Using Strain to Increase the Reliability of Scaled Spin MOSFETs

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***Abstract*—We investigate the surface roughness induced spin relaxation in scaled spin MOSFETs. We show that the spin-flip hot spots characterized by strong spin relaxation appear in thin MOSFET channel. Strain can efficiently move these hot spots outside of the states occupied by carriers, resulting in a substantial increase of the spin lifetime.**

Keywords—surface-roughness relaxation; phonon relaxation; ultra-scaled SOI MOSFETs; shear strain

I. INTRODUCTION

Novel microelectronic devices have to be smaller and faster than the traditional ones and be more efficient in order to reduce power consumption of future integrated electronic circuits. A promising alternative to the charge degree of freedom currently used in MOSFET switches is to take into account the electron spin. Spintronics attracts much attention, and a number of novel devices has already been proposed [1,2]. Silicon is an ideal material for spintronic devices [3], because it is composed of nuclei with predominantly zero spin and is characterized by small spin-orbit coupling. Both factors favor to reduce spin relaxation. Spin transport through a 350µm thick silicon wafer was demonstrated at low temperature [4]. Spin propagation at such long distances combined with a possibility of injecting spin at room temperature [5] makes the fabrication of spin-based switching devices in the near future plausible. However, the experimentally observed enhancement in spin relaxation in electrically gated lateral-channel silicon structures [6] could compromise the reliability and become an obstacle in realizing spin-driven devices. Thus, deeper understanding of spin relaxation mechanisms in silicon is urgently needed [7].

We investigate the surface roughness induced spin relaxation in an ultra-scaled double-gate spin MOSFETs. We predict a substantial increase of the spin lifetime with uniaxial strain applied.

II. MODEL DESCRIPTION

We consider (001) oriented thin silicon films. In order to find the surface roughness induced spin relaxation matrix elements the subband wave functions and subband energies have to be known. A perturbative $\mathbf{k}\cdot\mathbf{p}$ approach [8–10] 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 [11]. In order to find the subband wave functions and subband energies the Hamiltonian [11] is transformed to eliminate the coupling between the spins with opposite direction in different valleys

$$H = \begin{bmatrix} H_1 & H_3 \\ H_3 & H_2 \end{bmatrix} \tag{1}$$

where H_1, H_2, and H_3 are written as

$$H_{1,2} = \left[\frac{\hbar^2 k_z^2}{2m_l} + \frac{\hbar^2 \left(k_x^2 + k_y^2\right)}{2m_t} + (-1)^j \delta + U(z) \right] I \tag{2}$$

$$H_3 = \begin{bmatrix} \frac{\hbar^2 k_0 k_z}{m_l} & 0 \\ 0 & \frac{\hbar^2 k_0 k_z}{m_l} \end{bmatrix} \tag{3}$$

Here $U(z)$ is the confinement potential, I is the identity 2x2 matrix, $\delta = \sqrt{\left(D\varepsilon_{xy} - \frac{\hbar^2 k_x k_y}{M}\right)^2 + \Delta_{SO}^2\left(k_x^2 + k_y^2\right)}$, m_t and m_l are the transversal and the longitudinal silicon effective masses, $M^{-1} \approx m_t^{-1} - m_0^{-1}$, $k_0 = 0.15\times 2\pi/a$ is the position of the valley minimum relative to the *X*-point in unstrained silicon, ε_{xy} denotes the shear strain component, D = 14eV is the shear strain deformation potential, and Δ_{SO}=1.27meVnm is the effective spin-orbit interaction [8].

The surface roughness scattering matrix elements are taken to be proportional to the square of the product of the subband wave function derivatives at the interface [12,13]. The relaxation time τ can be calculated as a thermal average of the rates $\frac{1}{\tau(\mathbf{K})}$ [7,8,12].

