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Hybrid ferromagnet/semiconductor nanostructures: spin-valve effect and extraordinary magnetoresistance

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Abstract
We review our recent work on ferromagnet/semiconductor hybrid structures. In particular we focus on magnetotransport experiments performed on Co/InAs/Co hybrid structures fabricated on the cleaved edge of an InAs/InGaAs heterostructure. By modulation doping we inserted a high-mobility two-dimensional electron system (2DES) between the Co source and drain contacts which were separated by about 0.2 μm. This separation was smaller than the mean free path in the 2DES. Two additional metallic gate electrodes were integrated, thus forming a prototype spin field-effect transistor on a cleaved (110) surface of an InAs/InGaAs heterostructure. Intriguingly, we observe two characteristic magnetotransport signals at 4.2 K: (a) a hysteretic spin-valve-like signal and (b) a large positive magnetoresistance. We attribute the latter to the extraordinary magnetoresistance effect, i.e. the magnetic-field induced current redistribution between the Co contacts and the 2DES.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Transport in nanostructured hybrid systems involving a magnetic or nonmagnetic metal film in contact with a high-mobility low-dimensional electron system is of great current interest in both applied science and basic research. Recent investigations on hybrid structures

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consisting of a two-dimensional electron system (2DES) and of a noble metal [1, 2], e.g., have revealed the extraordinary magnetoresistance (EMR) effect [3, 4]. Here, very interesting perspectives such as magnetic-field sensors are now foreseen for such metal/semiconductor nanostructures [1, 5, 6]. The effect is based on the magnetic-field induced redistribution of current between the two classes of materials [2, 3] and is pronounced in the case of a low specific interface resistance ρ_c [7]. In ferromagnet/semiconductor hybrid structures, even more intriguing magnetotransport phenomena are expected when spin-polarized electrons are injected into the low-dimensional electron system [8–14]. Here, it has also been suggested by both recent theoretical [15] and experimental studies [16, 17] that an excellent interface quality is equally important. In addition, in the case of ballistic electron transport across an epitaxial and planar interface between a metallic ferromagnet, e.g., Co [18] or Fe [15, 19, 20], and a III–V semiconductor, an ideal spin filtering might be expected in a specific crystallographic direction. This would give rise to a highly spin-polarized current and a very large spin-valve effect [21]. To test these theoretical predictions a preparation technique aimed at excellent planar interfaces between a ferromagnetic metal and a 2DES in a III–V semiconductor would be needed. A conventional top-down approach using photolithography and deep-mesa etching of a heterostructure incorporating the 2DES does not seem to be appropriate since (i) the roughness of the etched edge might inhibit a planar interface and (ii) epitaxial growth at the vertical flank of the mesa is not straightforward.

In this paper we investigate the magnetotransport of hybrid structures involving a high-mobility 2DES in InAs and ferromagnetic source and drain contacts. The metal/semiconductor hybrid structures have been prepared using a special technique [2] which we adapted from the method of *cleaved edge overgrowth* (CEO), known from all-semiconductor systems [22]. This technique allows us to realize a planar interface between the 2DES and the metal. The CEO approach in particular opens up the perspective of epitaxial growth of source and drain contacts. We have fabricated a Co/InAs(2DES)/Co prototype spin field-effect transistor with two additional metallic gate electrodes. At low-magnetic field B, we observe a hysteretic spin-valve-like signal which is related to the magnetization reversal of the polycrystalline Co contacts. In a field B perpendicular to the 2DES, we in addition observe the EMR effect, i.e. the large positive magnetoresistance due to current redistribution. We argue that the occurrence of the latter demonstrates a low specific interface resistance ρ_c, i.e. the good interface quality obtained by the CEO approach.

2. Experimental technique

Our experiments are based on a 2DES residing in an InAs/InGaAs heterostructure incorporating a 4 nm thick InAs quantum well [23–25] which was grown on a (001) GaAs substrate by molecular beam epitaxy. We prefer an InAs-based heterostructure since, in combination with a metal, InAs does not form a Schottky barrier. Van-der-Pauw measurements on a reference 2DES have revealed a carrier density of $n_s = 6.5 \times 10^{11}$ cm^{-2} and a mobility $\mu = 120\,000$ cm^2 V^{-1} s^{-1} at 4.2 K in the dark. These values increased after illuminating by a short pulse of a light-emitting diode. The electron mean free path is of the order of micrometre. The fabrication of the hybrid structures on a cleaved (110) surface is shown in figures 1(a)–(f). First the 2DES was patterned into a stripe of a width $W < 40$ μm along a predetermined breaking point. This confines the current flow to a 2DES mesa in the x–y plane (figure 1(a)). Then the heterostructure was cleaved along the $[1\bar{1}0]$ direction, i.e. the x direction in figure 1(b). Atomic force microscopy on a InAs heterostructure showed that the cleavage produces a surface which can be flat at macroscopic distances in the x–z plane. We covered the cleaved edge with

