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Non-local detection of spin-polarized electrons at room temperature in $Co_{50}Fe_{50}$/GaAs Schottky tunnel junctions

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A clear spin-valve signal and a Hanle signal were observed in a $Co_{50}Fe_{50}$/n-GaAs Schottky tunnel junction through a four-terminal non-local geometry. The sign and magnitude of the spin-valve signal were strongly dependent on the bias current, suggesting that the spin polarization at the $Co_{50}Fe_{50}$/n-GaAs interface had strong energy dependence. A clear spin-valve signal was observed at temperatures up to 290 K. The magnitude of the spin-valve signal monotonically decreased by a factor of 7.9 as the temperature increased from 10 K to 290 K; this factor was significantly smaller than the factors reported for Fe/n-GaAs junctions which range from 35 to 80. © *2011 American Institute of Physics*. [doi:10.1063/1.3630032]

The injection of spin-polarized electrons from a ferromagnet (F) into a semiconductor (SC) and the detection of spin-polarized electrons which transport through a SC channel have attracted much interest for creating viable semiconductor-based spintronics. The spin-valve measurement and Hanle-type spin precession measurement using a non-local four terminal device provide direct evidence for proving the spin injection and transport occur, and these measurements have been demonstrated in several systems, such as Fe/GaAs,[1,2] $Co_{70}Fe_{30}$/GaAs,[3] GaMnAs/GaAs,[4] Fe/AlO_x/Si,[5] and Fe/MgO/Si (Refs. 6 and 7) junctions. Recently, these spin signals were observed at room temperature in Fe/GaAs (Ref. 2) and Fe/MgO/Si.[7] The spin-signals observed at room temperature, however, were typically more than one order of magnitude smaller than those at low temperatures of around 10 K. The achievement of a much slower spin signal decay rate with increasing temperature is one of the most important steps towards realizing spin-injection devices which can operate at room temperature. In this paper, we discuss our observation of a clear spin-valve signal and a Hanle signal using a four-terminal non-local geometry in fully epitaxial $Co_{50}Fe_{50}$/n-GaAs Schottky tunnel junctions. We found that the spin-valve signal decreased by a factor of about 7.9 with increasing temperature from 10 K to 290 K, and this factor was significantly smaller than the factors reported for Fe/n-GaAs junctions which range from 35 to 80.[2]

Layer structures consisting of (from the substrate side) i-GaAs (250 nm)/n^--GaAs (Si $= 3 \times 10^{16}$ cm^{-3} and 2500 nm)/n^+-GaAs (Si $= 5 \times 10^{18}$ cm^{-3} and 30 nm) were grown by molecular beam epitaxy (MBE) at 590 °C on GaAs(001) substrate. These layer structures are similar to those reported in Refs. 1 and 2. The samples were then capped with an arsenic protective layer and transported to a magnetron sputtering chamber. After the arsenic cap was removed by heating the samples to 300 °C, a 5-nm-thick $Co_{50}Fe_{50}$ film was grown by magnetron sputtering at room temperature. Using electron-beam (EB) lithography and Ar ion milling techniques, four-terminal non-local devices as shown in Fig. 1(a) were fabricated. The size of the injector contact (contact-2) and detector contact (contact-3) were 0.5×10 μm and 1.0×10 μm, respectively, and the spacing between them was 0.5 μm. The spin-valve signal and Hanle signal were measured using a four-terminal non-local geometry in which the non-local voltage (V_{NL}) between contact-3 and contact-4 was measured as a function of both the in-plane and out-of-plane magnetic field under a constant current (I) supplied between contact-2 and contact-1, as shown in Fig. 1(a). The bias voltage was defined with respect to the n-GaAs. For negative bias, the Schottky junction of contact-2 was reverse-biased, and spin polarized electrons were injected at contact-2 from a $Co_{50}Fe_{50}$ electrode