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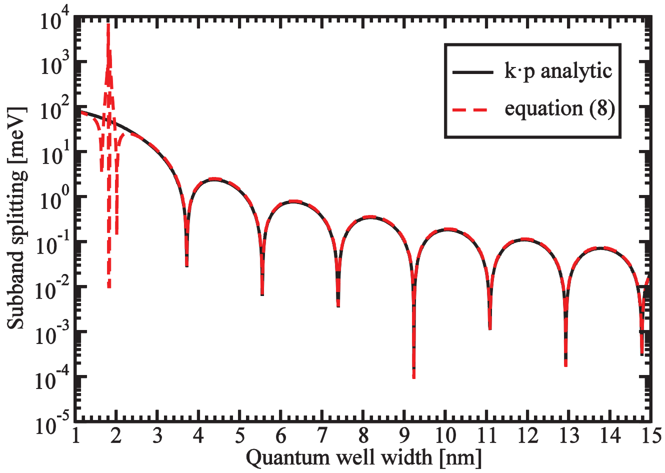

Figure 1. Splitting of the lowest unprimed electron subbands as a function of the silicon film thickness for the shear strain value of 0.5%, $k_x = 0.25\text{nm}^{-1}$, $k_y = 0.25\text{nm}^{-1}$.

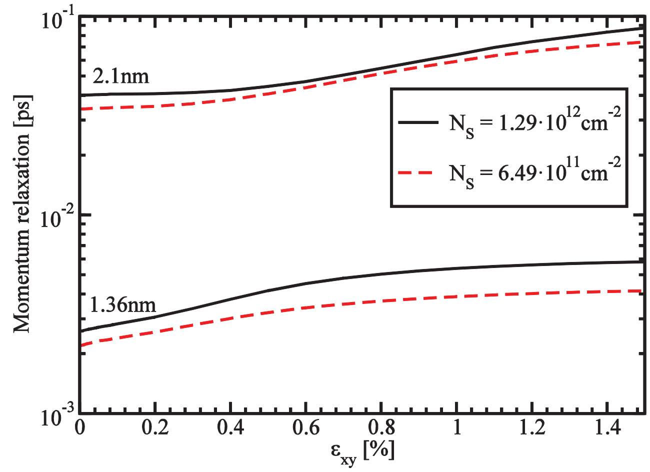

Figure 2. Dependence of the momentum relaxation time on shear strain for different film thicknesses and electron concentrations at T=300K.

$$\frac{1}{\tau} = \frac{\int \frac{1}{\tau(\mathbf{K_1})} f(\varepsilon)\left(1 - f(\varepsilon)\right) d\mathbf{K_1}}{\int f(\varepsilon)\, d\mathbf{K_1}} \tag{4}$$

$$f\,(\varepsilon) = \frac{1}{1 + \exp\left(\frac{\varepsilon - E_F}{k_B T}\right)} \tag{5}$$

$$\int d\mathbf{K_1} = \int_0^{2\pi}\int_0^{\infty} \frac{|\mathbf{K_1}(\varphi,\, \varepsilon)|}{\left|\frac{\partial\varepsilon(\mathbf{K_1})}{\partial\mathbf{K_1}}\right|} d\varphi\, d\varepsilon \tag{6}$$

$\boldsymbol{\varepsilon}$ is the electron energy, $\mathbf{K_1}$ is the in-plane wave vector after the scattering event, k_B is the Boltzmann constant, T is the temperature, and E_F is the Fermi level.

The surface roughness at the two interfaces is assumed to be independent and described by a mean value and a correlation length. The surface roughness induced momentum (spin) relaxation rate is calculated as

$$\frac{1}{\tau(\mathbf{K_1})} = \frac{2(4)\pi}{\hbar} \sum_{i,j=1,2} \int_0^{2\pi} \pi\Delta^2 L^2 \frac{1}{\epsilon_{ij}^2(\mathbf{K_2} - \mathbf{K_1})} \cdot \\ \cdot \frac{\hbar^4}{4m_l^2}\left[\left(\frac{d\Psi_{i\mathbf{K_1}\sigma}}{dz}\right)^* \frac{d\Psi_{j\mathbf{K_2}\sigma(-\sigma)}}{dz}\right]^2_{z=\pm\frac{t}{2}} \cdot \\ \cdot \exp\left(\frac{-(\mathbf{K_2} - \mathbf{K_1})^2 L^2}{4}\right) \frac{|\mathbf{K_2}|}{\left|\frac{\partial\varepsilon(\mathbf{K_2})}{\partial\mathbf{K_2}}\right|} \frac{1}{(2\pi)^2} d\varphi \tag{7}$$

