Effect of forming gas annealing on the enhancement of the electron spin lifetime in the inversion channel of Si-based spin MOSFETs

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Long spin lifetime is essential for highly-efficient spin transport in Si-based spin MOSFETs [1]. Our previous study revealed that the spin lifetime τ_S is proportional to the electron momentum lifetime τ, and the ratio τ_S/τ (~25000) was almost constant, irrespective of the applied gate voltage V_{GS} [2,3], indicating that the Elliott-Yafet mechanism governs the spin relaxation [4,5]. From this result, the enhancement of τ_S is expected with increasing τ. In this study, we perform a forming gas annealing (FGA), which is effective for increasing τ, on a spin MOSFET and studied the changes of τ_S and τ by FGA at various temperatures T.

Figure 1 shows our bottom-gated spin MOSFET device examined in this study [2], which has Fe/Mg/MgO/n^+-Si ferromagnetic tunnel junctions at the Source/Drain and a 8-nm-thick p-Si channel (N_A ~ 1×10^{15} cm^{-3}) with a 10 μm in length. Before FGA, Hanle precession signals were measured at T = 4 – 295 K and τ_S was estimated by fitting the signals as the same procedure described in [3]. On the other hand, the electron mobility μ and τ was estimated from another Hall-bar type device with the same channel structure. After that, the samples were annealed (FGA) at 250°C for 30 min in a 96% N_2 + 4% H_2 ambient. Then, τ_S, μ, and τ were estimated using the same procedure and compared with those estimated before the FGA, respectively.

Figure 2 shows μ as a function of the effective gate electric field E_{eff} [3], in which μ becomes about twice at 295 K, and becomes larger by six-times at 4 K by the FGA. We see remarkable enhancement of μ at the lower E_{eff} (~0.1 MV/cm), indicating that the Coulomb scattering was suppressed by the hydrogenation of fixed negative charges at the Si/SiO_2 interface. This is consistent with the fact that the flat-band voltage was negatively shifted after the FGA. Figure 3 shows the comparison of τ_S (right axis) and τ (left axis) before and after FGA at various temperatures. We found that FGA increases τ_S along with τ, whereas the ratio τ_S/τ remains almost constant (~25000). Therefore, we conclude that longer τ leads to longer τ_S in the Si inversion channel.

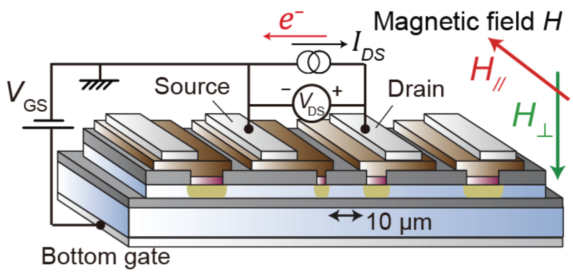

Fig. 1 Schematic illustration of our spin MOSFET device structure and the measurement setup.

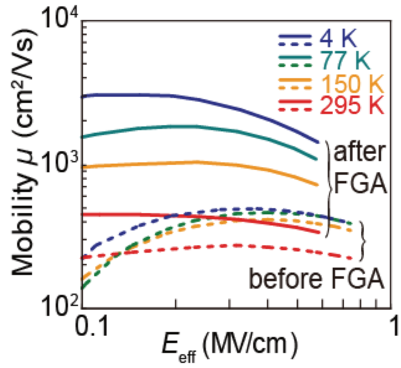

Fig. 2 Electron mobility μ in the inversion channel before FGA (dashed curve) and after FGA (solid curve).

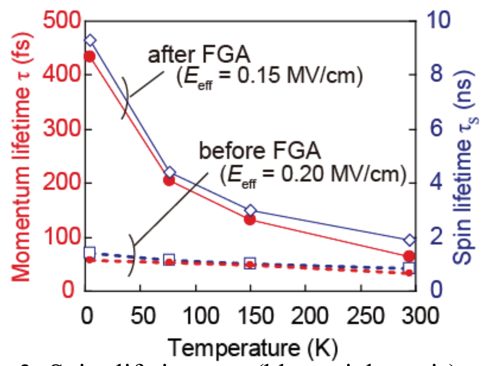

Fig. 3 Spin lifetime τ_S (blue, right axis) and momentum lifetime τ (red, left axis) before and after FGA.

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