Increasing Mobility and Spin Lifetime with Shear Strain in Thin Silicon Films

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1. Introduction

Because of an ongoing shift to FinFETs/ultra-thin body SOI based devices for the 22nm node and beyond, mobility enhancement in such structures is an important issue. Stress engineering used by semiconductor industry to boost the mobility was predicted to become less efficient in ultra-thin SOI structures [1] due to the less pronounced dependence of the transport effective mass on strain. Using the **k·p** Hamiltonian [2] which accurately describes the wave functions of electrons in silicon in presence of strain and spin-orbit interaction, we show that the wave functions and the matrix elements' dependences on strain compensate the weaker dependence of the effective mass, which results in an almost two-fold mobility increase even in ultra-thin (001) SOI films under tensile [110] stress. In addition, we demonstrate that the spin relaxation rate due to surface roughness and phonon scattering is also efficiently suppressed by an order of magnitude by applying tensile stress, which makes SOI structures attractive for spin driven applications.

2. Method and Results

The surface roughness matrix scattering elements are assumed independent and proportional to the product of the corresponding subband wave functions' derivatives at each interface. The electron-phonon scattering on acoustic phonons is taken in the deformation potential approximation. We generalize the deformation potential theory to include the corresponding deformation potentials responsible for spin relaxation in confined systems [3]. For spin lifetime calculations in (001) films both intra and intervalley processes between the valleys situated at the same crystallographic axis are considered. We approximate the confinement potential by an infinite square well potential. In order to calculate wave functions we use the **k·p** method. Our **k·p** Hamiltonian is written at the *X*-point for the two relevant valleys with the spin degree of freedom properly included [2], [4].

Figure 1 shows the electron mobility enhancement in [110] direction along tensile stress as a function of shear strain. Our simulations show that the mobility in thin silicon films increases by a factor of two. The increase depends on the electron concentration and the film thickness. For the thicknesses considered a strong mobility enhancement is observed up to a shear strain value around 0.5%. When shear strain is further increased the mobility saturates and even shows a slight decrease for the film thickness 2.1nm and 2.48nm.

The [110] mobility enhancement in surface layers due to tensile stress applied along the channel is usually explained by the effective transport mass reduction. However, the effective mass decrease in the lowest subband shown in Figure 2 may only account for roughly one half of the mobility enhancement obtained and cannot explain the two-fold mobility enhancement. Thus, a more detailed analysis is needed to understand the effect.

The ratio of the phonon electron mobility to the surface roughness limited mobility as a function of strain is shown in Figure 3a. The surface roughness limited mobility in 2.1nm thick film is of the same order as phonon electron mobility. Thus, the total mobility is determined by the interplay between these two mechanisms. For the 2.48nm thick film the contribution of phonons to mobility is higher than for 2.1nm thick film. The enhancement of the surface roughness and phonon limited mobility is shown in Figure 3b. The phonon mobility demonstrates an increase of about 40% consistent with the transport effective mass decrease. This behavior is supported by an almost negligible dependence of the electron-phonon scattering matrix elements with strain (Figure 4).

The surface roughness (SR) limited mobility for 2.1nm and 2.48nm thick films rises by about 200 and 300 percent, respectively, at around 1.2% shear strain and shows a slight decrease at strain values bigger than 1.2%. This behavior is dictated by the corresponding enhancement of the inverse SR scattering matrix elements (Figure 4). Mobility enhancement shown in Figure 3b and their ratio shown in Figure 3a are consistent with the total mobility enhancement observed in Figure 1. Indeed, for *t*=2.1nm film the unaccounted mobility enhancement is mostly due to SR mobility increase. Although the SR mobility growths even stronger for *t*=2.48nm, the main contribution to limit the mobility is the phonon scattering. For this reason the whole mobility is slightly less enhanced as compared to that in *t*=2.1nm film.

Due to strong dependence of the corresponding spin-flip matrix elements on the in-plane momentum **k** (Figure 5), the dependence of the scattering matrix elements on **k** must be preserved for the spin relaxation time calculations. A strong increase of the spin lifetime with strain is demonstrated in Figure 6. Thus, shear strain used to enhance mobility can also be used to increase spin lifetime efficiently.

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References

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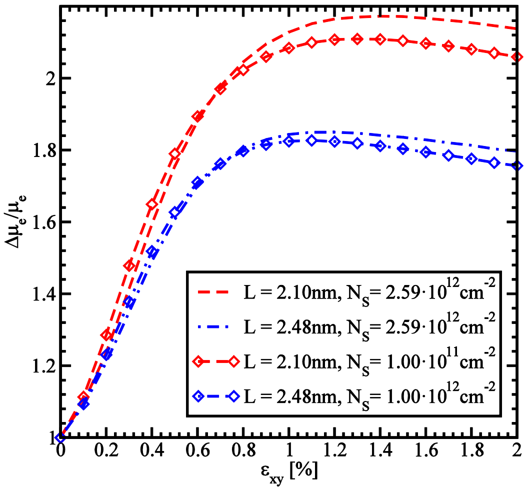

Fig.1: *Electron mobility enhancement, $\Delta\mu_e/\mu_e$, induced by shear strain as a function of strain for different thicknesses and electron concentration values for temperature 300K*