ϵ_{ij} is the dielectric permittivity, $\mathbf{K_2}$ is the in-plane wave vector of the state before scattering, L is the autocorrelation length, Δ is the mean square value of the surface roughness fluctuations, t is the film thickness, $\Psi_{i\mathbf{K_1}\sigma}$ and $\Psi_{j\mathbf{K_2}\sigma}$ are the wave vectors, σ is the spin projection to the [001] axis.

Result and Discussion

The subband splitting dependence on the silicon film thickness is presented in Figure 1. Theoretical values for the subband splitting in an infinite potential square well [14] are:

$$\Delta E_n = \frac{2y_n^2\delta}{k_0 t\sqrt{(1 - y_n^2 - \eta^2)(1 - y_n^2)}}\left|\sin\left(\sqrt{\frac{1 - y_n^2 - \eta^2}{1 - y_n^2}} k_0 t\right)\right| \tag{8}$$

with y_n, η, and B defined as

$$y_n = \frac{\pi n}{k_0 t} \tag{9}$$

$$\eta = \frac{m_l\delta}{\hbar^2 k_0^2} \tag{10}$$

$$\delta = \sqrt{\Delta_{SO}^2\left(k_x^2 + k_y^2\right) + \left(D\varepsilon_{xy} - \frac{\hbar^2 k_x k_y}{M}\right)^2} \tag{11}$$

A good agreement between the $\mathbf{k\cdot p}$ analytic and (8) is given for a film thicknesses over 2nm and below 1.5nm. A discrepancy appears only in a narrow interval around 1.81nm due to vanishing of the $(1 - y_n^2)$ term.

Figure 2 shows the dependence of the momentum relaxation on shear strain. The improvement of the momentum relaxation time due to the shear strain is around 120% for the film thickness of 2.1nm and around 130% for the film thickness 1.36nm. We point out that the increase of the momentum relaxation time is due to the corresponding scattering matrix elements' dependences on strain shown in Figure 3. The intrasubband scattering matrix elements decrease with strain within the first (lowest) subband, which gets splits

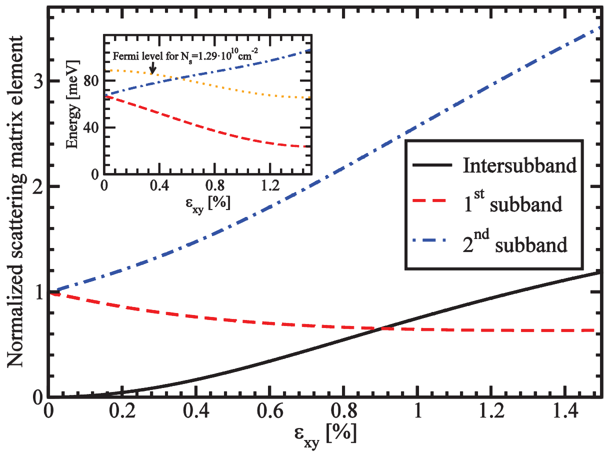

Figure 3. Inter- and intrasubband scattering matrix elements normalized to the value of the intrasubband scattering at zero strain as a function of shear strain. The inset shows the dependence of subband energies and Fermi levels on shear strain.

