GIANT MAGNETOCONDUCTANCE AT INTERFACE BETWEEN A TWO-DIMESIONAL HOLE SYSTEM AND A MAGNETIC SEMICONDUCTOR (GA,MN)AS

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We report finding of giant (two orders of magnitude at 0.05T) magnetoconductance (MC) at the interface between a two-dimensional hole system (2DHS) and a magnetic semiconductor (Ga,Mn)As. The MC, on one hand, clearly due to the ferromagnetism in (Ga,Mn)As, but also is a consequence of the elongation of the coherence length in 2DHS. A surprising property of the MC is the dependence on the sweep rate of the magnetic field, in other words, it has a finite dacay time.

1. Introduction

Since the first synthesis of (Ga,Mn)As[1], it has been attracting attentions as a promising material for spintronics because of its high ($\sim$ 160K) Curie temperature and connectivity to sophisticated III-V superstructures. A draw-back is, however, materials obtained so far by low-temperature molecular beam epitaxy (LTMBE) are heavily disordered and have very poor optical and electrical properties. Hence it seems more promising to use a (Ga,Mn)As as a matix to inject spin-polarized carriers into non-magnetic materials[2] sice it has half-metallic band structure[3], that is, very high spin-polarization ratio is expected.

In order for highly efficient spin injection, knowledge on physical properties of (Ga,Mn)As - non-magnetic structures should be accumulated[4]. In this article, we report the finding of giant magnetoconductance (MC) in the transport through the interface between (Ga,Mn)As and a two-dimensional hole system (2DHS). This has not been found even in similar transport through a double-barrier structure which has an electrode of (Ga,Mn)As. Hence this would have its origin in the properties of 2DHS. Peculiar features of the MC are presented and possible origins are discussed.

2. Experiment

2.1. *Growth of the Films*

There is an obstalce in the growth of structures including III-V based DMS, that is, the layers grown by LTMBE easily can be groken at an ordinal growth temperature of GaAs-based structures. This gives a strong constraint to the growth of the films that the layer(s) of the DMSs should be at the top of the structures. On the other hand, in order to get a high quality 2DHS, a doped layer should usually be at the top of the layers, hence there inevitably exists a doped layer between a DMS layer and a 2DHS, which structure would greatly reduces the cleaness of the interface.

In order to avoid this problem, we adopted an inverted structure for 2DHS as shown in the left of Fig.1. Despite of the conventional knowledge that the mobility in such inverted type 2DHG should be lower due to the roughness of the interface, the Hall mobility and the carrier concenteration at 4.2K are 9 m^2/Vs and 1.0$\times$ 10^{11} cm^{-2} respectively, indicating high quality of the 2DHS layer.

On top of the film, a (Ga,Mn)As layer with the Mn concentration of 5% was grown by conventional LTMBE. The transition temprature T_C is 110K.

2.2. *Sample Processing and Measurements*

The Au electrodes with the shape shown in the right panel of Fig.1 are fabricated by electron beam lithography on top of the film. The gap and the width of the electrodes are both 1μm. By using these electrodes as etching masks, part of the (Ga,Mn)As layer was selectively etched off. The $Al_{0.5}Ga_{0.5}As$ barrier layer worked as the stop-etching layer. Then the gap region was further fabricated into the structure of a bar with the width of 1 μm as shown in the right panel of Fig.1. We put direct In ball contacts to 2DHS through the barrier layer, in which process we took care not to raise the substrate temperature above 300 ℃ to keep the quality of the (Ga,Mn)As.

The sample was placed in a mixing chamber of a ^{3}He-^{4}He dilution refrigerator, directly immersed in the mixture and cooled down to 30-40mK. The magnetic field up to 15T was applied perpendicular to the growth plane by a superconducting solenoid. The interface resistance was measured by DC method in voltage-bias condition with taking care of the zero-point shift due to an imbalance in thermoelectric