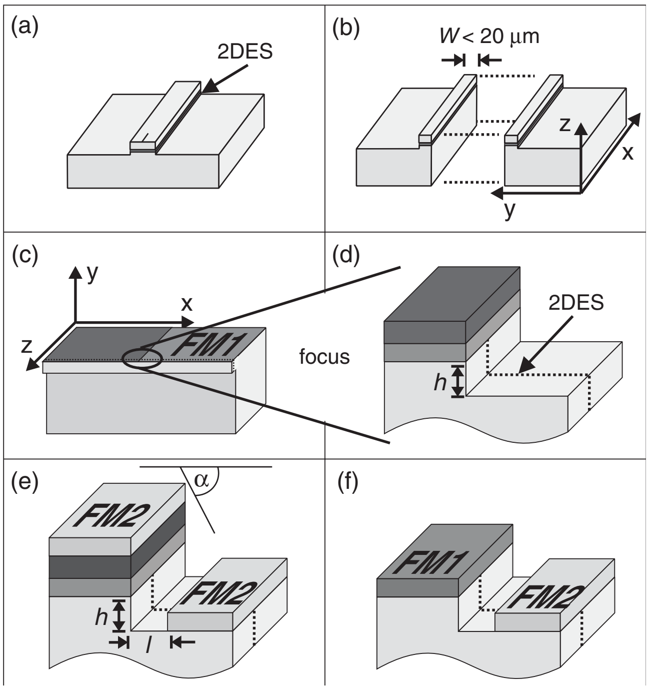

Figure 1. Schematic processing steps for the fabrication of two separate source and drain contacts on a cleaved edge of a heterostructure: (a) predetermined breaking point and etched 2DES mesa, (b) cleaving, (c) photoresist on the first ferromagnetic layer deposited on the cleaved surface, (d) ion beam etching of the step, (e) shadow evaporation of the second ferromagnetic layer, (f) hybrid structure after lift-off processing of the photoresist. The growth direction of the InAs/InGaAs heterostructure on the (001) GaAs was along the z direction.

a ferromagnetic (FM) layer FM1 resulting in a planar interface between FM1 and the 2DES[5]. To avoid electron beam lithography on the narrow cleaved surface we used in this work a self-aligning shadow evaporation technique to separate the magnetic source and drain contacts. For this, we covered half of the FM1 layer with a photoresist mask (figure 1(c)). Subsequently ion beam etching (IBE) was executed through the FM1 layer into the semiconductor leading to a step of height h (figure 1(d)). The etched step is essential to provide a self-aligning shadow mask: the second contact FM2 was deposited under an angle α such that a sub-μm separation of the FM contacts occurred (figures 1(e) and (f)). The separation was adjusted by the original step height h, by the resist thickness and by α to give a 200 nm gap between FM1 and FM2, i.e. smaller than the mean free path. The method allowed us to prepare two polycrystalline Co contacts of different thickness, resulting in different magnetization reversal characteristics. The Co contacts were microstructured using photolithography on the cleaved edge followed by IBE. In the next steps, the Co/InAs(2DES)/Co hybrid device was electrically isolated on the edge with a 300 nm thick SiO_2 film, and an Au layer was evaporated on the insulated cleaved edge providing a top field-effect electrode. In figure 2(a) we show a top view of the device. Between this electrode in the x–z plane and the drain contact, we applied the top-gate voltage V_{tg} to tune the conductivity of the step region. In the final processing step we attached

5 We note that so far the device processing was performed *ex situ* and the ferromagnets were polycrystalline. *In situ* processing and epitaxial growth are in principle possible which might further improve the interface quality and might be prerequisites for spin filtering to occur.

