Spin Lifetime Dependence on Valley Splitting in Thin Silicon Films

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Electron spin attracts much attention as an alternative to the electron charge degree of freedom for low-power re-programmable logic and non-volatile memory applications. In contrast to charge, spin is not a conserved quantity, and having sufficiently long spin lifetime is critical for applications. We investigate spin relaxation in (001) SOI structures depending on the splitting between the equivalent [001] valleys. In order to evaluate the wave functions and spin flip matrix elements we use the effective **k·p** spin-Hamiltonian, written at the vicinity of the X-point for the two relevant valleys along the Z-axis in the Brillouin zone [1]. The valley-orbit interaction leads to the energy splitting between the equivalent unprimed subbands in the confined electron system [2] or the valley splitting. The valley splitting in unstrained films is [2]: $\triangle E_C = \frac{2\pi^2\Lambda_\Gamma}{(k_0 t)^3} \cdot |\sin(k_0 t)|$, where $k_0 = 0.85\frac{2\pi}{a}$, a is the silicon lattice constant, and t is the film thickness. Λ_Γ is a parameter defining the strength of the valley-orbit interaction with its value ranging between 2eV [3] and 5.5eV [4], depending on the approach used to evaluate the band structure. Both methods reproduce the features of the conduction and valence band equally well, but require additional experimental verification at higher energies where the discrepancy appears. The valley-orbit interaction is significantly enhanced in (001) silicon films uniaxially stressed along [110] direction (ε_{xy}) [5]. We consider the surface roughness (SR) and the longitudinal (LA) and transversal (TA) acoustic phonons as the prominent spin relaxation mechanisms for our UTB sample [5].

We analyze the variation of the spin lifetime (τ^S) with ε_{xy} versus the electron concentration (N_S) in Figure 1. The spin relaxation becomes less severe for higher carrier concentrations for all three considered mechanisms. It is to notice that the spin lifetime enhancement is less pronounced when $\Lambda_\Gamma \neq 0$, although even in such a case ε_{xy} can boost τ^S by orders of magnitude. Figure 2 shows the increase in τ^S with ε_{xy} for different t. We notice that at high ε_{xy}, the values of τ^S become the same with respect to Λ_Γ.

In order to understand this behavior, we consider the spin-flip caused by the intra- and inter-valley transitions. Figure 3 shows the energy levels of the two lowest unprimed subbands primarily responsible [5] for the spin relaxation for several Λ_Γ. Figure 4 depicts the inter- and intra-subband scattering components of τ^S at two distinct temperatures (T). It is observed that the major contribution to spin relaxation comes from the inter-subband processes, which is greatly reduced at high strain, in accordance with Figure 3. At high valley splitting, the spin relaxation is determined by intra-valley scattering which is independent on $\triangle E_C$ and Λ_Γ. In Figure 5 we plot the variation of τ^S with the total valley splitting (ref: Figure 3). It is observed that τ^S strongly depends on Λ_Γ at the lower ranges of the valley splitting. This behavior is correlated with the suppression of the spin hot spots (Figure 6) with increasing $\triangle E_C$ [5]. Most importantly in all cases, the spin lifetime is boosted by several orders of magnitude.

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References

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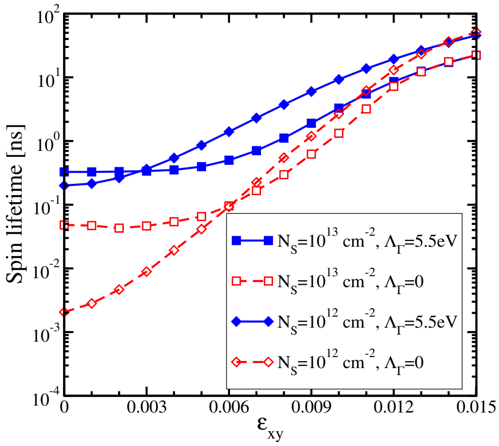

Fig. 1. Variation of the spin lifetime with $\varepsilon_{\mathrm{xy}}$ with the electron concentration as parameter. $t = 2.7\,\mathrm{nm}$, $T = 300\,\mathrm{K}$.

