Spin Lifetime Enhancement by Shear Strain in Thin Silicon-on-Insulator Films

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With semiconductor device scaling apparently approaching its fundamental limits, new engineering solutions and innovations are required to further improve the performance of microelectronic components. Spin as an additional degree of freedom is promising for future nanoelectronic devices. Silicon is the main element of microelectronics, possesses several properties attractive for spintronics: nuclei with predominantly zero spin and weak spin-orbit interaction. Spin relaxation in silicon thin films has not been addressed yet. Because of the paramount importance of SOI and FinFET 3D technology for technology nodes below 22nm, understanding details of spin propagation in silicon thin films is urgently needed.

In bulk silicon the conduction electrons are positioned close to the minima of the three pairs of valleys near the edges of the Brillouin zone along the *X*-, *Y*-, and *Z*-axes. Each state is described by the valley index, the wave vector **k** relative to the valley minimum, and the spin orientation (spin-up ↑ and spin-down ↓) on a chosen axis.

The main mechanism of spin relaxation in bulk silicon is due to the electron-phonon transitions between the spin-up and down states located in the different valley pairs: the *f*-processes [1, 2]. Uniaxial [001] stress removes the degeneracy between the *X(Y)*- and *Z*-valleys and is thus predicted to boost spin life time in bulk silicon [1].

In (001) thin silicon films the confinement leads to the formation of an unprimed subbands ladder from *Z* and a prime ladder from the *X(Y)*-valleys. Due to the difference in the quantization energies the *f*-processes in the unprimed subbands are suppressed. Thus, spin relaxation due to the intra- and intersubband transitions between the states with opposite spin projections must be considered.

The low field electron mobility in thin films is limited by surface roughness scattering [3]. We investigated the behavior of the spin lifetime in strained silicon films taken into account surface roughness as the major mechanism responsible for spin relaxation. A perturbative **k·p** approach [4, 5] is suitable to describe the electron subband structure in the presence of strain. We utilize a spin-dependent **k·p** Hamiltonian [4-6], where only the relevant [001] oriented valleys are considered.

For the considerations presented here we assume that the spin is injected along the *Z*-axis. Within the **k·p** approach the two states with the opposite spin projections are degenerate and satisfy the condition $\langle n_\uparrow|\sigma_z|n_\downarrow\rangle = 0$. Here σ_z is the Pauli matrix, $n_\downarrow\rangle$ stands for the spin-down state of an electron in the *n*-th subband. The surface roughness scattering between the subbands is taken to be proportional to the square of the product of the subband function derivatives at the interface [7]. The surface roughness at the two interfaces is assumed to be independent and described by a mean value and a correlation length.

Without shear strain the two lower subbands are degenerate [5]. This degeneracy, originating in the *Z*-valleys' degeneracy, produces a large mixing between the spin-up and spin-down states from the opposite valleys, resulting in hot spots characterized by strong spin relaxation. The hot spots are defined by the expression $D\varepsilon_{xy} - \hbar^2 k_x k_y \left(\frac{1}{m_t} - \frac{1}{m_0}\right) = 0$, where D = 14eV is the shear strain deformation potential, m_t is the transversal silicon effective mass, ε_{xy} is the shear strain component. Figure 1 demonstrates that in the unstrained film hot spots arise along the k_x- and k_y-axes, while for the strained sample intensive relaxation regions are in a hyperbolic form in the $k_x k_y$-plane. Most importantly, the hot spots are moved away from the center of the 2D Brillouin zone, which results in their smaller contribution to spin relaxation. A strong increase of the spin lifetime with shear strain is demonstrated in Figure 2. The spin lifetime increases for all three evaluated temperatures. This increase is a consequence of the fact that shear strain pushes out the regions of large mixing between the spin-up and spin-down states to higher kinetic energies outside of the occupied states, as can be seen in Figure 1.

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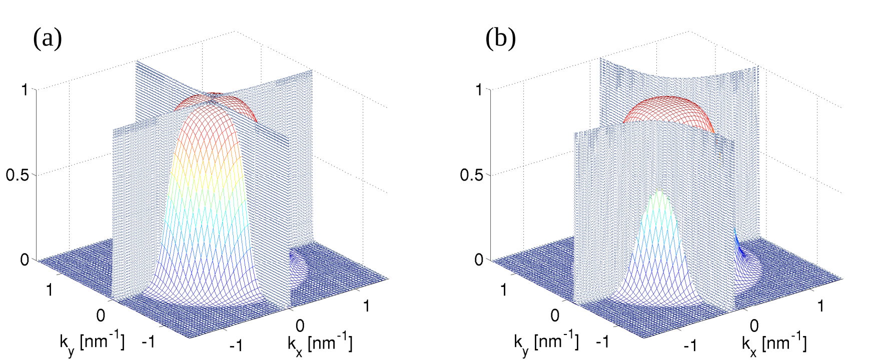

Fig. 1: Normalized intrasubband relaxation matrix elements for (a) an unstrained sample, (b) shear strain 0.5% for the film thickness of 1.36nm and a Fermi energy of 0.1eV. The Fermi distribution for 300K is also shown.

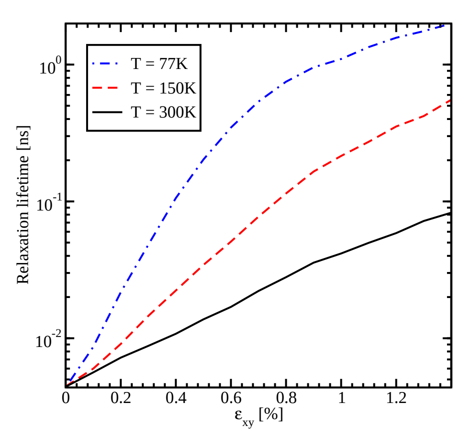

Fig. 2: Dependence of the spin lifetime on shear strain for a film thickness of 1.36nm and a Fermi energy of 0.1eV for different temperatures.