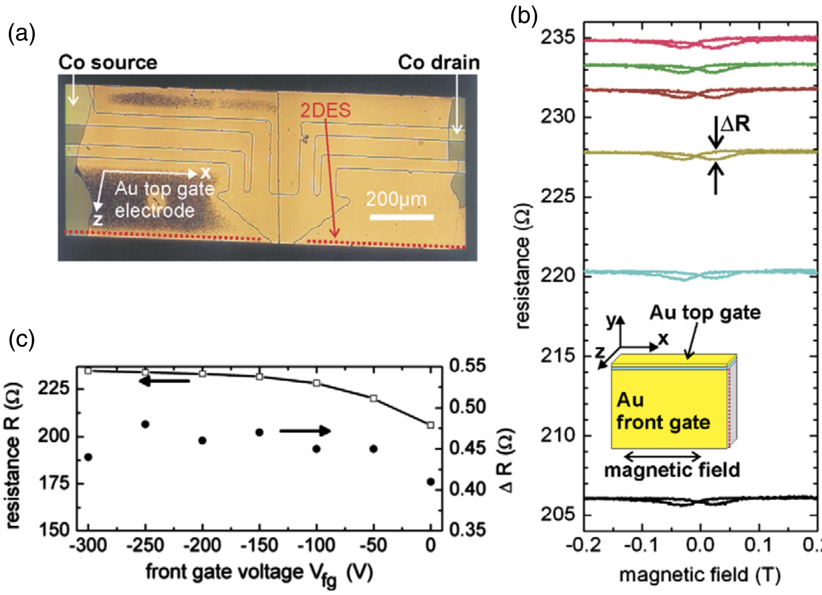

Figure 2. (a) Photograph of the step region on the cleaved edge with two Co contacts and the Au top-gate electrode. The 2DES is schematically indicated. It extends into the y direction. (b) Hysteretic behaviour of the magnetoresistance measured at 4.2 K with B applied along the x direction (see inset). From bottom to top V_{fg} is varied from 0 to -300 V. (c) Device resistance at $B = 0$ (left axis) and ΔR (right axis) as a function of front-gate voltage. The inset in (b) depicts the orientation of the field-effect electrodes in the coordinate system taken from figure 1.

an additional front-gate electrode which was in the x–y plane and parallel to the mesa. By means of the front-gate voltage V_{fg} we were then able to control independently the carrier density of the 2DES. The multi-terminal field-effect transistor (FET) with source, drain and the two independent gate electrodes was mounted on a Swedish rotator and magnetotransport measurements were performed in a superconducting magnet at 4.2 K using a conventional lock-in technique.

3. Magnetotransport experiments

3.1. Hysteretic spin-valve-like signal at low magnetic field

In figure 2(b) we summarize the magnetotransport characteristics obtained for sweeping a magnetic field B between ± 1 T when B was applied in the plane of the 2DES and of the Co contacts, i.e. B was applied along the x direction. Here, we focus on the hysteretic behaviour observed in the millitesla regime. From the bottom to the top curve the voltage on the front gate V_{fg} was decreased stepwise from 0 to -300 V. The hysteretic spin-valve-like signal is observed for all front-gate voltages. When we plot the device resistance $R(B = 0)$ as a function of V_{fg} (figure 2(c)), we find two regimes: (a) for $-100\ \text{V} < V_{fg} < 0$ V the resistance varies almost linearly with V_{fg} and (b) for $V_{fg} < -100$ V, $R(B = 0)$ saturates at a value of about 235 Ω. This behaviour suggests that at $V_{fg} \approx -100$ V the 2DES is depleted. As a consequence, for lower V_{fg} the variation of R with V_{fg} is considerably less pronounced. This conclusion drawn from figure 2(c) will be further substantiated when we discuss the EMR effect in section 3.2.

What is important here is that the spin-valve-like signal ΔR (closed symbols in figure 2(c)) persisted even if the 2DES was depleted. Figures 2(b) and (c) suggest that for the observed

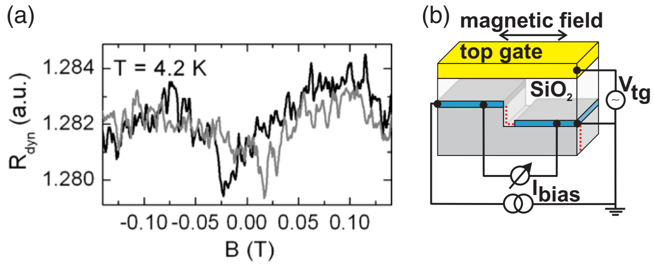

Figure 3. (a) Hysteretic behaviour of the dynamic resistance R_{dyn} measured at 4.2 K by modulating the top-gate voltage V_{tg} by 25 V_{rms}. The magnetic field was applied along the x direction. (b) Sketch of the experiment.

