Shear Strain: An Efficient Spin Lifetime Booster in Advanced UTB^2 SOI MOSFETs

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Introduction

Since microelectronics plays a significant role in everyday's life, big efforts are devoted to the problem of minimizing power consumption by reducing the physical dimensions of microelectronic devices. An alternative approach to reduce power consumption and boost the performance is to utilize spin properties of electrons. Spintronics attracts much attention recently, and a number of novel devices has already been proposed [1], [2]. Silicon is an ideal material for spintronic devices, because it is composed of nuclei with predominantly zero spin and is characterized by small spin-orbit coupling. Both factors favour to reduce spin relaxation. Understanding the details of the spin propagation in modern ultra-scaled silicon MOSFETs is urgently needed [3]. We present an analytical approach to analyze the surface roughness dominated spin relaxation in thin body silicon-on-insulator-based MOSFETs.

Model

We consider (001) oriented thin silicon films. In order to find the surface roughness induced scattering and spin relaxation matrix elements the subband wave functions and subband energies have to be known. A perturbative **k·p** approach [4–6] is suitable to describe the electron subband structure in the presence of strain and spin-orbit interaction. We consider only the two relevant valleys along the [001] axis. The Hamiltonian is written in the vicinity of the X -point along the k_z-axis in the Brillouin zone [7]. In order to find the subband wave functions and subband energies the Hamiltonian [7] is transformed to get rid of the coupling between the spins with opposite direction in different valleys

$$H = \begin{bmatrix} \frac{\hbar^2 k_z^2}{2m_l} + \frac{\hbar^2(k_x^2+k_y^2)}{2m_t} - \delta & 0 & \frac{k_0 k_z}{m_l} & 0 \\ 0 & \frac{\hbar^2 k_z^2}{2m_l} + \frac{\hbar^2(k_x^2+k_y^2)}{2m_t} - \delta & 0 & \frac{k_0 k_z}{m_l} \\ \frac{k_0 k_z}{m_l} & 0 & \frac{\hbar^2 k_z^2}{2m_l} + \frac{\hbar^2(k_x^2+k_y^2)}{2m_t} + \delta & 0 \\ 0 & \frac{k_0 k_z}{m_l} & 0 & \frac{\hbar^2 k_z^2}{2m_l} + \frac{\hbar^2(k_x^2+k_y^2)}{2m_t} + \delta \end{bmatrix},$$

were $\delta = \sqrt{\left(D\varepsilon_{xy} - \frac{\hbar^2 k_x k_y}{M}\right)^2 + \Delta_{SO}^2\left(k_x^2 + k_y^2\right)}$, m_t and m_l are the transversal and the longitudinal silicon effective masses, $k_0 = 0.15\times 2\pi/a$ is the position of the valley minimum relative to the X-point in unstrained silicon, ε_{xy} denotes the shear strain component, $M^{-1} \approx m_t^{-1} - m_0^{-1}$, Δ_{SO}=1.27meVnm [4], and D = 14eV is the shear strain deformation potential. Then the same approach as for the two-band **k·p** Hamiltonian written in the vicinity of the X- point of the Brillouin zone for silicon films under uniaxial strain [6] is applicable to find the eigenfunctions and eigenenergies.

The intra- and intersubband surface roughness scattering matrix elements are taken proportional to the square of the product of the subband function derivatives at the interface [8]. The surface roughness at the two interfaces is assumed to be independent and described by a mean value and a correlation length. Spin relaxation rates are then calculated in the following way [4], [8]

$$\frac{1}{\tau} = \frac{\int \frac{1}{\tau(\overrightarrow{k_1})} f(\varepsilon)\left(1-f(\varepsilon)\right) d\overrightarrow{k_1}}{\int f(\varepsilon)\, d\overrightarrow{k_1}},$$

$$f(\varepsilon) = \frac{1}{1+e^{\left(\frac{\varepsilon - M}{kT}\right)}},$$

$$\int d\overrightarrow{k_1} = \int_0^{2\pi}\int_0^{\infty} \frac{\left|\overrightarrow{k_1}(\varphi,\varepsilon)\right|}{\left|\frac{\partial\varepsilon(\overrightarrow{k_1})}{\partial\overrightarrow{k_1}}\right|} d\varphi\, d\varepsilon,$$

$$\frac{1}{\tau(\overrightarrow{k_1})} = \frac{4\pi}{\hbar}\sum_{i,j=1,2}\int_0^{2\pi}\Delta^2 L^2 \frac{1}{\epsilon_{ij}^2(\overrightarrow{k_\iota}-\overrightarrow{k_1})}\frac{\hbar^4}{4m_l^2}\left[\frac{d\Psi_{\mathrm{ik}_1}^*}{dz}\frac{d\Psi_{\mathrm{ik}_\mathrm{i}}}{dz}\right]_{z=\pm\frac{t}{2}}^2 \mathrm{e}^{\left(\frac{-(\overrightarrow{k_\iota}-\overrightarrow{k_1})^2 L^2}{4}\right)}\frac{\left|\overrightarrow{k_\iota}(\varphi,\varepsilon)\right|}{\left|\frac{\partial\varepsilon(\overrightarrow{k_\iota})}{\partial\overrightarrow{k_\iota}}\right|}\frac{1}{(2\pi)^2}\, d\varphi.$$

