Electron Momentum and Spin Relaxation in Silicon Films: A Rigorous k p-based Approach

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Growing technological challenges and soaring costs are gradually bringing the MOSFET scaling to an end. This intensifies the search of alternative technologies and computational principles. The electron spin attracts attention as a possible candidate to be used in future electron devices for complimenting or even replacing the charge degree of freedom employed in MOSFETs. The spin state is characterized by the two spin projections on a given axis and it thus has a potential in digital information processing. In addition, only a small amount of energy is needed to flip the spin orientation. Silicon is an ideal material for spintronic applications due to the long spin lifetime in the bulk. The spin lifetime is determined by the spin-flip scattering between the valleys located on different crystallographic axes [1]. This mechanism is suppressed in thin films; however, large spin relaxation in gated silicon structures was observed [2]. Understanding the spin relaxation mechanisms and ways to boost the spin lifetime in confined electron systems is urgently needed.

We investigate the spin relaxation in (001) silicon structures by taking into account surface roughness and electron-phonon scattering. The surface roughness scattering matrix elements are proportional to the product of the corresponding subband wave functions derivatives at each interface

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[3]. Electron-phonon scattering is considered in the deformation potential approximation. To find the wave functions and matrix elements we use the effective **k·p** Hamiltonian written at the X-point for the two relevant valleys along the OZ-axis with the spin degree of freedom included [1]. We generalize the deformation potential theory to include the shear strain deformation potential and the deformation potential due to spin-orbit interaction responsible for spin relaxation in confined systems [4].

In the two valleys + two spin projections basis the subband wave functions possess four components. Without spin-orbit interaction included the wave function conserves the spin projection which we assume along OZ-axis for concreteness. The two components corresponding to the up-spin projection are well described by $\psi_{11} = e^{ik_0 z}\sin(\frac{\pi z}{t})$(Fig.9a) and its conjugate corresponding to the usual envelope quantization function located at the valley minima $k_0 = \pm 0.15\frac{2\pi}{a}$. Under shear strain ε_{xy} the degeneracy between the two unprimed subbands is lifted which results in slightly different envelope functions (Fig.9b). The **down-spin** components are proportional to the spin-orbit interaction strength (Fig.10a). Under shear strain ε_{xy} these components are greatly suppressed (Fig.10b). As a confirmation of the Elliot-Yafet spin relaxation mechanism, the spin lifetime is proportional to the momentum relaxation time (Fig.11a). Under shear strain ε_{xy} the spin lifetime is enhanced much stronger than the mobility (Fig.11b) due to the **down-spin** components suppression (Fig.10b). In conclusion, shear strain boosts both electron mobility and the spin lifetime in silicon films.

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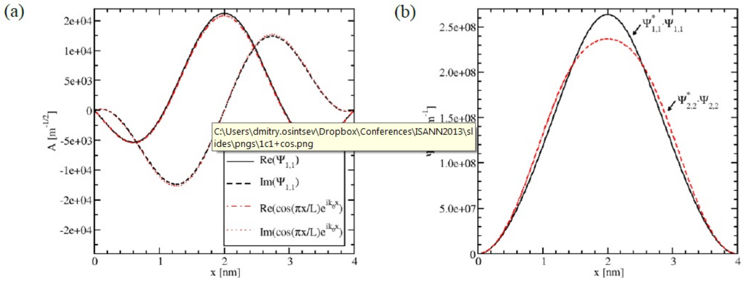

Figure 9: (a): The up-spin component of the wave function of the lowest unprimed subband in unstrained film located in the valley centered at k_0 (b): The up-spin components of the two unprimed subbands with $\varepsilon_{xy}0.05\%$

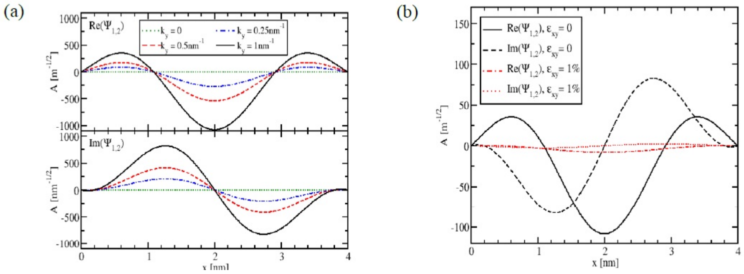

Figure 10: (a): The down-spin components are proportional to the strength of the spin-orbit interaction (b): The down-spin components are considerably suppressed by tensile shear strain

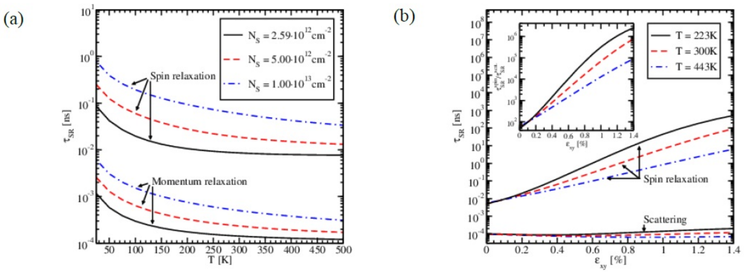

Figure 11: (a): The spin lifetime is proportional to the momentum relaxation time as function of temperature. This is an indication of the Elliot-Yafet spin relaxation mechanism [1] (b): Spin lifetime and momentum relaxation time enhancement with tensile shear strain. Inset: ratio of the spin to the momentum relaxation time