spin-valve-like signal electron transport near the cleaved edge is more important than within the 'bulk' of the 2DES. The 2DES within the mesa rather acts as a shunt diminishing the overall device resistance. To study further the electron transport in the step region we then used the top-gate electrode on the cleaved edge to perform a gate-modulation technique already introduced by Meier *et al* [17] for spin transport investigations. For this, we modulated V_{tg} while applying a dc bias current $I_{bias} = 1\ \mu$A between source and drain. The signal R_{dyn} measured at the lock-in amplifier should then reflect the electron transport in the step region alone. In figure 3 we observe again a hysteretic spin-valve-like signal, now in R_{dyn}. We interpret these findings as that spin-polarized transport takes place close to the cleaved edge and that the variation of the device resistance originates from the hysteretic magnetization reversal of the two different Co contacts. In our hybrid structure, the separation between the source and drain contacts is smaller than the mean free path and electrons can travel in particular (quasi-)ballistically between them. The negative signal of ΔR is consistent if we assume that spin–orbit interaction generates a spin precession of about 180° in the device [8]. The Rashba coefficient in our InAs heterostructure which was measured to be about 2×10^{-11} eV m [26] would be sufficient to generate this.

If we take the resistance $R = 235\ \Omega$ from figure 2(c) as an estimate for the channel resistance we can roughly estimate the number of ballistic modes M. According to the Sharvin point contact formula [27] $1/R = G = \frac{2e^2}{h} MT$ and assuming a transmission coefficient $T = 1$, we get $M \approx 55$. However, it is reasonable to assume that (a) $T < 1$ and (b) $R = 235\ \Omega$ also includes the series resistance of the contacts. In this more realistic scenario, M is hence even larger than 55. If we consider the maximum value of the relative spin-valve effect $\Delta R/R = 0.3\%$ and follow the spin injection theory of Johnson [28] we find a degree of spin polarization of about 4% in the InAs. This value and the observed negative ΔR are in reasonable agreement with further mesoscopic ferromagnet/semiconductor hybrid structures investigated in the quasi-ballistic transport regime [16, 17]. Theoretical studies [11] have suggested that the number of modes M should be significantly reduced to enhance the spin-valve signal.

3.2. Large magnetoresistance in a perpendicular magnetic field

In this section we discuss a large positive magnetoresistance (MR) effect which is *nonhysteretic* and which we observe in a magnetic field B perpendicular to the 2DES, i.e. when B is applied along the z direction. We will show that this effect does not originate from spin-dependent characteristics but from an *orbital* effect. The observation is interesting by itself since it reflects the so-called extraordinary magnetoresistance effect recently discovered in metal/semiconductor hybrid structures [3].

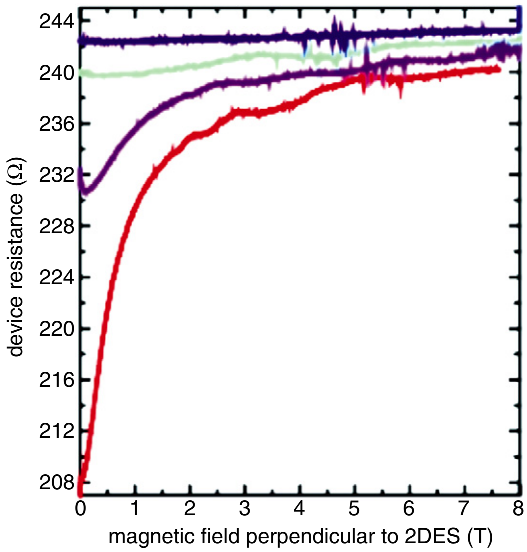

Figure 4. Magnetoresistance measured in a field B perpendicular to the 2DES at 4.2 K, i.e. B is along the z direction. From bottom to top the front-gate voltage V_{fg} is varied from 0 V to −100 V. At $V_{fg} = 0$, the relative magnetoresistance effect $[R(1\text{ T}) - R(0)]/R(0)$ is about 10%.

