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Electrical Creation of Spin Accumulation in *p*-type Ge

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1. Introduction

The electrical injection and detection of spin-polarized carriers in semiconductors (SC) is the key to develop spin-based devices such as the spin field-effect transistor [1, 2]. In most cases, GaAs [3-6] and Si [7-11] have been used as the SC material, in part because of their compatibility with existing technology. Germanium (Ge) is attractive since it is an important candidate for the high-mobility channel in next-generations of complementary metal-oxide-semiconductor transistors. Recently, electrical transport properties of metal/insulator/Ge junctions have been investigated intensively [12-14], and spin-dependent transports have been reported in heavily-doped *n*-type Ge [15, 16]. Spin-dependent effects in *p*-type Ge are necessary for developing Ge-based spintronic devices, but have not yet been reported.

Here, we report the successful electrical creation of a spin accumulation in moderately doped *p*-type Ge with an epitaxial Fe/MgO tunnel contact [17]. We find a large magnitude of the spin accumulation in the Ge and a strong variation with bias-voltage and temperature, which cannot be explained within the commonly used model for spin injection and accumulation.

2. Experimental

Films were grown by molecular beam epitaxy on *p*-type Ge(001) substrates with a hole concentration (p) of 3×10^{17} cm^{-3} at 300 K. After surface treatment by buffered hydrofluoric acid, the substrate was installed into the ultrahigh vacuum growth chamber and annealed at 700°C for 10 min to remove the surface oxide. Then, tunnel contacts consisting of MgO(2 nm)/Fe(10 nm)/Au(20 nm) were deposited by electron- beam evaporation at room temperature. The reflection high-energy electron diffraction pattern of the MgO(001) was diffusive, indicating that the Fe/MgO interface is not atomically flat. The junctions with an active tunnel area (A) of 100×200 μm^2 were prepared with standard micro-fabrication techniques.

3. Results and discussion

Figure 1 shows current-voltage (I-V) characteristics at various temperatures (T) measured by a conventional two-probe method. Bias-voltage is defined as V_{Ge}–V_{Fe}, where V_{Ge} and V_{Fe} are the potential of the Ge and Fe electrode, respectively. The I-V characteristics are almost symmetric with bias and have weak T dependence [R(5K)/R(300K) = 3.7 at 10 mV], as expected for tunneling [18]. Note that the current is even slightly higher for reverse bias (V<0, hole injection), which is opposite to the case of a Schottky diode. This indicates that the MgO/Ge interface is free from a Schottky barrier potential. This guarantees direct tunneling into the Ge bulk bands and avoids enhancement of the spin accumulation due to localized states at MgO/Ge interface [4].

For Hanle effect measurements [3-5, 7-9, 19], a magnetic field $B_\perp$ is applied perpendicular (⊥) to the film plane, while the FM electrode is magnetized parallel (ǁ) to the film plane. This causes precession of the spins in the Ge and a reduction of the spin accumulation. At constant tunnel current, this results in a reduction of the tunnel voltage by ΔV_{spin} with a Lorentzian line shape. However, it has recently been demonstrated that the spin accumulation can be partially suppressed by precession in inhomogeneous local magnetic fields B_{loc} arising from the finite roughness of the FM [19]. This effect can be suppressed by applying an in-plane field ($B_\parallel$), leading to an *increase* in tunnel resistance due to the recovery of spin accumulation (inverted Hanle effect) [19]. Since the surface roughness of our MgO is large enough to create a sizable B_{loc} of several tens of mT, we measured ΔV_{spin} for $B_\perp$ as well as $B_\parallel$ to obtain a real magnitude of spin accumulation.

