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Spin-polarized transport in a two-dimensional electron gas with interdigital-ferromagnetic contacts

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Ferromagnetic contacts on a high-mobility, two-dimensional electron gas (2DEG) in a narrow gap semiconductor with strong spin-orbit interaction are used to investigate spin-polarized electron transport. We demonstrate the use of magnetized contacts to preferentially inject and detect specific spin orientations. Spin dephasing and spin precession effects are studied by temperature and 2DEG channel length dependent measurements. Interdigital-ferromagnetic contacts suppress unwanted effects due to ferromagnetic microstrip inhomogeneities by averaging.

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The new field of spin-polarized transport has attracted growing interest recently. It combines the spin and charge properties of the electron and bridges the fields of magnetism and semiconductor physics. Magnetoelectronics (spintronics) is regarded as the technological basis for future sensor and electronics industry.[1,2] Of particular interest is the spin-polarized field-effect transistor the SPIN-FET proposed by Datta and Das.[3] Such an active, gated spintronic device requires: (1) efficient injection/extraction of spin-polarized two-dimensional electron gas (2DEG) carrier by using ferromagnetic contacts and (2) modulation of the spin precession angle by gate voltage control of the spin-orbit coupling parameter α.

We have demonstrated that it is possible to achieve 100% modulation of α in a gated $In_xGa_{1-x}As/In_xAl_{1-x}As$ quantum well.[4,5] Spin injection/extraction using ferromagnetic contacts is controversial.[6–11] Recent theories for spin transport in both diffusive[10] and ballistic systems[11] raise issues that relate to the efficiency of the spin injection process. Detailed experimental data are only published on devices with ferromagnetic-2DEG (FM-2DEG) diode structure.[12] Devices with two ferromagnetic contacts that serve as spin injector and detector (FM1-2DEG-FM2) are highly desired. It is here that the various theories covering the ballistic to diffusive regime could be tested, and a comparison with experiments is valuable. However, because of the complexity of the domain dynamic in the ferromagnetic microstrips and the difficulty in making reproducible nonalloying FM/2DEG contacts, there is a lack of systematic data.[8,9]

In this paper we report experimental results of spin-polarized transport in a FM1-2DEG-FM2 device based on a 2DEG with interdigital-ferromagnetic contacts (IDFC). We use ferromagnetic permalloy ($Ni_{40}Fe_{60}$) source (FM1) and drain (FM2) contacts deposited on a 2DEG confined in an InAs channel for spin injection/detection. Our experiment is carefully performed by designing devices with different geometry on the same chip fabricated in the same run. Systematic channel dependence, together with a consistent temperature-dependence behavior are therefore observed. Our IDFC devices allow measurements of ensemble averages over multiple FM1-2DEG-FM2 units, thereby suppressing effects related to random domain formation. The results are reproducible in two senses: for different devices with the same channel length, and for the same device measured in different cooling cycles. In devices with ballistic 2DEG channels, we hereby observe the predicted increase in device resistance ($\Delta R > 0$)[3,13] when the injector/detector magnetization configuration is switched from parallel (↑↑ or ↓↓) to antiparallel (↑↓ or ↓↑). The observed maximum $\Delta R/R(B=0) = \Delta R/R_0$ is very small but clear. The resistance modulation in our devices is found to be strongly temperature dependent, unlike the interface resistance modulation in devices measured by Hammer *et al.*[12] By increasing the 2DEG channel length, unpredicted negative $\Delta R/R_0$ values were observed in the case of quasiballistic channels. These effects demonstrate device sensitivity to both the spin injection/detection at the FM-2DEG interfaces and to spin effects within the 2DEG.

In our samples, the 2DEG is located in a 4 nm wide InAs channel inserted in a 16 nm wide $In_{0.53}Ga_{0.47}As$ quantum well in a high-mobility $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterojunction. The carrier density n_s and mobility μ at 1.4 K were determined by Shubnikov-de Haas measurements to be $1.7\times10^{12}\,cm^{-2}$ and 63 900 cm^{-2}/Vs, respectively, corresponding to a Fermi energy $E_F \approx 80$ meV and an elastic mean-free-path $l_e \approx 1.3\,\mu$m. The electron effective mass at E_F $m^* \approx 0.05\,m_e$ and the spin-orbit coupling parameter $\alpha \approx 5\times10^{-12}$ eVm were also determined.[4] A 2DEG mesa with width W was fabricated by the use of electron beam lithography EBL and electron cyclotron resonance dry etching. IDFC's with strip widths $F1$ and $F2$ and contact separation L were defined by EBL. Chemical wet etching was used to remove the $In_xAl_{1-x}As$ Schottky layer. Contacts between NiFe and the InAs 2DEG were made by evaporating 60 nm NiFe after Ar-plasma etching to remove surface oxides and the $In_xGa_{1-x}As$ layers. The NiFe surface was passivated by an 8 nm thick Au layer. After lift-off, the IDFC structure was obtained (see Fig. 1). Finally, AuGeNi/Au leads were fabricated by standard photolithographic techniques. Four terminal resistance measurements were performed in a ^{3}He cryostat with a superconducting solenoid using standard ac lock-in techniques. A magnetic field B was applied along the easy magnetization axis of the IDFC determined by the shape anisotropy of the fingers. Six samples on the same chip fabricated in the same run with different combinations of L ($0.4\,\mu m \leq L < 2\,\mu m$) and $F1$, $F2$ ($0.5\,\mu m \leq F1$, $F2$

