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 [2, 1]. 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 [5], 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

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

where $\rho_{\uparrow\uparrow}$ and $\rho_{\downarrow\downarrow}$ are the population of spin-up and spin-down electrons, respectively, and the diagonal elements $\rho_{\uparrow\downarrow}$ and $\rho_{\downarrow\uparrow}$ represent the coherence. The spin degrees of freedom of the electrons are coupled to the orbital degrees of freedom described by the wavevector $\vec{k}$ 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

$$H_D = \Gamma_D \langle k_y^2 \rangle (k_z\sigma_y - k_x\sigma_x). \quad (1)$$

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

$$H_R = \alpha_R(k_z\sigma_x - k_x\sigma_z). \quad (2)$$

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. The scaling up aimed to impose a stronger control of the spin from the gate has been also studied, revealing a negligible change in magnetization components as seen in Fig. 7. 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.

References

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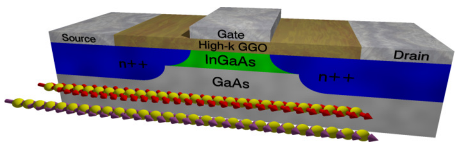

Fig. 1: 3D model of the studied $In_{0.3}Ga_{0.7}$As showing spin polarization of electrons along n-channel with 4% strain (red) and unstrained (purple).

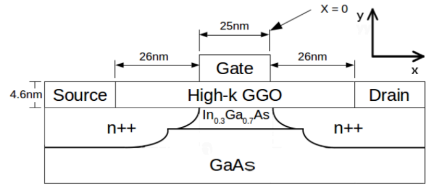

Fig. 2: Cross-section with dimensions of the 25 nm gate length, n-channel $In_{0.3}Ga_{0.7}$As MOSFET.

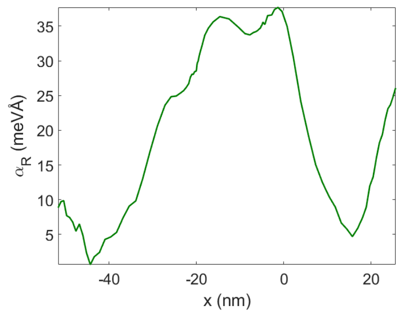

Fig. 3: Rashba coupling constant along the 25 nm gate length channel of $In_{0.3}Ga_{0.7}$As MOSFET. The zero in the channel is set at the drain side of the gate.

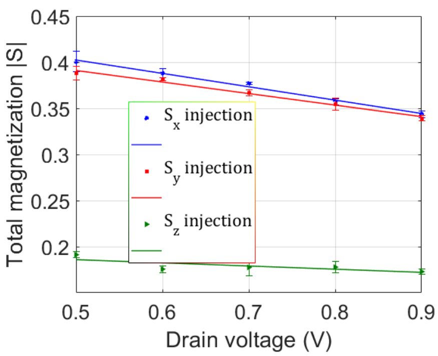

Fig. 4: Magnetization components of spin injection (averaged over 10 runs) vs. drain bias at V_G=0.7 V with indication of error in averages. The transport direction along the x-axis. The lines are only a guide to the eye.

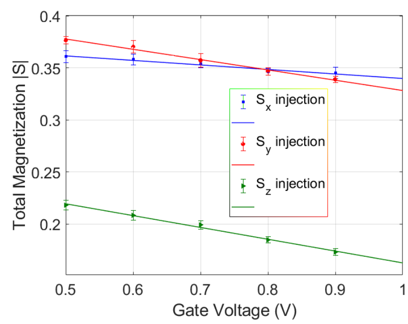

Fig. 5: Magnetization components of spin injection (averaged over 10 runs) vs. gate bias at V_D=0.9 V with indication of error in averages. The transport direction is along the x-axis.

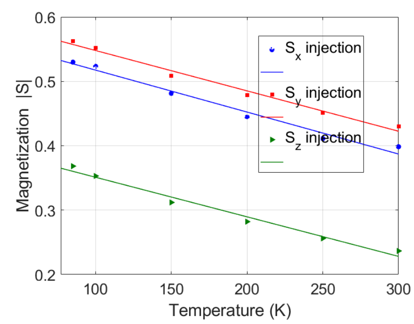

Fig. 6: Magnetization components of spin injection (averaged over 10 runs) vs. lattice temperature at V_G=0.7 V and V_D=0.9 V with errors in averages. The transport direction is along the x-axis.

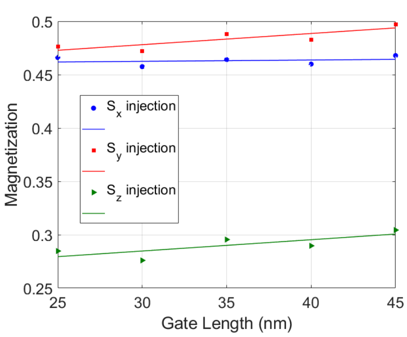

Fig. 7: Magnetization components (averaged over 10 runs) vs. the gate length of the transistor at V_G=0.7 V and V_D=0.9 V. The lines are only a guide to the eye.

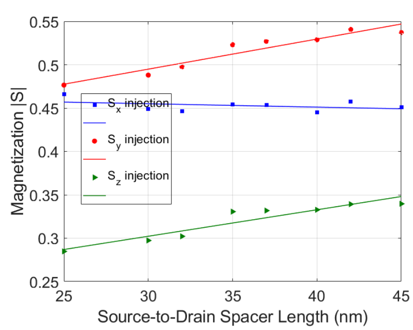

Fig. 8: Magnetization components (averaged over 10 runs) vs. the source-to-gate spacer of the transistor at V_G=0.7 V and V_D=0.9 V. The lines are only a guide to the eye.

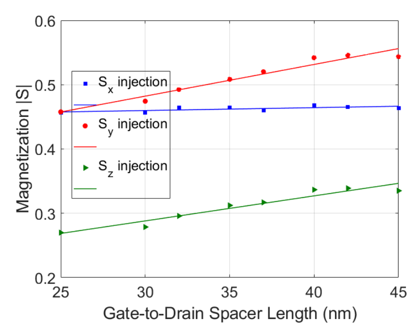

Fig. 9: Magnetization components (averaged over 10 runs) vs. the gate-to-drain spacer of the transistor at V_G=0.7 V and V_D=0.9 V. The lines are only a guide to the eye.