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Importance of Inter-valley Phonon Scattering on Mobility Enhancement in Strained Si MOSFETs

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INTRODUCTION It has recently been reported[1] that strained Si MOSFETs fabricated relaxed SiGe layer exhibits very high mobility at room temperature, almost twice as high as that in conventional Si MOSFETs. While strained Si MOSFETs, compatible with Si LSI technology, are promising as the devices for the high speed, room temperature applications, the understanding of the carrier transport in strained Si is still lacking. In order to clarify the mechanism of the mobility enhancement, calculations of the subband structure and phonon-limited mobility in the inversion layer of strained Si were performed for the first time, compared with the calculations for the inversion layer of unstrained (conventional) Si. The effect of the band splitting due to strain was successfully incorporated in the subband calculation. It is demonstrated that the suppression of inter-valley phonon scattering is essential to the mobility enhancement in strained Si MOSFETs.

CALCULATIONS Tensile strain in Si grown on (100) surface causes the energy of conduction band minima of the four valleys on the in-plane <100> axes higher than that of the two valleys perpendicular to the plane (Fig.1). This band splitting was incorporated in the self-consistent subband calculations, which were performed in the same manner as [2]. The mobility calculations including intra-valley and inter-valley phonon scattering were carried out under the relaxation time approximation, using the relaxation time described in [3]. Three parameter sets regarding inter-valley scattering were used in the calculations. Two of the models are conventional ones (set A(Jacoboni[4]) and B(Ferry[5])), and a new one (set C) is given by multiplying the deformation potential of set B by a constant value so as to increase the coupling with inter-valley phonons. It was found that the higher coupling with inter-valley phonons in parameter set C is necessary to quantitatively represent the mobility of the conventional Si MOSFETs (Fig.2) and its temperature dependence. Furthermore, this higher coupling can also explain the magnitude of the mobility enhancement in strained Si, as shown below.

RESULTS AND DISCUSSIONS The ratio of the phonon-limited mobility of strained Si to that of unstrained Si is shown as a function of the Ge content in the SiGe substrate, which is an indicator of strain in Si grown on relaxed SiGe, in Fig.3, together with the experimental results. It was found that the calculated values under parameter set C are in a good agreement with the experimental results taken from [6]. The mobility enhancement factor increases with an increase in the substrate Ge content and saturates to be ~ 1.8 at the Ge content of 20 %. It was clarified in this study that the mobility enhancement in strained Si MOSFETs is explained by two mechanisms; one is the suppression of inter-valley phonon scattering and the other is the decrease in the occupancy of 4-fold valleys having lower mobility. From the calculated Ge content dependence of the mobility (Fig.4), it was found that, while the mobility limited only by intra-valley phonon scattering has almost no Ge dependence, the mobility limited by intra- and inter-valley phonon scatterings increases with an increase in the Ge content and coincides, around the Ge content of 20 %, with the mobility limited by intra-valley phonon scattering. This fact demonstrates that the mobility enhancement is attributed to the suppression of inter-valley phonon scattering. Fig.5 shows that the occupancy of 2-fold valleys and the energy difference between 2- and 4-fold valleys as a function of the Ge content. It was found that the occupancy of 2-fold valleys rapidly increases up to 100% with an increase in the Ge content. The mobility in 4-fold valleys becomes smaller than that in 2-fold valleys because of more frequent inter-valley scattering(Fig.6). As a result, the mobility in strained Si, where the occupancy of 4-fold valleys is lower, becomes larger than that in unstrained Si.

CONCLUSION Phonon-limited electron mobility in strained Si MOSFETs was analyzed from the viewpoint of 2DEG (2-Dimensional Electron Gas) transport, for the first time. It was found that a higher coupling of 2-dimensional electrons with inter-valley phonons is required to consistently explain the behavior of the inversion-layer mobilities in both strained and unstrained Si. It was clarified that the reason for the mobility enhancement in the inversion layer of strained Si is twofold; one is the suppression of inter-valley phonons due to the band splitting and the other is the decrease in the occupancy of 4-fold valleys, which have lower mobility attributed to the higher inter-valley scattering rate than 2-fold valleys.

[REFERENCES][1] J.Welser et al., IEEE EDL-15(1994)100 [2] F.Stern, Phys.Rev.B5(1972)4891 [3] P.J.Price, Ann.Phys.133(1981)217 [4] C.Jacoboni et al., Rev.Mod.Phys.55(1983)645 [5] D.K.Ferry, Semiconductor (Macmillan, 1991) [6] J.Welser et al., IEDM Tech. Dig.(1994)373 [7] S.Takagi et al., IEEE ED-41(1994)2357

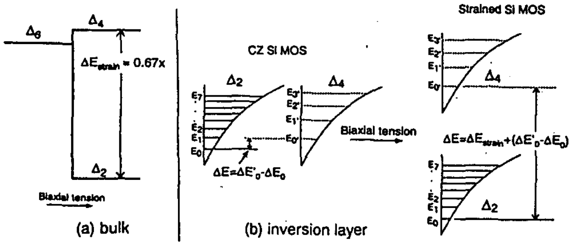

Fig.1 Energy lineups of the Si conduction band with and without the tensile strain for (a) in bulk and (b) in the inversion layer, respectively.

