

Electrical determination of the spin relaxation time of photoexcited electrons in GaAs

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Spin-dependent transport for photoexcited electrons in an epitaxial Fe/GaAs interface was characterized from 5 to 300 K. The presence of spin-dependent transport was confirmed at all the measured temperatures and the spin polarization across the interface is found to increase with decreasing temperature. A time-of-flight-type model based on the Dyakonov–Perel (DP) spin relaxation mechanism was employed to explain the temperature dependence, providing that the estimated spin relaxation time in GaAs is 62 ps at 5 K. This short spin relaxation time can be explained by the stronger efficiency of the DP mechanism for hot-electrons. © 2010 American Institute of Physics. [doi:10.1063/1.3291066]

Spintronics is a multidisciplinary field combining expertise from magnetic, semiconductor (SC) and optical physics with the aim of utilizing the spin degree of freedom in useful electronic/optical devices. The transfer of photon angular momentum (i.e., in circular polarization) into electron spin polarization can be achieved by spin orientation via absorption of photons in direct band gap SCs.¹ Understanding of the spin (angular-momentum) transfer between light and electrons is a key ingredient for future spin-based multifunctional devices.² Since a nonmagnetic SC is almost spin-degenerate, such optically induced spin polarization is a non-equilibrium state existing only for a finite time/length-scale. By using photons with the energies far greater than the band gap energy, electrons can be excited into states high above the conduction band minimum, so-called hot-electron states. The properties of hot-electrons spin transport can thus be investigated by measuring them within their specific energy/spin relaxation times. The importance of such hot-electron transport for spin injection/detection applications has been demonstrated by using spin-valve transistor devices.^{3,4} Furthermore, controlling the energy of hot-electrons offers a possibility of tuning the spin polarization across an Fe/GaAs interface.^{5,6} A useful technique that enables investigation of spin-dependent hot-electron transport across ferromagnetic metal (FM)/SC interface is spin-polarized photoexcitation,⁷ where photoexcited electrons in the SC can reach the FM/SC interface before losing their spin polarization and before thermalization. This is due to the fact that the incident light used in such experiments is illuminated onto a SC layer just beneath the FM layer, and therefore excited electrons can immediately reach the FM/SC interface; similar experiments were carried out by Crooker *et al.*⁸ where the incident light reaches a GaAs area next to their Fe/GaAs interface contact for investigating spin transport of thermalized electrons. In this letter, we present the measurement of the spin relaxation time τ_s of the photoexcited electrons traveling across an epitaxial Fe/GaAs interface. The temperature dependence of photoexcited electron spin transport was measured and a

time-of-flight (TOF) model was employed to determine τ_s . The model is based on the DP spin relaxation mechanism with ionized-impurity scattering as the dominant momentum scattering mechanism. The calculation results fit well to the experimental data from which spin relaxation time of the photoexcited electrons is evaluated and discussed.

A GaAs layer with a Si doping concentration of $1 \times 10^{24} \text{ m}^{-3}$ was grown on a GaAs(001) substrate with the same doping level, followed by As capping layer growth in a SC molecular beam epitaxy (MBE) chamber. Prior to the preparation of the Fe/GaAs interface, an Ohmic Ge-Pd layer was prepared on the backside of the sample by thermal evaporation. The GaAs substrate was then transferred to a metal MBE chamber with a base pressure of 3.0×10^{-10} mbar. In the chamber, the clean GaAs surface was prepared by removing the As layer. A 5 nm thick Fe layer was afterwards grown, which was capped by 3 nm Au layer. The clean GaAs surface and the epitaxial growth of the Fe layer were confirmed by low energy electron diffraction techniques. After the sample growth, Au (10 nm)/Cu (200 nm) contact pads were grown on the sample for electrical contacts and then the sample was mounted on a copper cold finger in a cryostat for low temperature measurements. All the measurements presented in this letter were carried out with four-probe configuration of electrical measurements. For photoexcitation measurements, a standard lock-in technique was also employed to measure photocurrent (I_{ph}) and helicity-dependent photocurrent (ΔI). A laser used in this study was a He-Ne laser with a wavelength of 632.8 nm. The laser was illuminated on the sample with an angle of 45° to the in-plane direction. The magnetic field was applied along the in-plane direction of the sample. Since the laser penetrated through the Fe layer before being absorbed in GaAs, the magnetic circular dichroism (MCD) from the Fe layer involves in measured ΔI . The subtraction of the MCD effect is carried out by using the equation, $\Delta I_{\text{SF}} = \Delta I - \alpha \Delta I_{\text{ph}}$,⁹ where α is a dimensionless coefficient.

