest subband energies, the electron occupancies of the 2-fold and 4-fold valleys and mobilities in the two kinds of the valleys as a function of T_{SOI}, respectively. It is confirmed that, in T_{SOI} thinner than 3 nm, the occupancy of the 2-fold valleys increases with decreasing T_{SOI} through the increase in the subband energy of the 4-fold valleys. Furthermore, in T_{SOI} thinner than 3 nm, all the electrons are occupied in the 2-fold valleys. In this T_{SOI} region, the inversion-layer thickness is defined physically by T_{SOI}. Thus, the mobility comes to have no E_{eff} dependence, because the E_{eff} dependence of mobility, seen in bulk MOSFETs, is basically provided through the E_{eff} dependence of the inversion-layer thickness [6]. A small peak in the mobility of the 2-fold valleys around 3 nm is attributable to the suppression of inter-valley scattering due to the increased subband energy of the 4-fold valleys.

5. Conclusion

It was found that the mobility of SOI MOSFETs with the SOI thickness of around 3 nm can be higher than that of bulk MOSFETs.

References 1) F.Stern, Phys.Rev. B5(1972)4891 2) S.Takagi, et al., J.Appl.Phys. 80(1996)1567 3) M.Shoji et al., J.Appl.Phys. 81(1997)786 4) S.Takagi et al., IEEE Trans.ED, 41(1994)2257 5) P.J.Price, Ann.Phys., 133(1981)217 6) S.Takagi et al., IEEE Trans.ED, 41(1994)2263

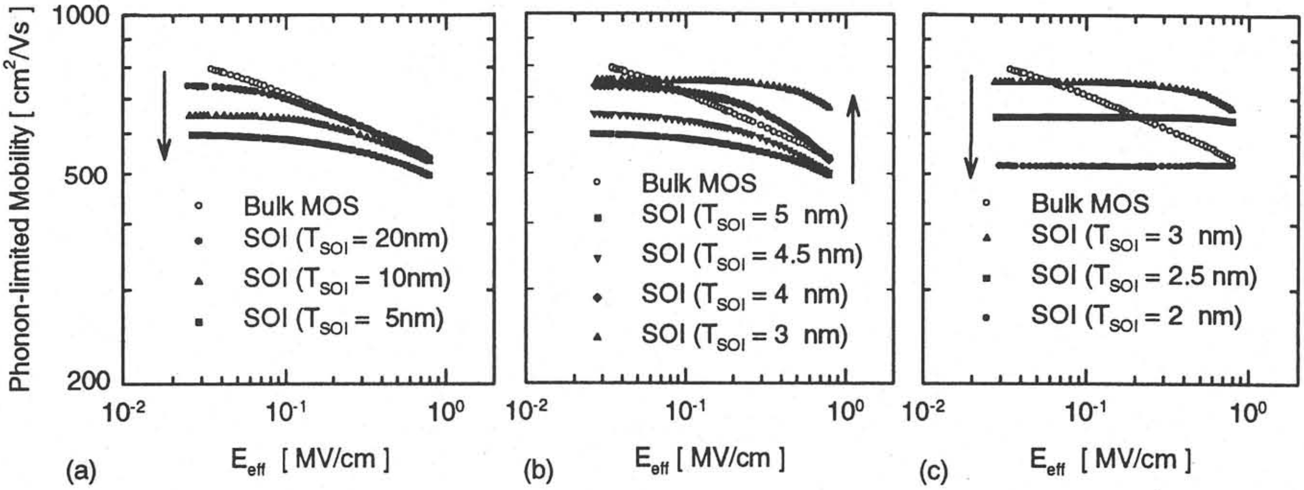

Fig.1 Calculated phonon-limited mobility of bulk and SOI MOSFETs with SOI thickness of 20 to 2 nm, as a function of E_{eff}.

