Temperature Affected Non-Equilibrium Spin Transport in Nanoscale $In_{0.3}Ga_{0.7}As$ Transistors

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Electron spin offers extraordinarily attractive possibilities in the operation of semiconductor devices thanks to the speed and low energy consumption in its control [1, 2]. One application and future candidate for high performance computing and memory applications with ultra-low power consumption are spin field effect transistors (SpinFETs). Originally proposed by Datta-Das [3], spin transport in a hot electron transistor was demonstrated in [4].

In this work, 2D finite-element quantum-corrected ensemble Monte Carlo simulation code to model a realistic nanoscale $In_{0.3}Ga_{0.7}As$ MOSFET [6] (Fig. 1), designed on ITRS prescriptions [6], was augmented to incorporate electron spin-degrees of freedom and spin-orbit coupling to simulate electron spin transport in a realistic nanoscale device. The dimensions of the $In_{0.3}Ga_{0.7}As$ MOSFET are illustrated in Fig. 2. The device is similar to the Datta-Das SpinFET [3] but only the source electrode is ferromagnetic. The spin states are described by a spin density matrix: $\rho = \begin{pmatrix} \rho_{\uparrow\uparrow}(t) & \rho_{\downarrow\uparrow}(t) \\ \rho_{\uparrow\downarrow}(t) & \rho_{\downarrow\downarrow}(t) \end{pmatrix}$

where $\rho_{\uparrow\uparrow}$ and $\rho_{\downarrow\downarrow}$ are the population of spin-up and spin-down electrons, respectively, and the diagonal elements $\rho_{\downarrow\uparrow}$ and $\rho_{\uparrow\downarrow}$ represent the coherence. The spin degrees of freedom of the electrons are coupled to the orbital degrees of freedom described by the wavevector ***k*** via a spin-orbit coupling Hamiltonian. Dresselhaus and Rashba coupling are the two main contributions to spin-orbit coupling. Dresselhaus coupling is due to asymmetry in a crystal, given by the Hamiltonian

$$H_D = \Gamma_D \langle k_y^2 \rangle \ (k_z\sigma_z - k_x\sigma_x)$$

Rashba coupling is due to potential asymmetry in the quantum well, given by

$$H_R = \alpha_R \ (k_z\sigma_x - k_x\sigma_z)$$

This assumes that the channel is in the [001] direction, x is the transport direction along the channel, and z is the growth direction orthogonal to the quantum well. α_R and Γ_D are Rashba and Dresselhaus coupling constants, respectively, which are material, strain and temperature dependent/ We monitor the 3D magnetization components over varying drain and gate biases at fixed large gate (0.7 V) and drain biases (0.9 V), respectively, as shown in Figs. 4 and 5. Fig. 6 presents magnetization components as a function of temperature showing substantial increase in magnetization components of about 65% when lattice temperature drops from 300 K to 77 K due to a substantial reduction in electron-phonon scattering.

However, Figs. 8 and~9 demonstrate that increasing the source-to-gate and gate-to-drain spacers can enhance the spin recovery, reported initially in the 25 nm gate length $In_{0.3}Ga_{0.7}As$ MOSFET [7]. The polarisation of the electrons initially decays along the channel but surprisingly partially recovers as the electrons reach a high fringing electric field on the drain side of the gate. There they undergo highly non-equilibrium transport during their acceleration, limited mainly by emission of polar phonons. The drain electrode was deliberately chosen to be non-magnetic so that recovery of the magnetization cannot be attributed to existing polarized carriers inside the drain.

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Fig. 1: 3D model of the studied $In_{0.3}Ga_{0.7}As$ showing spin polarization of electrons along n-channel with 4% strain (red) and unstrained (purple).

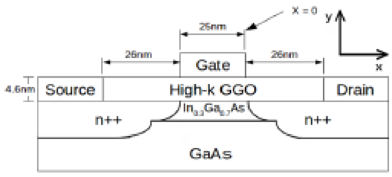

Fig. 2: Cross-section with dimensions of the 25 nm gate length, n-channel $In_{0.3}Ga_{0.7}As$ MOSFET.

