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Effective creation of spin polarization in *p*-type Germanium from a Fe/GeO_2 tunnel contact

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1. Introduction

Effective creation of spin-polarized carriers at room temperature (RT) from a ferromagnet (FM) into practical semiconductors such as Si [1] and Ge [2,3] is a key requirement for the development of semiconductor-based spintronics devices. In particular, owing to its high carrier mobilities, p-type Ge is an appealing candidate as a high-speed channel in the next generation of complementary metal-oxide-semiconductor (CMOS) transistors. Recently, we have demonstrated the creation of spin polarization into a bulk band of p-Ge from a crystalline MgO tunnel contact up to RT [2,4,5]. However, spin accumulation into p-Ge at RT using amorphous tunnel barrier has not been achieved yet.

In this study, amorphous GeO_2 was employed as a new tunnel barrier instead of crystalline MgO. We achieved effective creation of spin polarization in heavily p-doped Ge up to RT and demonstrated some noteworthy differences in the bias dependence of the spin signal, especially in the low voltage range.

2. Experimental

Films were grown by molecular beam epitaxy on Ga-doped p-type Ge(001) substrates with a hole concentration of 8×10^{18} cm^{-3} at 300 K. After surface treatment by buffered hydrofluoric acid, an *in situ* annealing was carried out at 700°C for 10 min to remove the Ge surface oxide. After this step, reflection high-energy electron diffraction (RHEED) pattern revealed a clear (2 × 1) reconstruction (Fig 1a), indicating an oxygen-free and atomically flat Ge surface. The GeO_2 tunnel barrier layer was grown by electron-beam evaporation at RT under oxygen atmosphere (~ 1×10^{-6} Torr). As shown in Fig.1b, no diffraction spots, streaks, or ring patterns were observed, indicating that an amorphous GeO_2 layer was grown on Ge. A polycrystalline 5-nm-thick Fe upper electrode was subsequently grown on the GeO_2 layer at RT (Fig.1c). Finally, a 20 nm-thick Au cap layer was deposited at RT. Junctions with an active tunnel area (A) of 100 × 200 μm^2 were prepared with standard micro-fabrication techniques. To detect the induced spin accumulation, Hanle-type measurements in a three-terminal configuration [1,6] were performed. Bias-V is defined as $V_{Ge} - V_{Fe}$, where V_{Ge} and V_{Fe} are the potential of the Ge and Fe electrode, respectively.

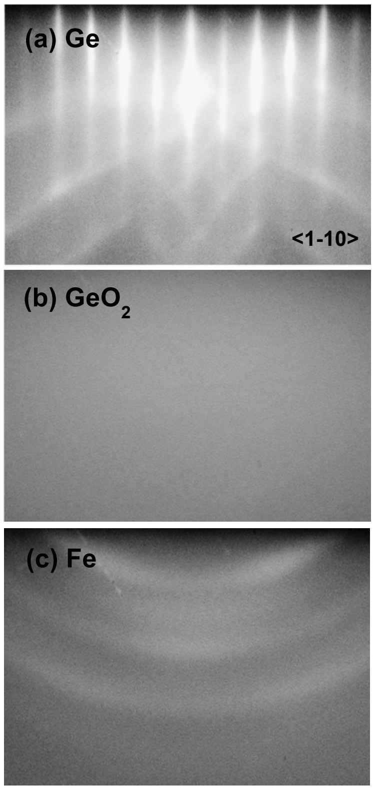

Fig. 1 RHEED patterns of (a) a clean Ge substrate, (b) GeO_2, and (c) Fe layers.

3. Results and discussion

The Hanle and inverted Hanle [7] curves measured at various temperatures (T) with a $V \sim + 100$ mV are given in Figs 2(a)-(c). The Hanle and inverted Hanle curves were obtained with magnetic fields applied perpendicular ($B_\perp$) and parallel ($B_{\parallel}$) to the tunnel interface, respectively. We can see clear Lorentzian line shapes centered around $B = 0$ in all the Hanle curves, indicating that a spin accumulation is induced in the Ge by the Fe/GeO_2 tunnel contact up to 300 K. Interestingly, the amplitude of the Lorentzian part of the inverted Hanle curves decreases with increasing T and almost disappears at 300 K. Note that inverted Hanle effect originates from magneto-static fringe fields produced by interface roughness of the FM [7]. On that account, if the