The temperature dependence of current-voltage characteristics through the epitaxial Fe/GaAs(001) interface is shown in Fig. 1(a). Clear rectifications are confirmed for the curves measured at various temperatures. In order to evaluate

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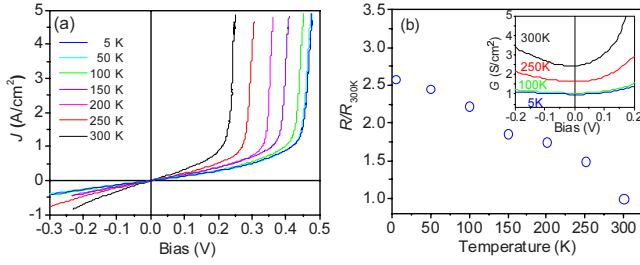


FIG. 1. (Color online) (a) Temperature dependence of current-voltage curves of the epitaxial Fe/GaAs(001) interface. (b) Zero-bias resistances of the Fe/GaAs(001) interface at various temperatures. The values are normalized by the zero-bias resistance at 300 K. [(b): inset] Numerically deduced conductance from the current-voltage measurements at the different temperatures.

the barrier property, we exploited an equation from the thermionic emission theory¹⁰

$$J = A^{**} T^2 \exp\left(-\frac{q\Phi_{\text{Bn}}}{nk_{\text{B}}T}\right) \left[\exp\left(\frac{qV}{nk_{\text{B}}T}\right) - 1 \right]. \quad (1)$$

Here, J , V , A^{**} , T , q , k_{B} , n , and Φ_{Bn} are the current density, bias voltage, effective Richardson constant, temperature, elementary charge, Boltzmann constant, the ideality factor, and Schottky barrier height, respectively. By fitting the current-voltage curves with this equation, Φ_{Bn} and n at room temperature are found to be 0.38 eV and 4.1, respectively. The value of n is not close to unity, indicating that the dominant transport mechanism cannot be the thermionic emission. More refined analysis on electron transport across the interface is possible by using the Rowell criteria,^{11,12} which is a decisive assessment of the presence of tunnel transport. Numerically deduced conductance and zero-bias resistance measurements in Fig. 1(b) show that our device satisfies the second and third Rowell criteria, thereby suggesting that the main electron transport mechanism in our device is tunneling. These results are consistent with the above value of n . Similar results were obtained by Hanbicki *et al.*¹³ for electron transport across their Fe/AlGaAs interface. From the measured values of I_{ph} and ΔI , ΔI_{SF} was obtained for each temperature shown in Fig. 2. A clear peak of ΔI_{SF} in the forward bias region is observed at all temperatures and therefore spin-dependent photoelectron transport across the Fe/GaAs(001) interface occurs in this measurement temperature range. A Gaussian fit has been applied to the curves to obtain the voltage position (V_{peak}) and the height of ΔI_{SF} . In order to discuss the efficiency (P_{SF}) of the spin-dependent transport across the interface, ΔI_{SF} is normalized by I_{ph} at the bias of

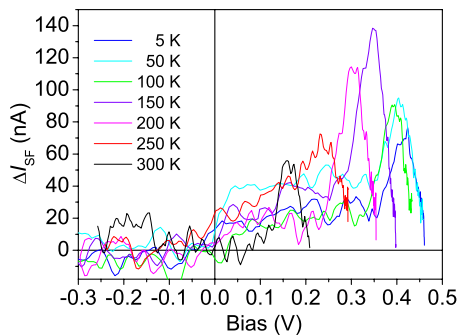


FIG. 2. (Color online) ΔI_{SF} of the Fe/GaAs(001) interface measured at different temperatures.

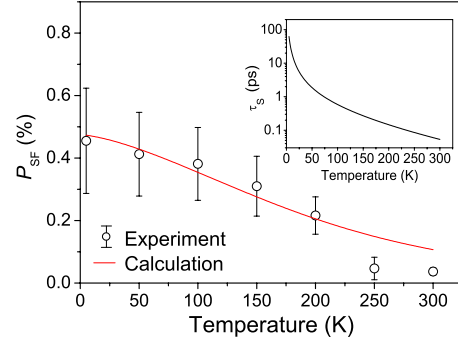


FIG. 3. (Color online) P_{SF} (circle) and calculated P_{total} (red line) as a function of temperature, and (inset) the temperature dependence of τ_s evaluated from fitting experimental/theoretical data.

V_{peak} for each ΔI_{SF} curve as, $P_{\text{SF}} = \Delta I_{\text{SF}}(V_{\text{peak}}) / I_{\text{ph}}(V_{\text{peak}})$. Here, we restrict ourselves to the analysis of the main peak only, although some small peaks can be observed in ΔI_{SF} . As shown in Fig. 3, P_{SF} increases with decreasing temperature. In what follows we attempt to understand the temperature dependence of P_{SF} using a simple TOF model for electron spin relaxation in GaAs. Among several proposed spin relaxation mechanisms in GaAs, the DP mechanism is reported to be dominant in n-type GaAs.^{14–16} The spin relaxation rate of the DP mechanism, $1/\tau_s$, is given by¹

$$\frac{1}{\tau_s} = \frac{32\gamma\tau_p\alpha_c^2 E_k^3}{105\hbar^2 E_g}. \quad (2)$$