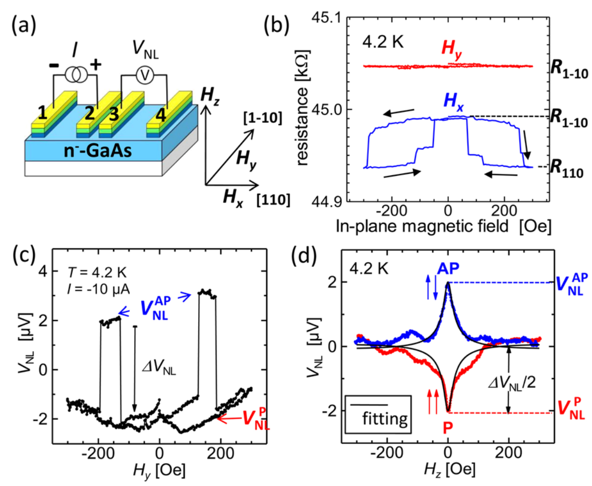

FIG. 1. (Color online) (a) Schematic device structure of a four-terminal nonlocal device and circuit configuration for non-local spin-valve and Hanle measurements. (b) Magnetoresistance curves measured at 4.2 K for a $Co_{50}Fe_{50}$/n-GaAs single junction under injector contact-2 through the three-terminal geometry. The bias voltage was −0.15 V and an in-plane magnetic field along the $[110]_{CoFe}$ direction (H_x) or along the $[1\text{-}10]_{CoFe}$ direction (H_y) was applied. The curve for H_y has an offset of 60 Ω for clarity. (c) Non-local voltage vs. in-plane magnetic field (H_y) (spin-valve signal) for a $Co_{50}Fe_{50}$/n-GaAs junction measured at 4.2 K. (d) Non-local voltage vs. out-of-plane magnetic field (H_z) (Hanle signal) for a $Co_{50}Fe_{50}$/n-GaAs junction measured at 4.2 K for both P (lower curve) and AP (upper curve) configurations. The solid lines are the result of the fitting from Eq. (1). In (c) and (d), the background signal was subtracted.

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into an n^{-}-GaAs channel (spin injection) and drifted toward contact-1. For positive bias, majority- or minority-electrons, depending on the spin polarization at the interface, were extracted from the n^{-}-GaAs channel and injected into the $Co_{50}Fe_{50}$ electrode at contact-2 (spin extraction). The magnetoresistance (MR) and the current-voltage characteristics of the $Co_{50}Fe_{50}$/n-GaAs single junction under injector contact-2 were also measured at 4.2 K through the three-terminal geometry, in which the voltage between contact-2 and contact-4 (V_{24}) was measured when the current was supplied between contact-2 and contact-1.

Figure 1(b) shows the MR curves measured at 4.2 K for a $Co_{50}Fe_{50}$/n-GaAs single junction under contact-2 through the three-terminal geometry. The bias voltage was -0.15 V, and an in-plane magnetic field along the $[110]_{\mathrm{CoFe}}$ direction (H_x) or along the $[1\text{–}10]_{\mathrm{CoFe}}$ direction (H_y) was applied. The curve for H_y has an offset of 60 Ω for clarity. The curve for H_x shows clear MR due to a tunneling anisotropic MR (TAMR) effect. We previously observed the TAMR effect in $Co_{50}Fe_{50}$/n-GaAs and Co_2MnSi/n-GaAs Schottky tunnel junctions and showed that the TAMR effect produces a resistance difference between R_{110} and R_{1-10}, where R_{110} and R_{1-10} stand for the tunnel resistances when the magnetization of the ferromagnet is oriented along [110] and [1–10], respectively.[8–11] Considering the difference between R_{110} and R_{1-10}, the curve for H_x in Fig. 1(b) can be explained as follows. Since the [110] direction corresponds to the hard axis direction for the shape anisotropy of the junction, the magnetization (M) of $Co_{50}Fe_{50}$ would have oriented to the [1–10] direction at small $|H_x|$, resulting in the junction resistance of R_{1-10}, and it would have oriented to the [110] direction at large $|H_x|$, resulting in the junction resistance of R_{110}. On the other hand, since the [1–10] direction is an easy axis, there was no state for $M \parallel [110]$ when the magnetic field was swept along the [1–10] direction, resulting in the almost constant junction resistance corresponding to R_{1-10} for all values of H_y investigated.

Figure 1(c) plots V_{NL} measured at 4.2 K at $I = -10\ \mu$A as a function of H_y. The background signal that was almost linear in H_y was subtracted. The graph shows a clear spin-valve-like signal. As shown in Fig. 1(b), no significant MR was observed for a $Co_{50}Fe_{50}$/n-GaAs single junction under the application of H_y. Thus, the spin-valve-like signal observed in the four-terminal non-local geometry shown in Fig. 1(c) was produced by parallel (P)/anti-parallel (AP) switching in the magnetization configuration between the injector contact-2 and the detector contact-3. A non-local voltage change (ΔV_{NL}) of approximately 4 μV was obtained, which was defined as $\Delta V_{\mathrm{NL}} = V_{\mathrm{NL}}^{\mathrm{AP}} - V_{\mathrm{NL}}^{\mathrm{P}}$, where $V_{\mathrm{NL}}^{\mathrm{AP}}$ and $V_{\mathrm{NL}}^{\mathrm{P}}$ are non-local voltages for the AP and P configurations, respectively, between injector contact-2 and detector contact-3.

