P:32 Spin recovery in the 25 nm gate length InGaAs field effect transistor

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In recent years, there has been an increasing interest in electron spin and its potential for use in semiconductor devices enabling the creation of novel devices with a wide variety of potential applica- tions [1, 2]. Amongst the most promising of these devices are spin field effect transistors (SpinFETs) which are considered a future candidate for high performance computing and memory applications with ultra-low power consumption [3, 4, 5].

A through understanding of the dynamics of electron spins inside real semiconductor materials and device structures is crucial to making use of the spin as part of the device operation. To this end, we apply finite-element quantum-corrected ensemble Monte Carlo simulations with electron spin to a nanoscale III-V field effect transistor to investigate a spin transport within a realistic semiconductor device.

The simulation was adapted to include electron spin as a separate degree of freedom using the spin density matrix $\rho 0(t)$ [6].

$$\rho_0(t) = \begin{pmatrix} \rho_{\uparrow\uparrow}(t) & \rho_{\uparrow\downarrow}(t) \\ \rho_{\downarrow\uparrow}(t) & \rho_{\downarrow\downarrow}(t) \end{pmatrix} \tag{1}$$

where $\rho\uparrow\uparrow$ and $\rho\downarrow\downarrow$ represent the probability of finding the electron in either a spin up or spin down state and $\rho\uparrow\downarrow$ / $\rho\downarrow\uparrow$ represent the coherence. This can be parametrized by the electron spin-polarization vector as $S\zeta = Tr(\sigma\zeta\ \rho 0(t))$ where $\zeta = x, y, z,$ and $\sigma\zeta$ are the Pauli matrices.

The spin-orbit interaction consists of two terms the Dresselhaus Hamiltonian (HD) which accounts for spin-orbit coupling as a result of bulk inversion asymmetry of the crystal, and the Rashba Hamiltonian (HR) which accounts for spin-orbit coupling due to structural inversion asymmetry of the quantum well.

$$H_D = \beta\langle k_y^2\rangle(k_z\sigma_z - k_x\sigma_x) \qquad\qquad H_R = \eta(k_z\sigma_x - k_x\sigma_z) \tag{2}$$

Here x is taken to be the transport direction along the device channel and y the growth direction of the quantum well and k_x^2 , k_z^2 « $\langle k_y^2\rangle$.

Discretizing the equations, we obtain the update rule for the density matrix,

$$\rho(t+\tau) = e^{-i(H_R+H_D)\tau/\hbar}\rho(t)e^{i(H_R+H_D)\tau/\hbar}. \tag{3}$$

Using basic matrix algebra it can easily be shown that

$$e^{-i(H_R+H_D)\tau/\hbar} = \begin{pmatrix} \cos(|\alpha|\tau) & i\frac{\alpha}{|\alpha|}\sin(|\alpha|\tau) \\ i\frac{\alpha^*}{|\alpha|}\sin(|\alpha|\tau) & \cos(|\alpha|\tau) \end{pmatrix} \tag{4}$$

With

$$\alpha = \hbar^{-1}[(\eta k_z - \beta\langle k_y^2\rangle k_x) + i(\eta k_x - \beta\langle k_y^2\rangle k_z)]. \tag{5}$$

This shows that the evolution of the spin polarization vector is equivalent to a rotation determined by the direction of the electron momentum.

Using this simulator, we investigated the spin dynamics across the channel of an $In_{0.3}Ga_{0.7}As$ MOS-FET (Fig. 1). The device we study is similar to the Datta-Das spin-FET [3] except that only the source electrode is ferromagnetic. We simulated the e_ects of varying both the drain and gate biases and the application of mechanical strain. The simulation results are interesting because they suggest that the polarisation of the electrons initially decays as they traverse the device, as expected, but partially recovers as the electrons approach the drain (see Fig. 2a).

As the drain electrode was deliberately chosen to be non-magnetic, the recovery of the magnetization cannot be attributed to existing polarized carriers inside the drain but must be assumed to be due to partial re-phasing of electron spins resulting in a net magnetization. Finally the decay and the recovery depend on the gate voltage (Fig. 2b) and can therefore be controlled we also see a similar dependence on the applied strain which has the potential to be used in the operation of a nanoscale strain sensor.

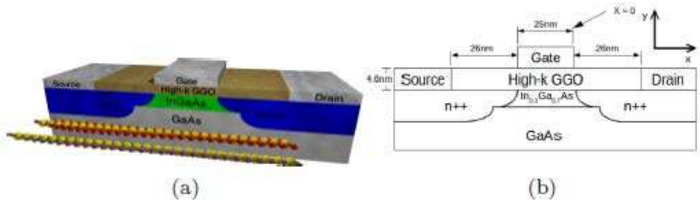

Figure 1: (a) 3D model of $In_{0.3}Ga_{0.7}As$ MOSFET showing spin polarization of electrons along *n*-channel with 4% strain in the [001] direction (Red) and unstrained (Purple). (b) Schematic of $In_{0.3}Ga_{0.7}As$ MOSFET.

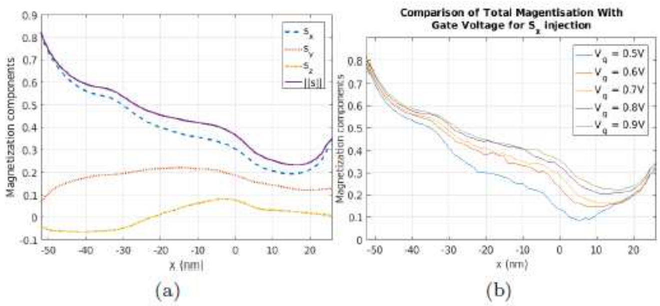

Figure 2: (a) Magnetisation components vs. position along the channel (averaged over 10 runs) taken for S_x injection at $t = 8ps$, i.e., after a steady state was reached. (b) Total magnetisation versus position at $t = 8ps$ with different gate voltages (V_g) and a fixed source-drain voltage (V_d) of 0.9 V.

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