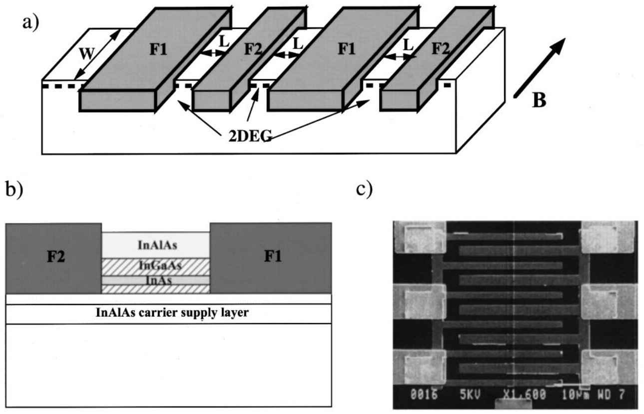

FIG. 1. (a) Sketch of the device with interdigital ferromagnetic contacts (IDFC) connected to 2DEG channels. (b) Cross-sectional view of the junction (c) top scanning electron microscopic (SEM) view of a device with $L=1.8\,\mu$m, $W=2\ \mu$m, $F1=2\ \mu$m, and $F2=3\ \mu$m.

$\leqslant 3\ \mu$m) were measured in the temperature range from 0.3 to 10 K. Five samples have channel width $W=2\ \mu$m, one has $W=4\ \mu$m. Due to the EBL proximity effect, the pattern dimensions differ slightly from the design values.

Figure 2(a) shows the normalized variation of the source-drain resistance $\Delta R(B)/R_0=[R(B)-R_0]/R_0$ of a ballistic sample with $L=0.45\,\mu$m and $(F1,F2)=(0.5,1.5)\ \mu$m measured as a function of B at different temperatures. R_0 of this device with 14 parallel units is about 100 Ω. We estimate, therefore, the interface resistance of about 650 Ω by taking the square resistance for the 2DEG of about 60 Ω. By sweeping the applied B field over the range of ±1000 G, the magnetization configuration of the NiFe contacts was changed due to different coercive fields B_{c1} and B_{c2} of the contacts.[14] For $F1<F2$ and therefore $B_{c1}>B_{c2}$,[15] the (FM1, FM2) contact magnetizations are expected to be *antiparallel* (↑↓ or ↓ ↑) in the field ranges $(-B_{c1},-B_{c2})$ and (B_{c2},B_{c1}), and otherwise *parallel* for the ideal single domain behavior (↑↑ or ↓↓). For the antiparallel case, models predict $\Delta R>0$,[3,13] in accordance with our observations as seen in Fig. 2(a). With increasing temperature, the normalized resistance change at the peak position $\Delta R/R_0$ drops continuously from its low-temperature maximum value of 0.2% and disappears for $T>10\,$K.

In Fig. 2(b) we show $\Delta R(B)/R_0$ measured at 0.4 K on samples with different channel length L. The peak amplitude $\Delta R/R_0$ decreases substantially when L is increased from 0.45 to 0.87 μm. At even larger L, dips instead of peaks are observed with an amplitude that increases with increasing L from 1.4 to 1.8 μm. For $L=0.45\,\mu$m, two samples with different sets of $(F1,F2)$ were used. As expected, in both samples, similar $\Delta R/R_0>0$ were observed but in different field ranges (B_{c1},B_{c2}). For $L=0.87\,\mu$m, two samples with widths W of 2 and 4 μm were measured, in both samples $\Delta R/R_0$ was smaller than 0.05%. Therefore, a systematic channel length dependence of the normalized $\Delta R/R_0$ value as shown in Fig. 3(b) is clearly observed. On the contrary, the interface resistance of about several hundred ohms differs from sample to sample, no correlation of its value to any of the device geometry parameter could be identified.