Hanle and inverted Hanle effects were clearly observed

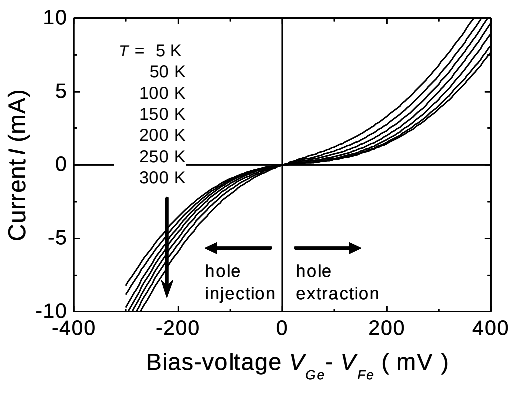

Fig. 1 Current-voltage characteristics of the Fe/MgO tunnel contacts on *p*-type Ge at various temperatures [17].

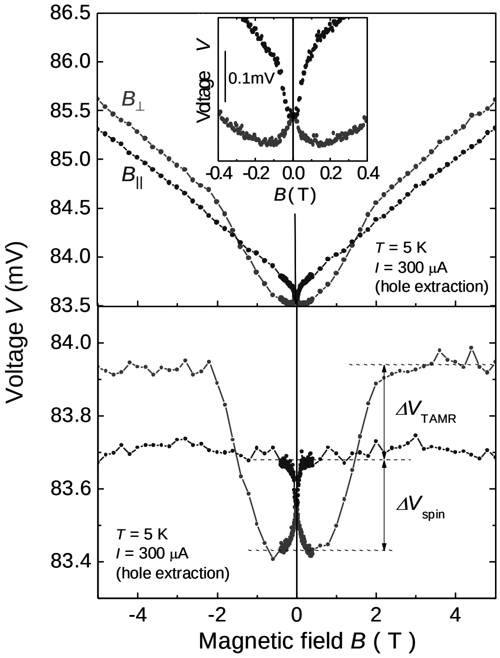

Fig. 2 (a) Hanle and inverted Hanle curves of Fe/MgO contacts on p-type Ge for magnetic fields applied perpendicular ($B_{\perp}$) and parallel ($B_{\|}$) to the film plane, respectively. The inset shows an expanded view of the low-field range, at T= 5 K and I = +300 μA. (b) Same data shown in (a), but now with the linear background slope subtracted. The signals related to the spin accumulation (ΔV_{spin}) and the TAMR (ΔV_{TAMR}) are indicated [17].

at T= 5 K (inset of Fig. 2(a)), demonstrating the successful creation of spin accumulation in the bulk region of Ge. In addition to the Hanle and inverted Hanle effects, there is a linear slope at large field and the voltage is larger for $B_{\perp}$ (Fig. 2(a)). The latter is due to the the tunneling anisotropic magnetoresistance (TAMR) [20]. In Fig. 2(b), the spin accumulation and the TAMR signals are plotted by subtracting the linear slope from the data of Fig.2 (a). A total ΔV_{spin} of about 240 μV is then obtained. Beyond the low-field regime, only the voltage for $B_{\perp}$ increases due to the out of plane rotation of M. It saturates just above 2 T, which corresponds to the demagnetization field of Fe.

The measured spin resistance-area-product (spin-RA) is obtained as $(\Delta V_{spin}/I)\cdot A$ = 16.0 kΩμm^2. According to the diffusion model [21, 22], it should be equal to $P^2 \cdot \rho_{Ge} \cdot \lambda_{sf}$, where P is the tunnel spin polarization, ρ_{Ge}= 27 mΩcm at 5 K and λ_{sf} is the spin-diffusion length. Assuming P = 0.6, an unrealistically large λ_s value of 158 μm is required for λ_{sf}. Indeed, the required value is about three orders of magnitude larger than that of p-type Si [9]. In other words, the observed spin signal is much larger than the value predicted from the model.

4. Conclusions

We successfully demonstrated electrical creation and detection of spin accumulation in the bulk region of p-type Ge using an epitaxial Fe/MgO tunnel contact. The magnitude of the spin accumulation cannot be explained within the existing diffusion model for spin injection, while enhancement of spin accumulation in localized states at the MgO/Ge interface can be ruled out due to the absence of a Schottky barrier in the p-type Ge contacts. Our results thus provide new information that is useful to understand the physics of spin accumulation not only in Ge, but also in semiconductors in general.

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