Intersubband Spin Relaxation Reduction and Spin Lifetime Enhancement by Strain in SOI Structures

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Growing technological challenges and increasing costs are gradually guiding MOSFET scaling to an end, which drives the search for alternative technologies as well as computational principles based on electron spin. We investigate spin relaxation in (001) silicon-on-insulator structures by using the effective $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian, with the spin degree of freedom, written at the vicinity of the X-point for the two relevant valleys [1] along the Z-axis in the Brillouin zone. In bulk silicon, the spin lifetime is determined by the spin-flip scattering between the valleys located on different crystallographic axes [1]. A large spin relaxation in gated silicon structures was observed [2] and a several orders of magnitude boost of spin lifetime in films subjected to [110] uniaxial tensile stress was predicted [3]. We investigate the dependence of the total spin lifetime on uniaxial stress (ε_{xy}) for varied sample thicknesses (t), operating temperature (T), and the electron concentration (N_S) in detail and elucidate the physical reasons of the spin lifetime enhancement. We also report a further modification of the spin lifetime, when the spin injection direction is changed.

We consider the surface roughness (SR) and the longitudinal (LA) and transversal (TA) acoustic phonons to cause the prominent spin relaxation mechanisms [3], as the contribution of optical phonons can be safely ignored for a film thickness of less than $3\,\mathrm{nm}$. First we assume that the spin is injected along the perpendicular OZ-direction. We begin with the variation of the spin lifetime (τ^S) with ε_{xy} versus temperature, Figure 1. A strong increase of τ^S is noticed for all four evaluated temperatures. The figure also confirms that at higher temperature the phonon scattering rate will increase to reduce τ^S compared to that at lower temperature. The increment of τ^S with shear strain is also noticed for a varied electron concentration (Figure 2). The spin relaxation becomes more efficient for higher carrier concentrations for all three considered mechanisms. Figure 3 shows the increase in τ^S with increase in ε_{xy} at constant T and N_S, indicating the change of τ^S with t.

In order to understand the spin relaxation mechanism with its components, we investigate the intersubband and intrasubband components of the spin and momentum relaxation time (Figure 4) at room temperature for a sample thickness of $t = 2.1\,\mathrm{nm}$. It is revealed that the major contribution to spin relaxation comes from the intersubband processes due to the presence of the spin hot spots characterized by the sharp peaks of the intersubband spin relaxation matrix elements, whereas at higher stress the intrasubband component also becomes significant. In contrast, intrasubband scattering solely determines the momentum relaxation time. This is in agreement with the selection rule that the elastic processes result in strong intrasubband momentum relaxation.

Figure 5 delineates the surface roughness induced spin relaxation with its components at two distinct temperatures. The inset shows the dependence of the lowest unprimed subbands energies and their splitting on shear strain. One can see that, when the temperature decreases, the intersubband scattering becomes less efficient already at lower strain, and hence the total intrasubband component of the spin relaxation time starts playing the significant role at higher ε_{xy}. It is also revealed that at higher ε_{xy}, the surface roughness scattering intrasubband components become close to each other for different temperatures. Based on our analysis we can conclude that the increase of the spin lifetime is a consequence of the fact that shear strain introduces a splitting between the usually considered unprimed subbands. It pushes out the regions of large mixing between the spin-up and spin-down states to higher kinetic energies outside of the occupied states [3].

Now we intend to investigate, if an alteration of spin injection direction has any further impact on the spin lifetime. Hence we consider an in-plane (say, OX-direction) spin injection and estimate the spin and momentum lifetime. The momentum relaxation time stays unaltered irrespective of the spin injection direction. Alternatively, the spin relaxation rate (time) decreases (increases) when injected in-plane. Figure 6 depicts a comparison of the total spin lifetime, when the spin is injected in OZ- or OX-direction, over a wide range of applied stress. We also point out an almost constant ratio (around 2) of the obtained values in the inset figure. The physical reasons for the obtained factor 2 in the ratio of the spin lifetime for in- and perpendicular-plane spin injection orientation has yet to be revealed. We point out that the dependence of spin lifetime on the injection direction was also reported in bulk silicon [4]. Therefore, we conclude that the spin lifetime can be further increased, when spin is injected in-plane.

Acknowledgment

This work is supported by the European Research Council through the grant #247056 MOSILSPIN.

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ISBN: 978-88-9030-695-2

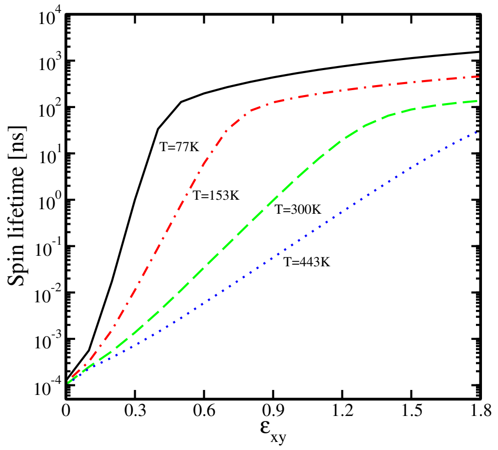

Fig. 1: *Variation of spin lifetime with ε_{xy} with temperature as parameter.* $t = 1.36\,\mathrm{nm}$, $N_S = 10^{12}\,\mathrm{cm}^{-2}$.