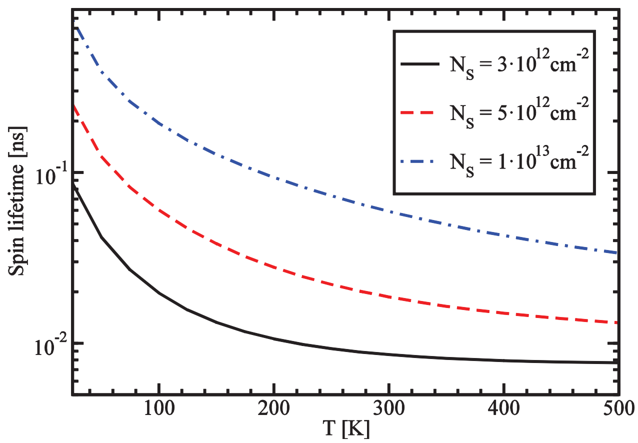

Figure 5. Dependence of the surface roughness limited spin lifetime on temperature for an unstrained film thickness of 2.48nm for different values of the electron concentration.

from the second one due to strain-induced valley splitting (inset in Figure 3). The occupation of the second subband at high strain becomes insignificant as confirmed by the Fermi level dependence (inset in Figure 3). Thus, the interplay of intrasubband scattering within the first subband and intersubband scattering mainly contribute to the momentum relaxation at high strain resulting in the overall increase of the momentum relaxation time (Figure 2). Combined with the strain induced transport effective mass decrease, it should result in an even better mobility improvement supporting the use of uniaxial tensile strain as the mobility booster in fully depleted ultra-thin SOI MOSFETs.

Figure 4 shows the lowest unprimed intersubband energy splitting as a function of shear strain. The surface roughness

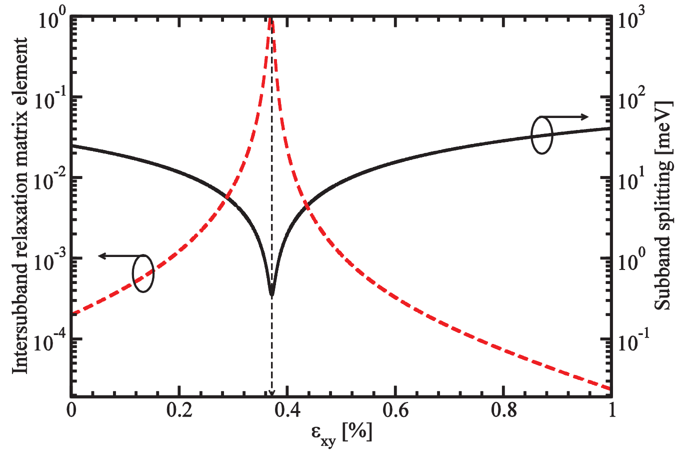

Figure 4. Intersubband relaxation matrix elements normalized to the intrasubband scattering elements at zero strain and the subband splitting for a film thickness of 2.48nm, k_x =0.4nm^{-1}, and k_y=0.4nm^{-1}.

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 a shear strain value of 0.37%. Since the intersubband valley splitting is proportional to the δ term, the position of the minimum is determined by the minimum of this term. At this point $D\varepsilon_{xy} - \frac{\hbar^2 k_x k_y}{M}$ vanishes and the subband splitting is determined only by the spin-orbit term $\Delta_{SO}^2\left(k_x^2 + k_y^2\right)$. Thus, the spin-orbit interaction leads to a large mixing between the spin-up and spin-down states from the opposite valleys, resulting in narrow hot spots characterized by strong spin relaxation. For a fixed shear strain value the hot spots' positions are determined by the kinetic energy of the carrier. Figure 5 shows the dependence of the surface roughness induced spin lifetime on temperature for an unstrained film. While the temperature increases, the number of hot spots which lie in the energy range determined by the Fermi distribution increases, thus reducing the spin lifetime.

Figure 6 displays the normalized spin relaxation matrix elements for an unstrained film. The hot spots are located along the [100] and [010] directions. Shear strain moves the strong spin relaxation points to higher energies (Figure 7) 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 at room temperature is demonstrated in Figure 8. For the film of 2.1nm thickness and the film of 1.36nm thickness the surface roughness induced spin relaxation increases by orders of magnitude with shear strain of 1.5% applied. Thus, uniaxial stress is efficient to boost the spin lifetime in ultra-thin SOI MOSFETs.