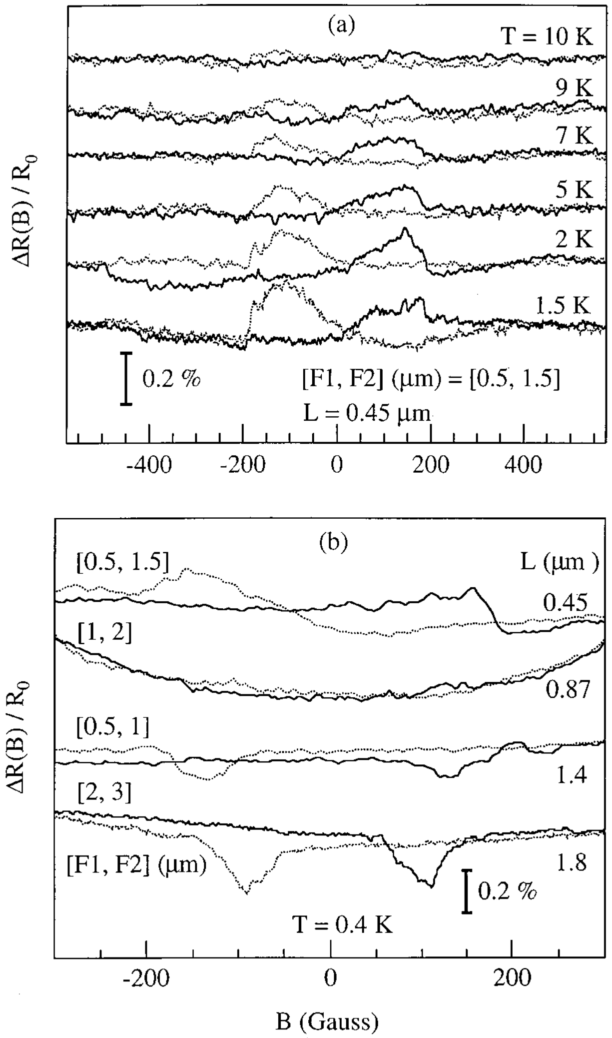

FIG. 2. $\Delta R(B)/R_0$ measured (a) for a device with 14 parallel units and $L=0.45\ \mu$m at different temperatures (R_0 of this device is about 100 Ω) and (b) at 0.4 K for devices with different L. The solid (dotted) lines correspond to up (down) sweep direction of the B field.

The strong temperature dependence of $\Delta R/R_0$ as shown in Fig. 3(a) is consistent for samples with different channel length. This is clearly different from the recent data for a FM-2DEG diode device,[12] which shows no temperature dependence between 77 and 300 K. It may be argued that if kT is comparable to the spin-orbit splitting energy Δ_s, spin phenomena are significantly suppressed due to thermal smearing. It can, however, be shown that the spin polarization P of a 2DEG is independent of temperature for the range $k_BT \ll E_F$, which means that the thermal smearing of the spin effect depends very much on the spin-scattering processes. Indeed, in our samples, Δ_s is estimated to be about 5 meV $(\approx k60\,\text{K})$.[4] The peak and dip features disappear, however, at a much lower temperature ≈10 K. The characteristic difference between our FM1-2DEG-FM2 devices and the FM-2DEG diode device[12] is that we measure $\Delta R/R_0 =2\,\eta^2\exp(-L/l_s)$ (Ref. 13) which is sensitive to the temperature dependence of the spin-relaxation length l_s,[16] while for the diode[12] $\Delta R/R_0=2\ \eta$P, which is sensitive to the spin-