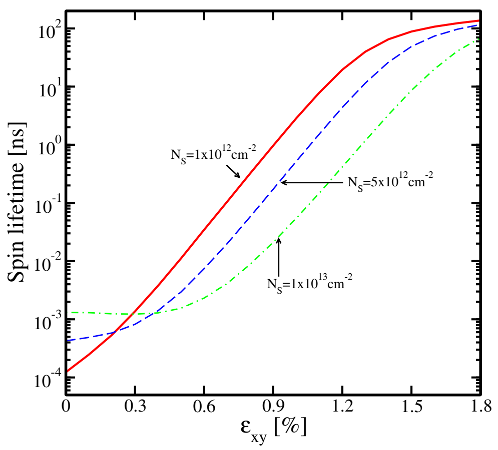

Fig. 2: *Variation of spin lifetime with ε_{xy} with the electron concentration as parameter.* $t = 1.36\,\mathrm{nm}$, $T = 300\,\mathrm{K}$.

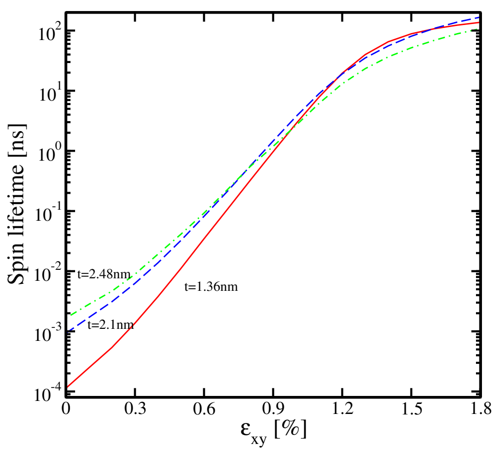

Fig. 3: *Variation of spin lifetime with ε_{xy} with thickness as parameter.* $N_S = 10^{12}\,\mathrm{cm}^{-2}$, $T = 300\,\mathrm{K}$.

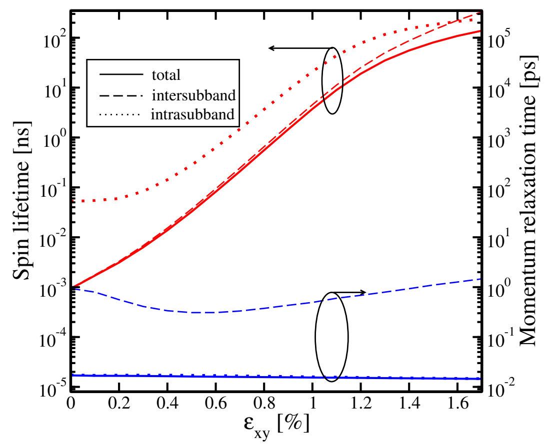

Fig. 4: *Spin and momentum relaxation time with their components.* $N_S = 10^{12}\,\mathrm{cm}^{-2}$, $T = 300\,\mathrm{K}$, $t = 2.1\,\mathrm{nm}$.

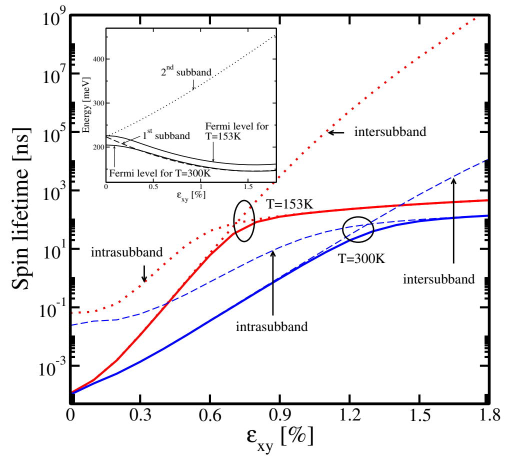

Fig. 5: *Surface roughness spin relaxation time with components. The inset shows the Fermi energy and the lowest subband energy level.* $N_S = 10^{12}\,\mathrm{cm}^{-2}$, $t = 1.36\,\mathrm{nm}$.

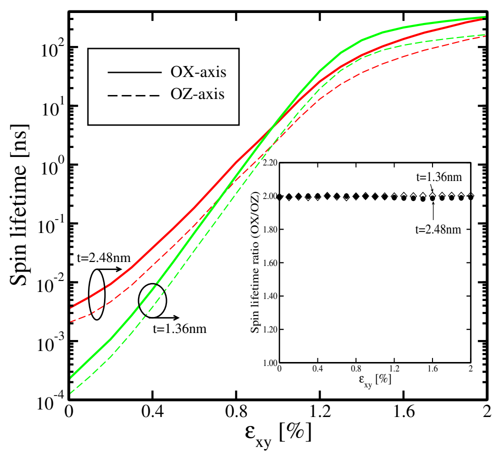

Fig. 6: *Spin lifetime when injected in OX- and OZ-direction. The inset shows the ratio.* $N_S = 10^{12}\,\mathrm{cm}^{-2}$, $T = 300\,\mathrm{K}$.