Figure 1(d) shows V_{NL} vs. out-of-plane magnetic field (H_z) for both the P and AP configurations. The V_{NL} for the P (AP) configuration gradually increased (decreased) as $|H_z|$ increased and the two curves merged at large H_z. These results clearly indicate the Hanle effect; that is, the spins injected in the GaAs channel dephased due to the precession by H_z, resulting in decreased spin accumulation in the GaAs channel. The observation of the Hanle effect provides the most rigorous evidence of injection, transport, and detection of spin-polarized electrons in a $Co_{50}Fe_{50}$/n-GaAs/$Co_{50}Fe_{50}$ lateral junction. The Hanle curves can be expressed by[1–7,12]

$$V_{\mathrm{NL}}(H_z) = \pm \frac{P_{\mathrm{inj}}P_{\mathrm{det}}}{2}\left(\rho\frac{l_{sf}}{S}\right)\left(\frac{2l_{sf}}{\tau_s}\right) I \int_0^\infty \frac{1}{\sqrt{4\pi D t}} \times \exp\left(-\frac{d^2}{4Dt}\right)\cos\omega_L t\,\exp\left(-\frac{t}{\tau_S}\right)\mathrm{d}t, \quad (1)$$

where $P_{\mathrm{inj(det)}}$ is spin polarization of the injector (detector) contact, ρ is resistivity of the GaAs channel, S is the area of the channel cross-section, l_{sf} is the spin-diffusion length, d is the distance between contact-2 and contact-3, τ_S is the spin lifetime, $D = l_{sf}^2/\tau_S$ is the diffusion constant, and ω_L is the Larmor frequency which is a function of H_z. The sign of + (−) on the right-hand side of Eq. (1) corresponds to the P (AP) configuration. Although the observed Hanle curves can be fitted well with Eq. (1) at $|H_z| < 30$ Oe, the curve for the P configuration deviates from the fitting at about $30 < |H_z| < 110$ Oe, probably due to an extrinsic disturbance, such as temperature drift during the measurement. The estimated values of τ_s, l_{sf}, and the effective spin polarization defined by $(P_{\mathrm{inj}}P_{\mathrm{det}})^{1/2}$ were $\tau_s = 20$ ns, $l_{sf} = 3\ \mu$m, and $(P_{\mathrm{inj}}P_{\mathrm{det}})^{1/2} = 0.04$. These values are comparable to those reported for Fe/n-GaAs.[1,2]

Figure 2 shows the bias-current dependence of ΔV_{NL} measured at both 4.2 K and 290 K. For 4.2 K, the relation of ΔV_{NL} vs. I was non-linear in the negative bias region, where electrons tunnel from $Co_{50}Fe_{50}$ into n-GaAs (spin injection); however, in the positive bias region, where electrons tunnel from n-GaAs into $Co_{50}Fe_{50}$ (spin extraction), ΔV_{NL} was almost proportional to I. Based on Eq. (1), $\Delta V_{\mathrm{NL}}/I$ was proportional to $P_{\mathrm{inj}}P_{\mathrm{det}}$. Thus, the magnitude of $P_{\mathrm{inj}}P_{\mathrm{det}}$ was strongly voltage-dependent in the negative bias region, and it was almost constant, but the sign of $P_{\mathrm{inj}}P_{\mathrm{det}}$ became negative, in the positive bias region. Such a complex bias dependence of ΔV_{NL} was also reported for Fe/n-GaAs junctions.[1,2] In particular, the negative sign of $P_{\mathrm{inj}}P_{\mathrm{det}}$ under the positive bias condition was observed for Fe/n-GaAs junctions (see Fig. 4(b) in Ref. 1 or Fig. 2(b) in Ref. 2. Note that our

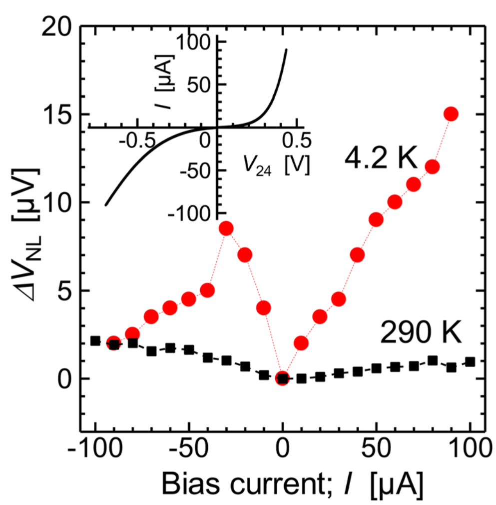

FIG. 2. (Color online) Bias-current dependence of ΔV_{NL} measured at both 4.2 K and 290 K for a $Co_{50}Fe_{50}$/n-GaAs junction. Inset shows current-voltage characteristics of the Schottky junction of contact-2 measured at 4.2 K.