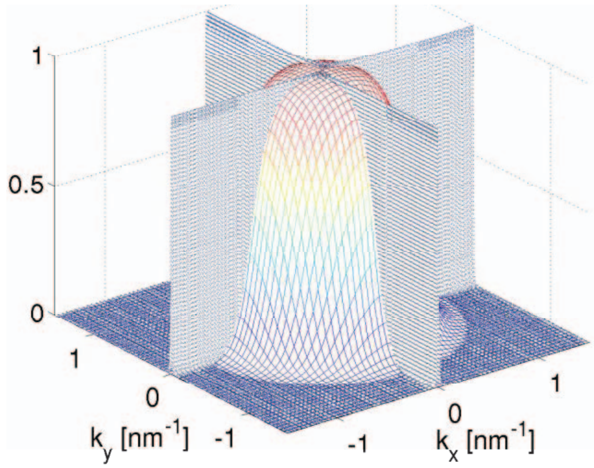

Figure 6. Intersubband relaxation matrix elements normalized to the intrasubband scattering elements at zero strain for an unstrained sample. The Fermi distribution for T=300K is also shown.

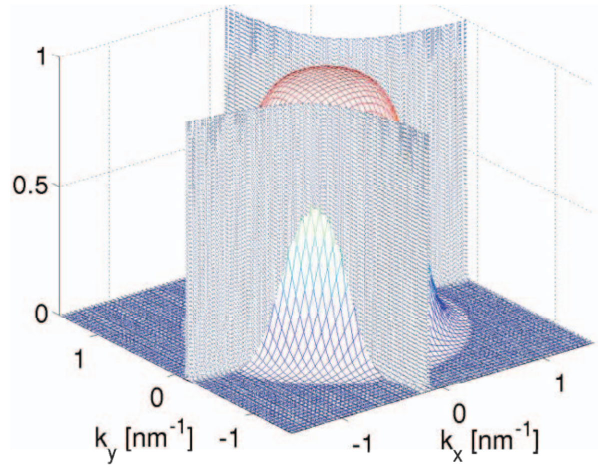

Figure 7. Normalized intersubband relaxation matrix elements for shear strain 0.5% shown together with the Fermi distribution at T=300K.

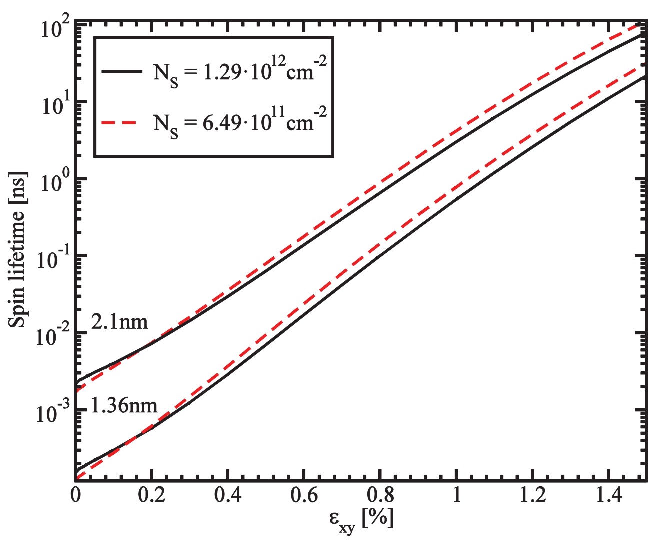

Figure 8. Dependence of the spin lifetime on shear strain for different film thicknesses and electron concentrations at T=300K.

III. CONCLUSION

By utilizing a $\mathbf{k} \cdot \mathbf{p}$ approach including the spin-orbit interaction effects we found the subband wave functions and subband energies in (001) thin silicon films. We have shown that the momentum relaxation time can be improved by almost a factor of two for ultra-thin films. We have demonstrated a strong, several orders of magnitude, increase of spin lifetime in strained silicon films. Thus shear strain used to boost mobility can also be used to increase spin lifetime.

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