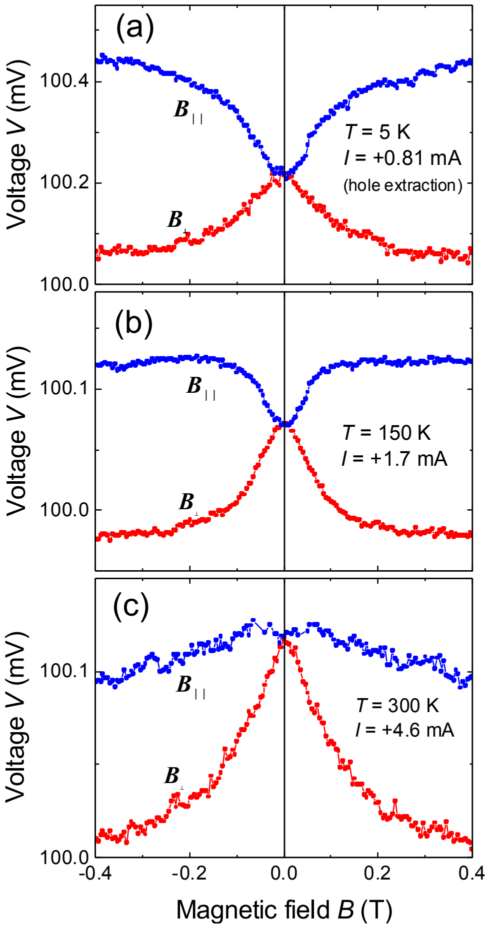

Fig. 2 Hanle ($B_\perp$) and inverted Hanle ($B_{//}$) curves of the Fe/GeO_2/p-Ge device measured at (a) 5 K, (b) 150 K, and (c) 300 K with a $V \sim +100$ mV (hole extraction).

spin lifetime (τ_s) in the Ge becomes shorter with T, the induced spins become less sensitive to the fringe fields with increasing T. Because Elliott-Yafet mechanism is the dominant process in Ge, τ_s should be proportional to the momentum relaxation time [8] and therefore to the hole mobility μ. In the present Ge, we determined μ to be 3.8×10^2 cm^2/Vs at 5 K and 2.5×10^2 cm^2/Vs at 300 K using the van der Pauw method. Thus, we expect a decrease of τ_s with increasing T, which is qualitatively consistent with the observed suppression of the inverted Hanle signal at elevated T.

The absence of the inverted Hanle signal at RT gives a good opportunity to estimate the intrinsic τ_s from the Hanle curve because there is no artificial broadening of the width of the Hanle curve [7]. We obtained a value of τ_s = 15 ps at 300 K from the Hanle curve. The obtained τ_s is close to that of the device with the Fe/MgO contact (13 ps) that exhibits a very small inverted Hanle signal [2].

We examined the detection of the spin accumulation at lower V. The Hanle curves at 300 K measured below 100 mV in both polarities are given in Fig. 3. It should be pointed out that the Lorentzian line shapes are visible for hole extraction ($V > 0$) as well as for hole injection ($V < 0$) even in the low V region. In contrast to Fe/MgO tunnel contact, amorphous GeO_2 tunnel barrier leads to a symmetric and linear bias dependence of the spin signal in p-Ge. Further studies are needed to understand the origin of the noticeable differences in the V dependence of the spin accumulation signal.

4. Conclusion

We fabricated Fe/GeO_2 tunnel contacts on heavily doped p-type Ge and examined the spin accumulation in the Ge using three-terminal Hanle measurements. Clear spin accumulation signals were succesfully observed up to 300 K and we found that the bias dependence of the spin signal exhibits a linear behaviour in both polarities. We also obtained an intrinsic spin lifetime of 15 ps at 300 K. These results demonstrate that amorphous GeO_2 tunnel barrier is suitable for achieving effective spin polarization in p-Ge even in the low voltage range.

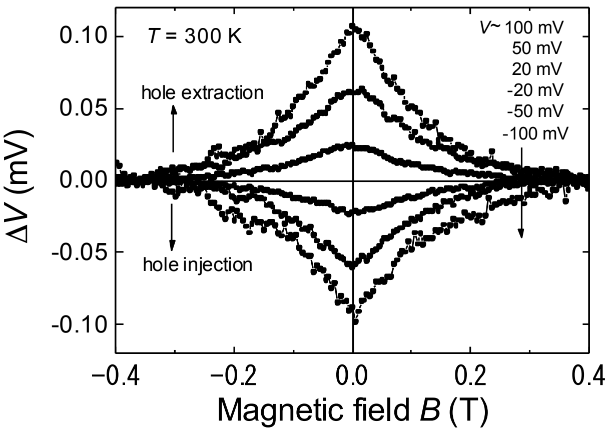

Fig. 3 Hanle curves of the Fe/GeO_2/p-Ge device at 300 K with different V.

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