In figure 4 we show magnetotransport data obtained on the Co/InAs(2DES)/Co hybrid structure in a magnetic field perpendicular to the 2DES. For $V_{fg} = 0$ we observe two characteristic features: (i) a large positive MR starting at $B = 0$ and (ii) Shubnikov–de Haas (SdH) oscillations superimposed on the saturating device resistance R. If we apply a negative V_{fg} in figure 4, the positions of the SdH oscillations shift and the device resistance increases as already discussed in section 3.1. At the same time the large positive MR *vanishes* gradually. At $V_{fg} = -100$ V an almost magnetic-field independent device resistance is found.

We explain the large *nonhysteretic* positive MR at $V_{fg} = 0$ not by a spin-transport effect but by the magnetic-field induced current redistribution between the metallic contacts and the high-mobility 2DES in the InAs heterostructure. The redistribution effect due to the Lorentz force is most convincingly demonstrated with control samples which we fabricated using Au as a *nonmagnetic* contact material and where we injected the bias current directly into the 2DES (figure 5(a)). In figure 5(b) a typical MR curve measured on a Au/InAs(2DES) hybrid structure is depicted. Here, we observe a similar positive MR as in figure 4. Modelling the hybrid structure by means of the Drude theory and the finite-element method [7] gives a perfect agreement between measurement and theoretical prediction in figure 5(b). This underlines again that the observation is of classical origin and does not depend on spin properties. It has been shown theoretically [7] that the important prerequisite for a pronounced current redistribution is a low-ohmic specific interface resistance ρ_c. The occurrence of the EMR effect in figure 4 might therefore be independent proof of the good interface quality in the Co/InAs(2DES)/Co hybrid structure on the cleaved edge. In our best Au/InAs(2DES) hybrid structure we measured a contact resistance of about 10^{-8} Ω cm^2, very close to the Sharvin resistance [2, 7] which is the lowest limit for ρ_c. The CEO technique is hence capable to accomplish excellent interfaces.

In figure 4 we observe that if we deplete the 2DES the EMR effect vanishes. This is also consistent with our assumption that the behaviour is governed by the magnetic-field induced

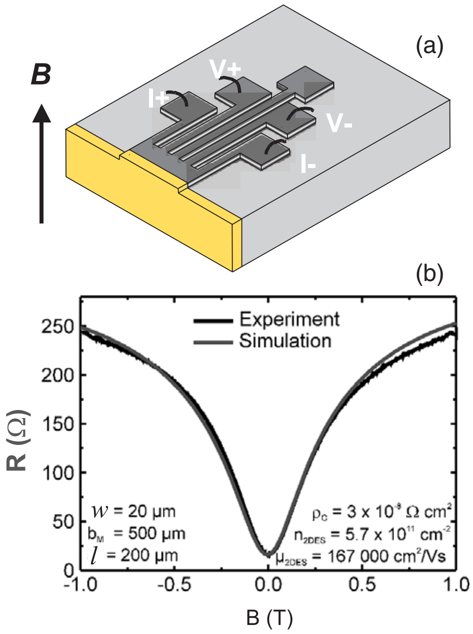

Figure 5. (a) Sketch of the experiment on the Au/InAs(2DES) hybrid structure, where the cleaved edge of height b_M is covered by Au. The mesa containing the 2DES is dark-grey. Current leads and voltage probes are indicated. (b) Magnetoresistance trace at 4.2 K (black curve). Simulations on the EMR effect (grey curve) are in excellent agreement with the data. Sample parameters are given in the figure. Here, w and l are the width and length of the mesa containing the 2DES, respectively. The relative magnetoresistance effect $[R(1\ \mathrm{T}) - R(0)]/R(0)$ is 1100%. The direction of B is depicted in (a).

current redistribution between the metallic contacts and the 2DES. As soon as the 2DES is depleted the redistribution can no longer take place. This is observed at $V_{fg} = -100$ V when R has become magnetic-field independent. Consistently, this is the same threshold value for depletion which we found in figure 2(c).

4. Conclusion

We have presented a novel preparation technique for spin FETs on a cleaved edge. Devices, which have been processed *ex situ* so far, showed a hysteretic spin-valve-like signal at small magnetic field. In a high magnetic field perpendicular to the heterostructure we observe in addition a large positive MR which is an intriguing Lorentz-force induced effect. This is the so-called extraordinary magnetoresistance which might enable high sensitive magnetic field sensors in an optimized device geometry [5]. Our preparation technique based on cleaved-edge overgrowth is suitable for the fabrication of a spin FET with *in situ* processed planar interfaces and epitaxially grown contacts in the future.

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