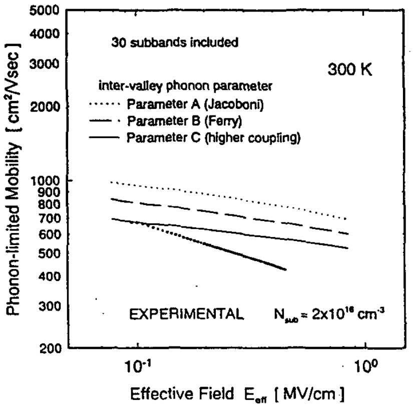

Fig.2 E_{eff} dependence of phonon-limited mobility in an inversion layer in unstrained Si (for conventional Si MOSFETs). The closed circles represent the experimental results taken from [7]. The dotted, dashed and solid lines represent the calculated results using the inter-valley phonon scattering parameter sets A, B and C, respectively.

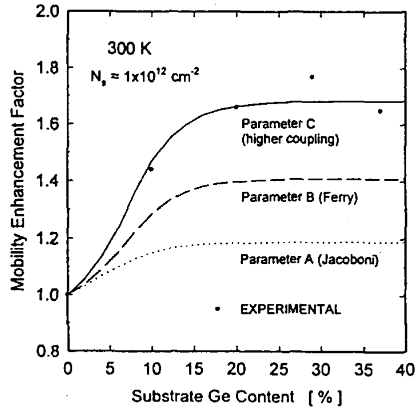

Fig.3 Mobility enhancement factor (the ratio of the mobility in strained Si to that in unstrained Si) versus the Ge content of a SiGe substrate on which the strained Si layer is formed. The experimental results were taken from [6]. The dotted, dashed and solid lines represent the calculated results using the inter-valley phonon scattering parameter sets A, B and C.

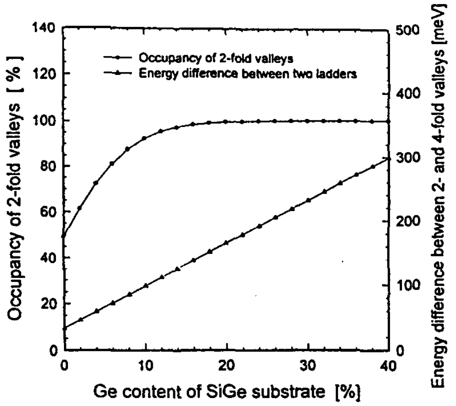

Fig.4 Calculated occupancy of 2-fold valleys at Ns of 1×10^{12} cm^{-2} and energy difference between the lowest subband in the 2-fold and the 4-fold valleys at room temperature as a function of the Ge content of the SiGe substrate on which the strained Si layer is formed. The substrate impurity concentration is 2×10^{16} cm^{-3}.

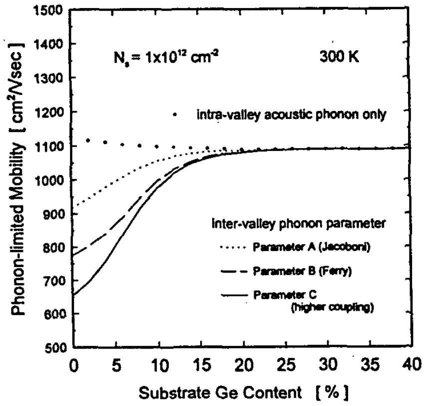

Fig.5 Calculated phonon-limited mobility at Ns of 1×10^{12} cm^{-2} at room temperature versus Ge content of a SiGe substrate on which strained Si layer is formed. The dotted, dashed and solid lines represent the calculated mobilities using the inter-valley phonon scattering parameter sets A, B and C. The closed circles represent the mobility limited only by intra-valley acoustic phonon scattering.

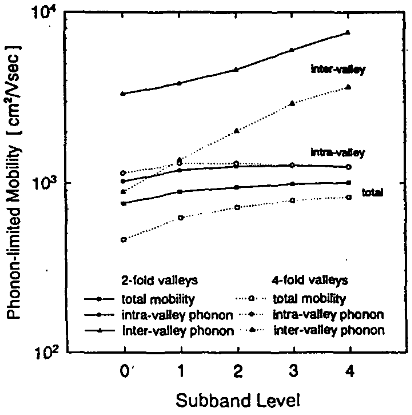

Fig.6 Calculated mobility in each subband of 2-fold and 4-fold valleys for unstrained Si MOSFETs. The circles, triangles and squares represent the mobilities limited by intra-valley phonon scattering, inter-valley phonon scattering, and the combination of both types of scattering, respectively, using parameter set C. Solid and dashed lines are drawn for guiding eyes.