Results and discussion

Figure 1 shows the energy splitting within the lowest unprimed subband (valley splitting) induced by the confinement and the bulk dispersion non-parabolicity. The surface roughness spin relaxation matrix elements normalized to the scattering matrix elements at zero strain as a function of shear strain are also shown. The valley splitting is significantly reduced around the shear strain value of 0.37%. This point is determined by the condition $D\varepsilon_{xy} - \frac{\hbar^2 k_x k_y}{M} = 0$. In this case the splitting between the subbands is determined only by the spin-orbit term. Under this condition the spin-orbit interaction leads to a large mixing between the spin-up and spin-down states from the opposite valleys, resulting in the “hot spots” formation characterized by strong spin relaxation. Figure 2 displays the normalized spin relaxation matrix elements for an unstrained film. The hot spots are along the [100] and [010] directions. Shear strain moves the hot spots to higher energies (Figure 3) outside of the states occupied by carriers. This leads to a reduction of the surface roughness induced spin relaxation. A strong increase of the spin lifetime with shear strain is demonstrated in Figure 4. The spin lifetime increases for all evaluated temperatures. Thus, stress used to enhance mobility can also be used to boost spin lifetime in advanced UTB^2 SOI MOSFETs.

Acknowledgments

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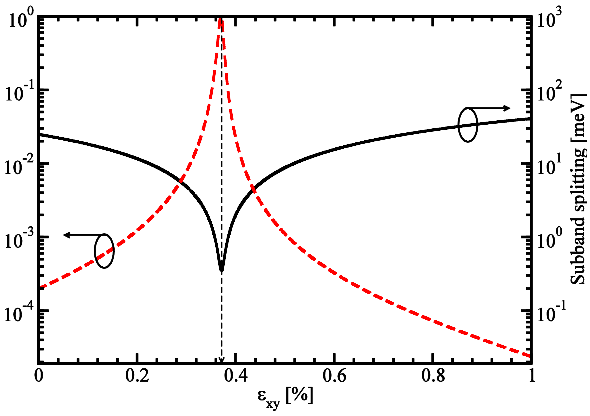

Figure 1. Intersubband relaxation matrix elements normalized to the intrasubband scattering elements at zero strain and the subband splitting for the film thickness 2.48nm, k_x=0.4nm^{-1}, and k_y=0.4nm^{-1}.

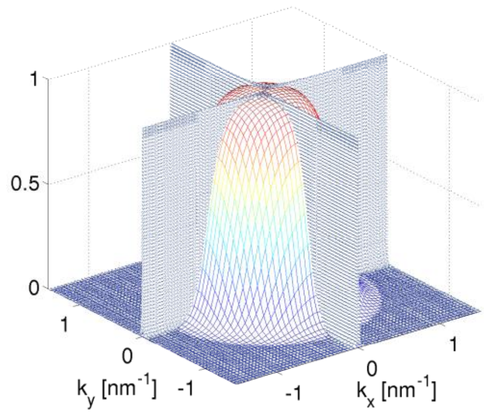

Figure 2. Intersubband relaxation matrix elements normalized to the intrasubband scattering elements at zero strain for an unstrained sample. The Fermi distribution for 300K is also shown.

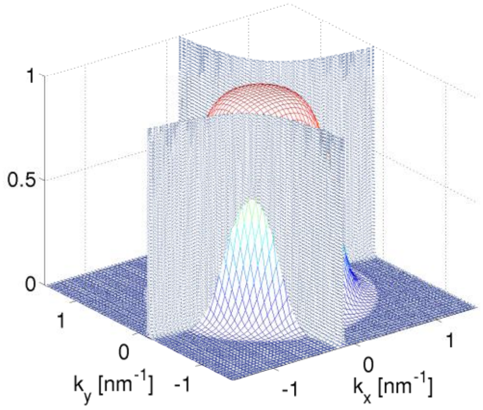

Figure 3. Normalized intersubband relaxation matrix elements for shear strain 0.5% shown together with the Fermi distribution at 300K.

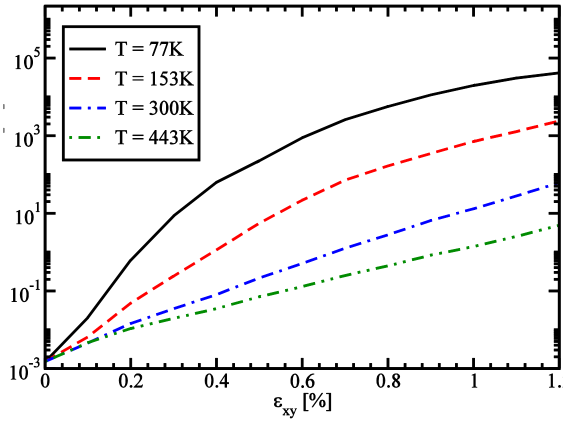

Figure 4. Dependence of the spin lifetime on tensile shear strain for a film thickness 2.48nm and an electron concentration 10^{12}cm^{-2}, for different temperatures.