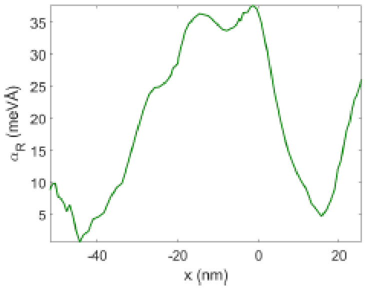

Fig. 3: Rashba coupling constant along the 25 nm gate length channel of $In_{0.3}Ga_{0.7}As$ MOSFET. The zero in the channel is set at the drain side of the gate.

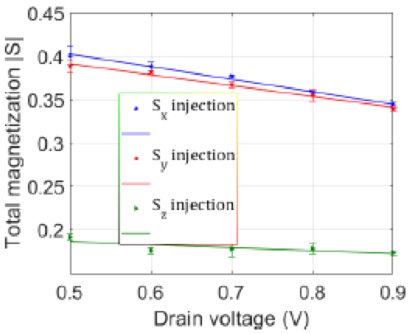

Fig. 4: Magnetization components of spin injection (averaged over 10 runs) vs. drain bias at V_G=0.7 V with indication of error in averages. The transport direction along the x-axis. The lines are only a guide to the eye.

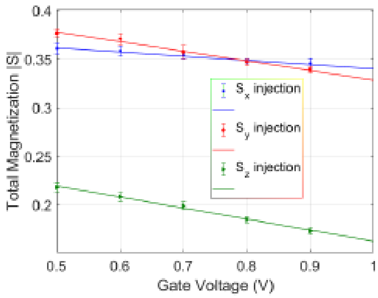

Fig. 5: Magnetization components of spin injection (averaged over 10 runs) vs. gate bias at V_D=0.9 V with indication of error in averages. The transport direction is along the x-axis.

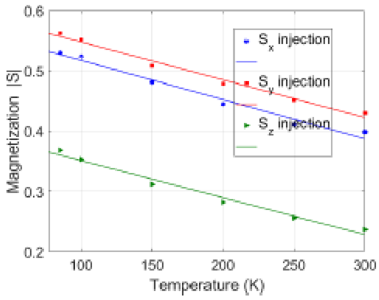

Fig. 6: Magnetization components of spin injection (averaged over 10 runs) vs. lattice temperature at V_G=0.7 V and V_D=0.9 V with errors in averages. The transport direction is along the x-axis.

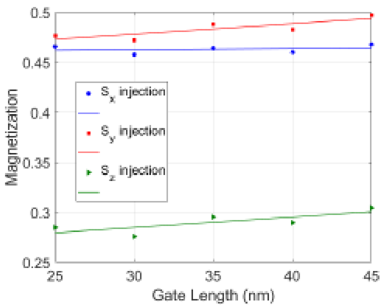

Fig. 7: Magnetization components (averaged over 10 runs) vs. the gate length of the transistor at V_G=0.7 V and V_D=0.9 V. The lines are only a guide to the eye.

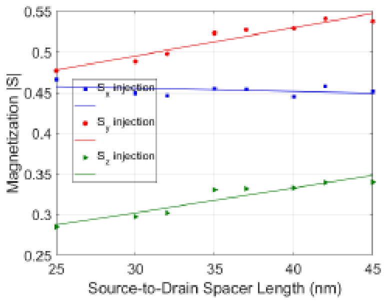

Fig. 8: Magnetization components (averaged over 10 runs) vs. the source-to-gate spacer of the transistor at V_G=0.7 V and V_D=0.9 V. The lines are only a guide to the eye.

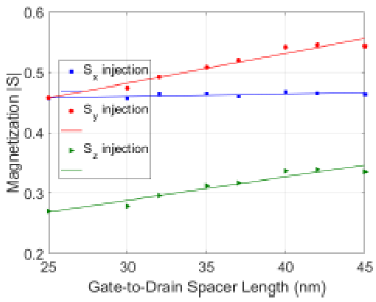

Fig. 9: Magnetization components (averaged over 10 runs) vs. the gate-to-drain spacer of the transistor at V_G=0.7 V and V_D=0.9 V. The lines are only a guide to the eye.