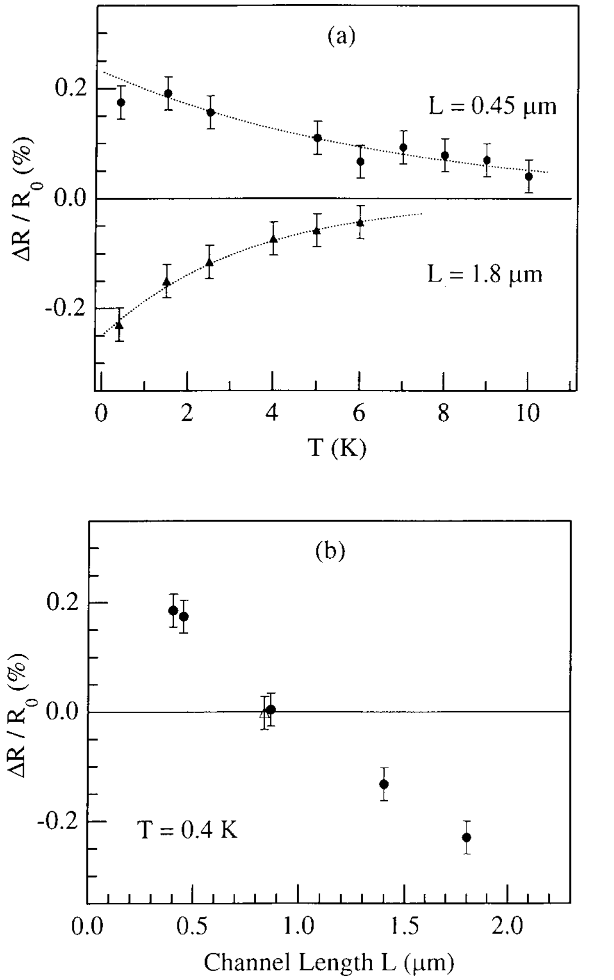

FIG. 3. (a) Temperature and (b) channel length dependence of $\Delta R/R_0$ (averaged for up and down *B*-field sweeps). Dotted lines in (a) are guides to the eye.

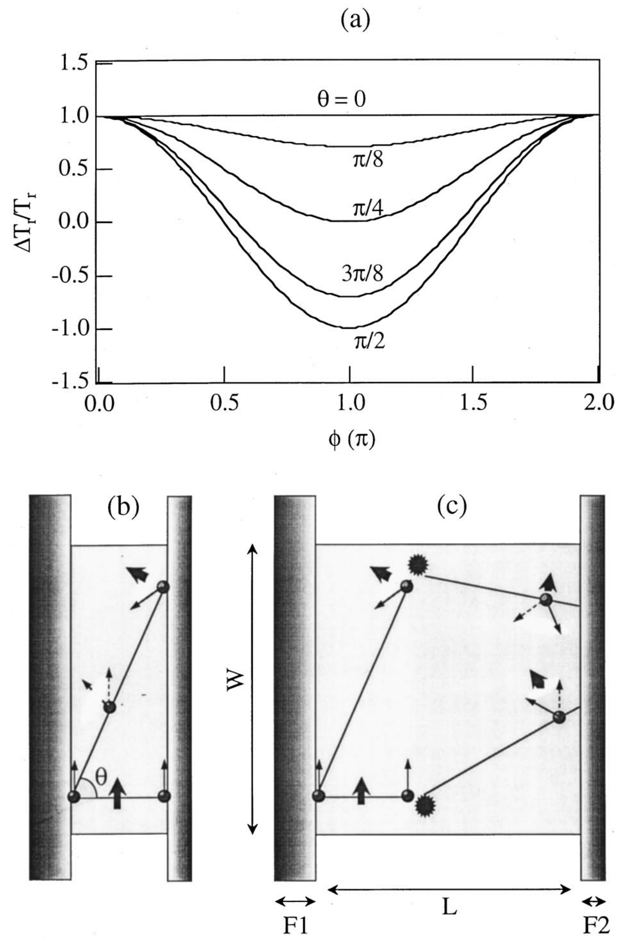

FIG. 4. (a) The normalized transmission coefficient vs spin precession angle ϕ calculated for a number of values of the injection angle θ. (b) a constructive $(\theta=0)$ and a destructive $(\theta>\pi/4,\ \phi=\pi)$ trajectory in the ballistic regime, and (c) trajectories with a few momentum scattering events in the quasiballistic regime. Thin and thick arrows illustrate the carrier spin and the direction of the Bychov and Rashba *B* field, respectively.

polarization *P* of the 2DEG.[13] Here, η is the parametrized fractional spin polarization of the current crossing the FM-2DEG interface. Our data show that even for a degenerate 2DEG in the $In_xGa_{1-x}As$ system, l_s varies strongly with temperature. In principle, in our injection-detection experiment, it should be possible to determine $l_s(T)$ by comparing devices with different channel lengths, however, 1D channel devices are required.

To understand the channel length dependence of $\Delta R/R_0$ as seen in Fig. 3(b), we note that the width *W* of the 2DEG channel in our samples is 2 or 4 μm, comparable to *L* $(0.4<L<2\ \mu\text{m})$ implying that electrons are injected into the channel over a range of angles θ. In the ballistic case, by use of the spin eigenstates of the effective mass Hamiltonian including the Bychov and Rashba term,[17] we obtain the θ dependence of the normalized modulation of the transmission coefficients T_r:

$$\frac{\Delta T_r}{T_r}=\frac{T_r^{\uparrow\uparrow}-T_r^{\uparrow\downarrow}}{T_r^{\uparrow\uparrow}+T_r^{\uparrow\downarrow}}=1-2\sin^2\theta\sin^2\frac{\phi}{2}, \tag{1}$$

where $\phi=2m^*\alpha L/(\hbar^2\cos\theta)$ is the differential phase shift between the two spin eigenstates. In the ideal case with no spin scattering between the two spin channels, we have $\Delta R/R_0\propto\Delta T_r/T_r$ for a given θ.