Here, γ is a dimensionless coefficient which depends on the dominant scattering mechanism, $\alpha_c = C' \alpha_c^T$ where α_c^T and C' are temperature-dependent and -independent coefficients, respectively, τ_p is the momentum scattering time, E_k is the electron kinetic energy, \hbar is the reduced Planck constant and E_g is the band gap energy. In this model, photoexcited electrons have an initial spin polarization, P_0 , and a single E_k is determined by the energy conservation during the light absorption as follows: $h\nu = E_g + E_k + E_{\text{kh}}$ based on the electron/hole effective-mass approximation, where E_{kh} is the kinetic energy of the excited holes. Transport of the photoexcited electrons in the GaAs layer is involved in small-angle elastic scatterings. Upon this assumption, the kinetic energy for the photoexcited electrons is conserved and the travel time, t , for electrons excited at distance, x , away from the interface is approximately given by $t = x / \sqrt{m^* / 2E_k}$ (where m^* is the effective electron mass in GaAs). As a result, the spin polarization of photoexcited electrons at x (P_i) and the interface (P_0), are given by using the spin relaxation during the transport in GaAs as, $P_i(x) = P_0 \exp(-x / \sqrt{m^* / 2E_k} \tau_s)$. By integrating P_i over x with taking into account the light absorption rate in GaAs,¹⁷ we obtain the total spin polarization, P_{total} , at the interface as

$$P_{\text{total}} = \frac{\int_0^\infty P_i \exp(-\alpha x) dx}{\int_0^\infty \exp(-\alpha x) dx} = \frac{P_0}{(\sqrt{m^* / \alpha} \sqrt{2E_k} \tau_s) + 1}, \quad (3)$$

where α is the absorption coefficient of GaAs. For the GaAs doping density used here, the ionized-impurity scattering is expected to dominate the scattering events. Since τ_p for the impurity scattering mechanism has a $T^{3/2}$ temperature dependence,¹⁰ by combining the temperature dependence of τ_p with Eq. (2), Eq. (3) can be rewritten as

$$P_{\text{total}} = \frac{P_0}{[\sqrt{m^*}(\alpha_c^T)^2 E_k^{5/2} / \sqrt{2\alpha C_1 E_g}] T^{3/2} + 1}, \quad (4)$$

where C_1 is a temperature-independent coefficient including C' . Fitting of the calculated P_{total} to P_{SF} (where P_0 and C_1 were the fitting parameters) was achieved by including the temperature dependence of E_k , E_g , and α_c^T ; temperature dependence in the three figures are taken from Refs. 18 and 19. Here, we use E_k for electrons excited from the split-off hole band since electrons from the heavy-hole and light-hole bands are less likely to contribute to ΔI_{SF} , having higher energies than the Schottky barrier height.⁵ The resulting fit is shown in Fig. 3. The curve is in good agreement with the experimental data, suggesting that the DP mechanism with ionized-impurity scattering is the dominant spin relaxation mechanism for photoexcited electrons. In the higher temperature regime, the fitting curve deviates from the experimental data. This can be understood by contribution of optical phonon scattering in GaAs which cannot be negligible after 200 K, confirmed by mobility calculations of GaAs with the sample doping density (the results not shown). From the fitting parameter value the temperature dependence of τ_s was calculated and is shown in the inset of Fig. 3. The calculated τ_s are shorter than those of thermalized electrons previously reported. For instance, τ_s of our photoexcited electrons is 62 ps at 5 K, whereas τ_s of the thermalized electrons is about several hundreds picoseconds at 5 K.¹⁵ This difference can be qualitatively explained by the stronger efficiency of the DP mechanism for hot-electrons as follows. Equation (2) shows that the spin relaxation rate is proportional to the cube of the kinetic energy. Since the electrons photoexcited with 1.96 eV photons are elevated into higher energy states in the GaAs conduction bands, the excess kinetic energy brings a faster spin-precession rate than that of equilibrium electrons. Therefore, the DP mechanism is more efficient for such high-energy electrons than for thermalized electrons, causing the faster spin relaxation.

In this letter, the temperature dependence of spin-dependent transport for photoexcited electrons across an epitaxial Fe/GaAs interface is presented. The electron transport characterization at various temperatures manifests tunnel transport through the interface in support of the Rowell criteria. The presence of spin-dependent transport was confirmed from 5 to 300 K and the spin polarization across the interface P_{SF} is found to increase with decreasing temperature. The TOF-type calculations based on the DP mechanism with ionized-impurity scattering is used to explain the temperature dependence, providing spin relaxation time of the

photoexcited electrons to be 62 ps at 5 K. This faster spin relaxation for the photoexcited electrons can be attributed to the stronger efficiency of the DP mechanism for such high-energy electrons. This presented approach to extract a spin relaxation time from electron transport measurements is applicable to various FM/SC interfaces to investigate spin relaxation times in different optically-active SC materials. Furthermore, these calculated τ_s are of paramount importance for designing future spintronic devices which use spin information transfer between light and electrons.

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