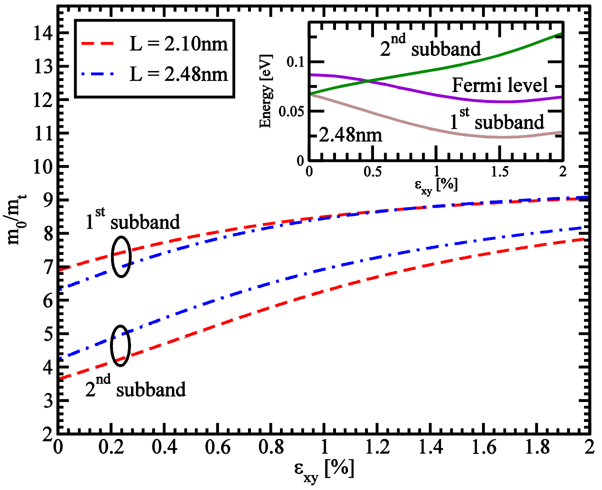

Fig.2: *One over effective mass for the two lowest subbands as a function on shear strain for different film thicknesses, inset shows the subbands energies and the Fermi level as a function of shear strain*

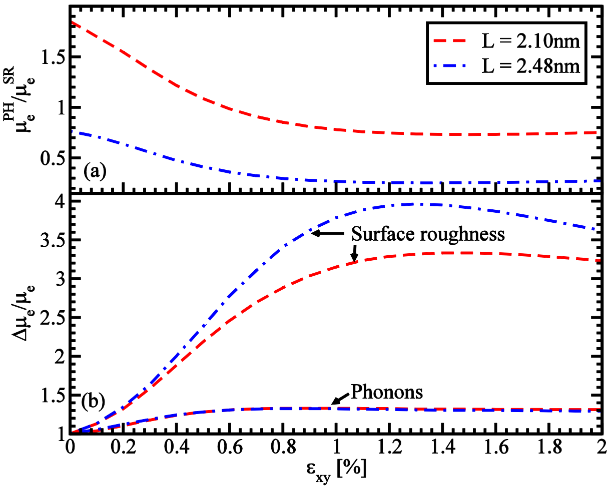

Fig.3: *Dependence of (a) the phonon electron mobility to the surface roughness mobility ratio and (b) phonon and surface roughness electron mobility enhancement on shear strain for several thicknesses for electron concentration 2.59·10^{12}cm^{-2}*

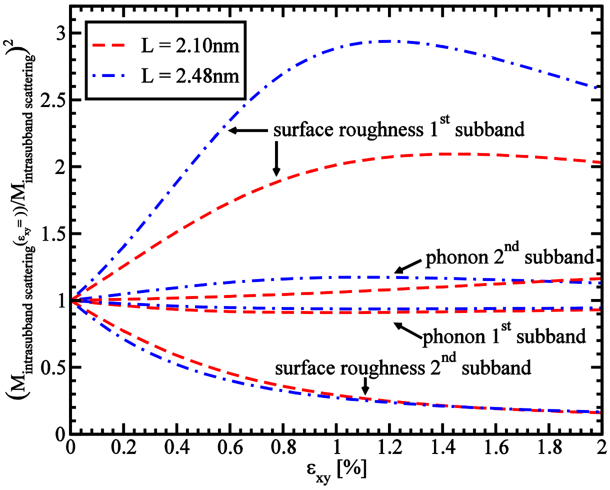

Fig.4: *Dependence of the inversed normalized square of surface roughness and phonon intrasubband matrix elements for different film thicknesses*

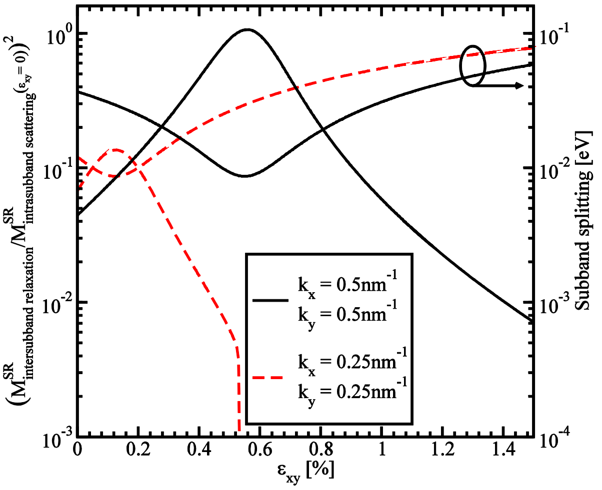

Fig.5: *Normalized intersubband relaxation matrix elements and subband splitting as a function of shear strain calculated with taking into account zero-strain splitting*

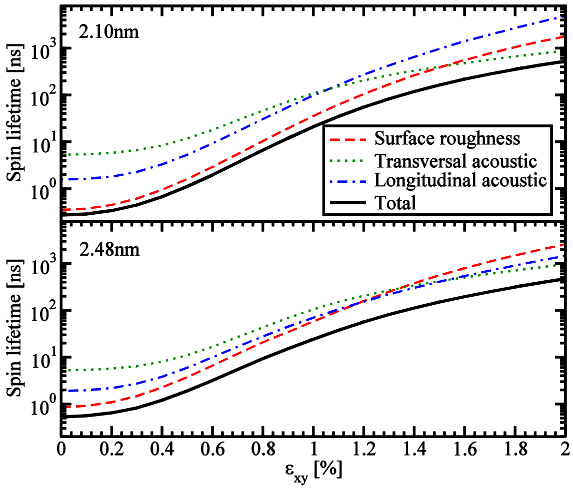

Fig.6: *Dependence of the acoustic, transversal phonons, and surface roughness limited spin lifetime on shear strain for two thickness value and T=300K*