In Fig. 4(a), we plot the calculated $\Delta T_r/T_r$ vs ϕ for various values of the injection angle θ. Here $\theta=0$ corresponds to a 1D channel with no spin precession since the Bychov and Rashba-effective *B* field[17] is aligned with the spin of the injected electrons. Here we expect that the resistance for the (↑↓ or ↓↑) case is larger than for the (↑↑ or ↓↓) case $(\Delta R>0)$. $\theta=\pi/2$ is used in the device geometry proposed by Datta and Das[3] for the spin transistor. Here, ΔR can be either positive or negative depending on the precession angle ϕ, which may be controlled by a gate voltage.[4,5] In a classical picture, constructive trajectories with $\Delta R>0$ are found for sets of $(\theta,\ \phi)$ where the projection of the electron spin on the magnetization direction of the injector has not changed sign when the electron reaches the detector contact (while for destructive trajectories the sign has changed), see Fig. 4(b). In our ballistic samples where $L/W<1$,$\Delta R/R_0$ is an average overall possible trajectories.[18] A simple average of $\Delta T_r/T_r$ over $-\pi/2<\theta<\pi/2$ gives $1>\Delta T_r/T_r>0$, depending on the precession angle ϕ, therefore in ballistic samples we expect $\Delta R/R_0>0$. Spin precession will reduce this value but cannot change its sign. This is what we observe. For $L=0.45\ \mu$m, the average value of $\Delta T_r/T_r$ is about 0.5 and we estimate a polarization of $\eta=4.5\%$ for the current through the interface. It is almost an order of magnitude smaller than the polarization in the FM contacts, $\eta_0=45\%$.[19] Both the parallel conductance of Au cap within the spin-diffusion length in Py and a relatively low-transmission interface dilute the effective polarization. Mismatch effects at the FM/2DEG interfaces[10,11] also reduce the effective polarization. However, for a clear quantitative interpretation, the assumptions of ideal FM/2DEG interfaces probably have to be revised.

One surprising result is the negative $\Delta R/R_0$ values observed in quasiballistic samples, $L\geqslant l_e$. In this regime, the trajectories include one or a few scattering events, which change the momentum direction (and hence, the direction of the Bychov and Rashba-effective B field) without changing the electron-spin wave function.[20] The spin precession angle is accumulated over the entire path. Our data suggest that, with strong spin-orbit interaction, the momentum scattering might have different effects on constructive and destructive trajectories, which could cause the destructive trajectories to dominate in the quasiballistic regime for certain device geometries [note that the dominant constructive trajectories around $\theta=0$ with $\Delta T/T\approx 1$ will have a very small probability to survive in the quasiballistic regime, see Fig. 4(c)]. An alternative two-component model proposed very recently by Seba *et al.*[21] reveals the unexpected result that in mesoscopic disordered systems, the quantum coherence affected by spin-flip processes can lead to the higher conductance of two-terminal devices with antiparallel contact magnetization. We note that spin-polarized transport in 2DEG's is a new field awaiting both careful experiments and better theoretical understanding.

Finally, we would like to comment on other possible mechanisms that might cause a change in the resistance in a B-field sweep experiment for a FM/2DEG device, e.g., the anisotropic magnetoresistance (AMR)[22] of the permalloy electrodes and the fringe field induced local Hall effect (LHE).[23,24] An early study on AMR (Ref. 25) and recent experiment on LHE (Ref. 26) demonstrate that both effects survive at high temperatures, contrary to the temperature dependence of our data. One component coherent phenomena such as weak localization has a temperature dependence similar to what we observe here. It may be possible that they are combined with the fringe field effect to cause some resistance change in a B-field sweep experiment. However, there is no model in which these spurious phenomena can show a systematic channel length dependence while being insensitive to other device geometry parameters.

In summary, we have observed spin-polarized transport in a device consisting of a 2DEG channel with interdigital ferromagnetic contacts, IDFC. Temperature and channel length dependence of the spin injection-detection measurements allow us to study the influence of spin dephasing, spin precession, and momentum scattering effects on spin-polarized transport. We estimate the spin polarization of the current through the FM-2DEG interface to be about 4.5%.

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