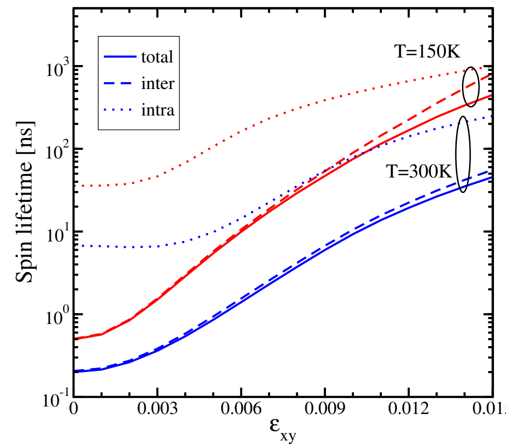

Fig. 4. Spin relaxation time with the respective components. $N_S = 10^{12}\,\mathrm{cm}^{-2}$, $t = 2.7\,\mathrm{nm}$, and $\Lambda_\Gamma = 5.5\,\mathrm{eV}$.

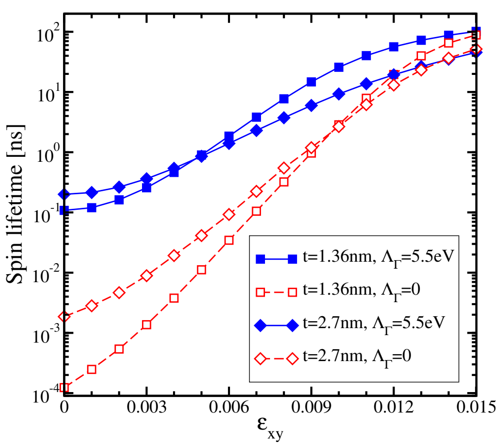

Fig. 2. Variation of the spin lifetime with $\varepsilon_{\mathrm{xy}}$ with the sample thickness as parameter. $N_S = 10^{12}\,\mathrm{cm}^{-2}$, $T = 300\,\mathrm{K}$.

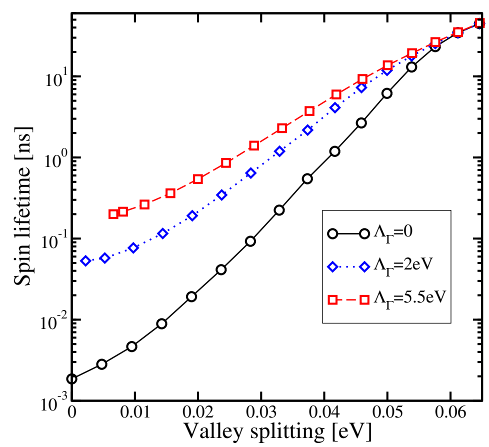

Fig. 5. Variation of the spin lifetime with the valley splitting results shown in Figure 3.

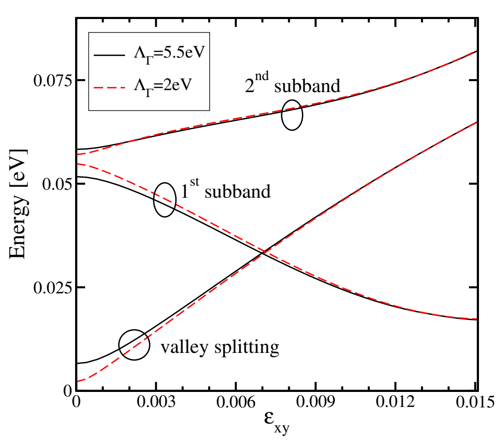

Fig. 3. The energies of two lowest unprimed subbands with $\varepsilon_{\mathrm{xy}}$ at two distinct Λ_Γ values. $N_S = 10^{12}\,\mathrm{cm}^{-2}$, $t = 2.7\,\mathrm{nm}$, $T = 300\,\mathrm{K}$.

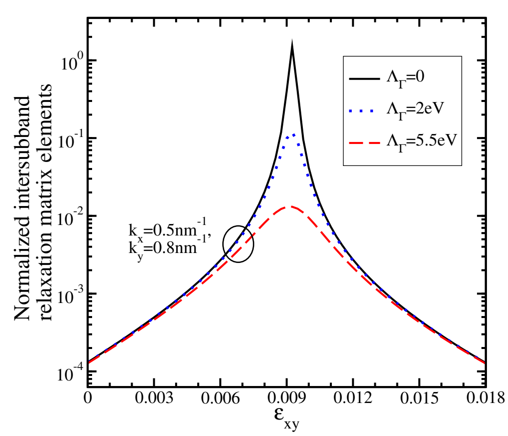

Fig. 6. Variation of the SR spin relaxation inter-subband matrix elements with $\varepsilon_{\mathrm{xy}}$ and with Λ_Γ around the spin hot spot.