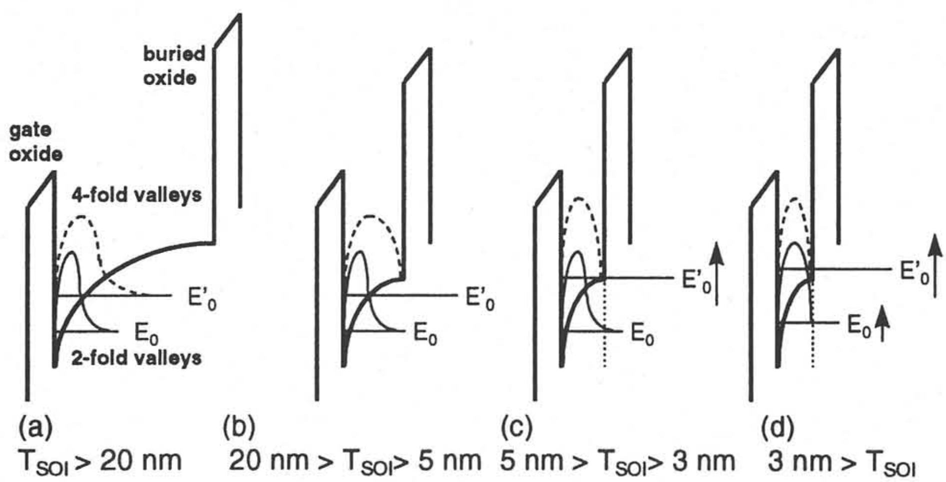

Fig.2 Schematic diagrams of the band structure of SOI MOSFETs. Here, E_0 and E'_0 denote the lowest subband energies of the 2-fold and the 4-fold valleys.

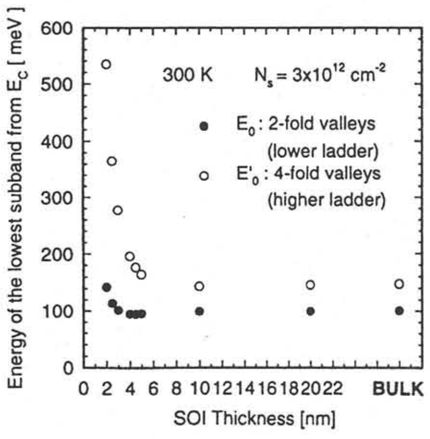

Fig. 3 Calculated lowest subband energies of the 2-fold and the 4-fold valleys, E_0 and E'_0, as a function of T_{SOI}

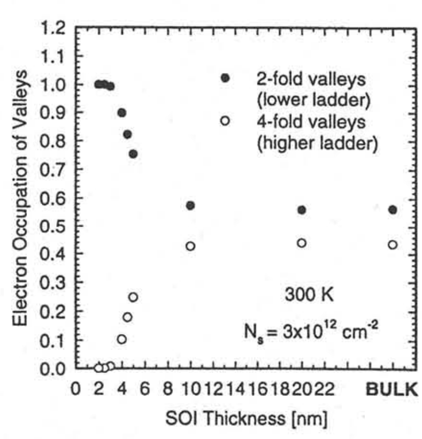

Fig. 4 Calculated electron occupancies of the 2-fold and the 4-fold valleys as a function of T_{SOI}

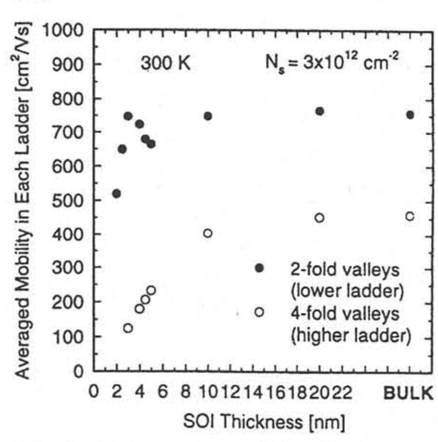

Fig. 5 Calculated mobilities of electrons in the 2-fold and the 4-fold valleys as a function of T_{SOI}