Spin Accumulation in Nondegenerate and Heavily Doped p-Type Germanium

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1. Introduction
Recently the electrical creation and detection of spin-polarized carriers in a semiconductor (SC) by tunneling from a ferromagnetic contact have been intensively studied. Dash et al. [1] and Saito et al. [2] pointed out that the magnitudes of spin accumulation in the “bulk” bands of SCs such as Si and Ge are several orders of magnitude larger than the predicted value from the standard theory of spin injection and diffusion [3]. However, what controls the magnitude of the spin accumulation induced in the SC is not understood. Recently, Ando et al. [4] reported that the spin accumulation in nondegenerately doped Si with CoFe/Si Schottky contacts is not enhanced and can be well explained by the standard theory. Here, we report the magnitude of spin accumulation versus doping density in Fe/MgO/p-Ge tunnel devices that are free of rectification and Schottky barrier, guaranteeing spin injection into the Ge and preventing spin accumulation enhancement by two-step tunneling via interface states [5]. The scaling of the magnitude of the spin accumulation with doping concentration is compared to spin injection and diffusion theory. It is shown that the observed spin accumulation is smallest for nondegenerate doping and increases for heavily doped Ge. This trend is opposite to what is expected from spin injection and diffusion theory [6].

2. Experiments
Films were grown by molecular beam epitaxy on p-type Ge(001) substrates with different hole concentrations \( p = 5 \times 10^{13}, 4 \times 10^{17}, \) and \( 7 \times 10^{18} \) cm\(^{-3}\) (referred to using labels LO, ME, and HI, respectively). Tunnel contacts consisting of Au (20 nm)/Fe (10 nm)/MgO (2.0-2.5 nm) were deposited at room temperature. Junctions with an active tunnel area (\( A \)) of 100 \( \times 200 \) \( \mu \)m\(^2\) were prepared as previously described [2]. The spin accumulation was probed at a temperature (\( T \)) of 40 K using Hanle and inverted Hanle measurements in a three-terminal configuration [7].

3. Results and discussion
Current-voltage (\( I-V \)) characteristics of the Fe/MgO/Ge contacts at 40 and 300 K are presented in Figs. 1(a) and 1(b), respectively. We observed similar \( I-V \) characteristics without any diode behavior for all the contacts at 300 K as well as 40 K. Also, the junction resistance \( R \) has a weak \( T \) dependence; for example, \( R(40K)/R(280K) \) is about 2.5 at 10 mV bias. All this demonstrates that the MgO/Ge contacts are free from a Schottky barrier. This guarantees direct tunneling from the Fe into the Ge and rules out the spin accumulation in MgO/Ge interface states [5]. Then, our Hanle measurement can probe the magnitude of the spin accumulation in the “bulk” bands of the Ge.

Figure 2(a) present Hanle and inverted Hanle curves at 40 K for the samples on HI-doped substrates, obtained with the magnetic field applied perpendicular (\( B_\perp \)) and parallel (\( B_\parallel \)) to the tunnel interface, respectively. Clear Lorentzian

![Fig. 1 Current-voltage characteristics for Fe/MgO/Ge tunnel contacts on the three substrates at (a) 40 K and (b) 300 K [6]. The bias voltage is defined as \( V_{Ge} - V_{Fe} \), where \( V_{Ge} \) and \( V_{Fe} \) are the potentials of the Ge and Fe electrodes, respectively.](image1)

![Fig. 2 Hanle and inverted Hanle curves at 40 K for Fe/MgO/Ge devices with (a) HI-doped (b) MI-doped Ge substrates [6].](image2)
line shapes centered around zero field can be seen. We also observed similar Lorentzian line shapes in the ME-doped substrates as shown in Fig. 2(b). The magnitude of the spin signal ($\Delta V_{\text{spin}}$) corresponds to the sum of the voltage change in the Lorentzian part of the Hanle and inverted Hanle curves [7]. The values are about 200 $\mu$V for sample HI and 330 $\mu$V for sample ME. As shown in Fig. 3(a), the spin signal for sample LO was overshadowed by a large positive background due to Lorentz magnetoresistance (LMR) in the Ge substrate, which was also observed in control devices using a nonmagnetic Au contact. This LMR is larger for the LO substrate owing to its larger mobility (LMR is quadratic in mobility), and because the larger substrate resistance is a larger fraction (10%) of the total three-terminal resistance. Nevertheless, clear deviations from a quadratic function are found in the low $B$ range, suggesting that a spin accumulation is also induced in the LO substrate. To further visualize the spin signal, the voltage difference between the Hanle and inverted Hanle data [$V(B_+)$ - $V(B_-)$] is given in Fig. 3(b). A peak centered at zero with a Lorentzian line shape is observed, but only for the device with the Fe contact, indicating that a spin accumulation is created in the nondegenerate Ge. The corresponding $\Delta V_{\text{spin}}$ is about 80 $\mu$V.

The observed $\Delta V_{\text{spin}}$ is converted to a spin resistance-area-product [spin-RA = $\Delta V_{\text{spin}}/J$, where $J$ is the current density $I/A$], and plotted in Fig. 4 (solid red circles). According to the standard theory [3], the spin-RA equals to $P^2 \rho_{\text{Ge}} \lambda_d$, where $P$ is the tunnel spin polarization ($\approx 0.6$ in our Fe/MgO contacts [2]), and $\rho_{\text{Ge}}$ is the resistivity of the Ge measured at 40 K, and $\lambda_d$ is the spin-diffusion length. The predicted spin-RA versus $p$ is also plotted in Fig. 4 (open blue circles), for different values of $\lambda_d$. We found that the observed spin-RA was smallest for the lightly doped device ($p=5 \times 10^{15}$ cm$^{-3}$) and increases for heavily doped Ge. This trend is opposite to what is expected from the standard theory [3]. For the heavily doped device ($p=7 \times 10^{18}$ cm$^{-3}$), a match of experiment and theory requires an unrealistically large value of $\lambda_d$ (610 $\mu$m). In other words, the measured spin-RA for the heavily doped Ge is about 2-3 orders of magnitude larger than the theory predicts. In addition, we point out that for lightly doping, the experiment is closest to the prediction of the theory, but the variation with temperature is not according to the expectation. As shown in Fig. 3(b), the spin-RA obtained at 20 K is comparable to that at 40 K, whereas the theory predicts that it should be a factor of 5 larger because $\rho_{\text{Ge}}$ at 20 K is a factor of 5 larger, and $P$ and $\lambda_d$ are not expected to be smaller at 20 K. This indicates that for the lightly-doped sample, the data is not in agreement with the theory.

4. Conclusions

We carried out the Hanle measurements with a three-terminal configuration for the Fe/MgO/p-Ge samples with different $p$ of the Ge substrate. We found that the measured spin-RA versus hole concentrations has the trend opposite to what is expected from the standard diffusion theory. It was found that the spin-RA of the sample with the heavily-doped Ge substrate is several orders of magnitude larger than the theory. In addition, even with the lightly-doped Ge, the evolution of the spin-RA as a function of the temperature does not follow the standard theory.

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References