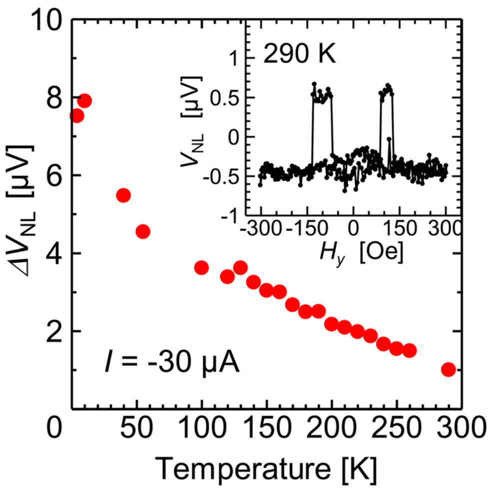

FIG. 3. (Color online) Temperature dependence of ΔV_{NL} at $I = -30$ μA for a $Co_{50}Fe_{50}$/n-GaAs junction. Inset shows a spin-valve signal measured at 290 K.

definition of the bias polarity is opposite that used in Refs. 1 and 2). Since the voltage drop across the junction of detector contact-3 was always close to zero, P_{det} was almost constant against changes in the bias conditions. On the other hand, the voltage drop across the junction of injector contact-2, estimated from the current-voltage characteristics of junction-2 as shown in the inset of Fig. 2, varied from -0.70 V for $I = -90$ μA to $+0.43$ V for $I = +90$ μA. Thus, if P_{det} is assumed to be a positive constant, P_{inj} becomes positive for a negative bias region (spin injection mode) and becomes negative for a positive bias region (spin extraction mode). To explain the negative spin polarization observed in Fe/GaAs junctions, Dery and Sham[13] suggested that the reversal of spin polarization is due to localized states in the semiconductor formed by inhomogeneous doping. Chantis *et al.*[14] predicted by first-principle calculations that a negative spin polarization under the spin extraction mode could be explained by an enhancement of the transmission coefficient of minority-spins through a resonant state at the Fe/GaAs interface. Furthermore, Honda *et al.*[15] theoretically investigated the influence of the Schottky barrier on the spin polarization of an Fe/n-GaAs interface and showed that the spin polarization can be negative for a wide range of bias voltage, depending on the Schottky barrier height. The origin of the observed strong bias-voltage dependence of spin polarization at the $Co_{50}Fe_{50}$/n-GaAs interface is also thought to be qualitatively similar to that of Fe/GaAs.

The non-linear characteristics of ΔV_{NL} vs. I for the negative bias at 4.2 K almost disappeared at 290 K, and $\Delta V_{NL}/I$ of approximately 33 mΩ was obtained at -50 μA $\leq I < 0$. Figure 3 shows the temperature (T) dependence of ΔV_{NL} at $I = -30$ μA. It is noteworthy that a clear spin-valve-like signal was observed even at 290 K, as shown in the inset of Fig. 3. The ΔV_{NL} at $I = -30$ μA decreased almost monotonically by a factor of 7.9 as T increased from 10 to 290 K. Salis *et al.*[2] investigated the T dependence of ΔV_{NL} in Fe/GaAs Schottky junctions and reported that the decay rate of the spin signal with T strongly depends on the annealing condition and the bias voltages. They showed that the variation of the decay rate depending on the annealing condition and the bias voltages was related to a change in the T dependence of $P_{inj}{\cdot}P_{det}$ related to the annealing condition and the bias voltages. The decay rate of $\Delta V_{NL}/I$ observed for $Co_{50}Fe_{50}$/GaAs in the present study was smaller than what was observed for Fe/n-GaAs,[2] and the $\Delta V_{NL}/I$ of approximately 33 mΩ at 290 K for $Co_{50}Fe_{50}$/GaAs was more than one order of magnitude larger than observed for Fe/GaAs.[2] Although the mechanism of the T dependence of the spin signal is not well understood, our experimental finding suggests that spin polarization of the $Co_{50}Fe_{50}$/GaAs interface is less sensitive against T than that of Fe/GaAs.

In summary, we observed a clear spin-valve signal and a Hanle signal through a four-terminal non-local geometry at 4.2 K in $Co_{50}Fe_{50}$/n-GaAs Schottky tunnel junctions. The strong bias-voltage dependence of the spin-valve signal suggested that the sign and magnitude of spin polarization at the $Co_{50}Fe_{50}$/n-GaAs interface depended on the bias voltage. Furthermore, we observed a clear spin-valve signal at 290 K; the magnitude of this signal was one order of magnitude larger than those observed for Fe/GaAs. This result is promising for realizing a future spin injection device which can operate at room temperature.

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