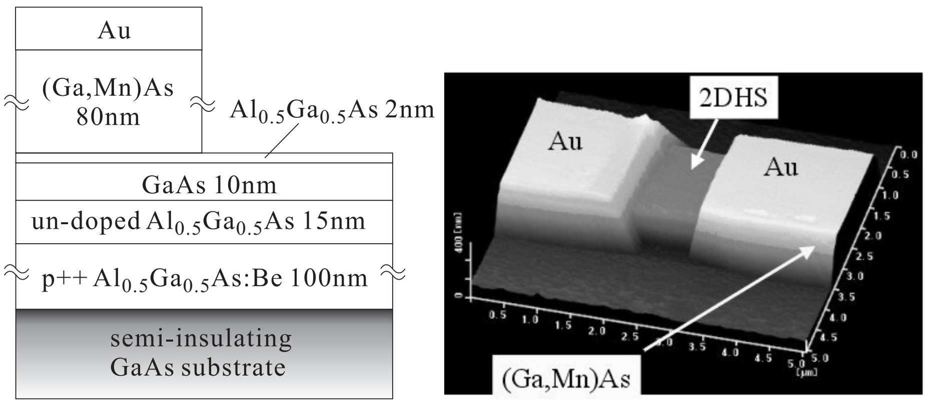


Figure 1. Left: schematic cross sectional view of the sample. Right:atomic force micrograph of the sample. The distance between the ticks in plane is 0.5μm.

power. The resistance of 2DHS was mesured with AC of 25Hz by conventional lock-in technique.

3. Results and Discussion

3.1. *Magnetoresistance: Response up to the Quantum Hall Regime*

As shown in the left panel of Fig.2, the differential resistance of the sample is strongly temperature dependent below 600mK especially for low bias voltage $V_{\rm sd}$. Note that the Shubnikov-de Haas (SdH) oscillation and the quantum Hall effect in the 2DHS is also clear only in a similar temprature region. The right panel of Fig.2 shows magnetoresistance for various bias voltages. As shown in the both panels, the current-voltage (I-V) characteristic of the sample is strongly non-linear and large oscillations in high fields are periodic in the inverse of magnetic field $(1/B)$ and apparently due to the SdH oscillation in the 2DHS. Large hystereses around the peaks are due to the large resistance change in the 2DHS and the non-linear I-V characteristics of the interface. Huge increases in the resistance around the peaks are probably due to the formation of the edge states around the (Ga,Mn)As electrodes and the effective insulation.

The lower is $V_{\rm sd}$, the more prominent is the oscillation and below 60mV, a hysteretic structure appears around zero magnetic field, which is apparently not from the SdH but due to the ferromagnetism in the (Ga,Mn)As. It grows with

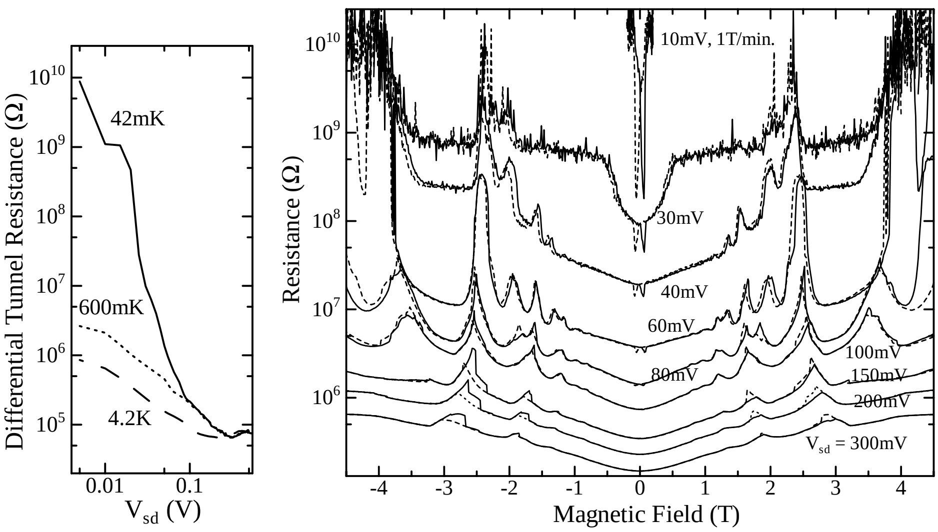
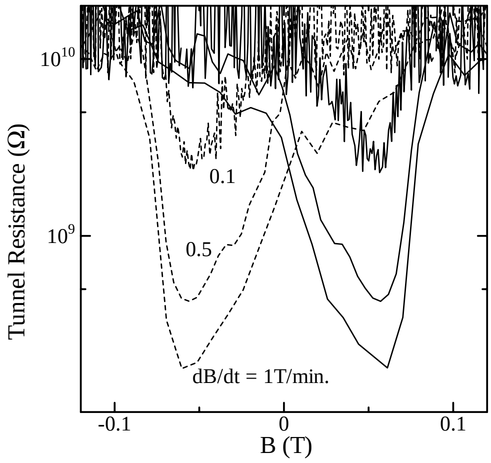
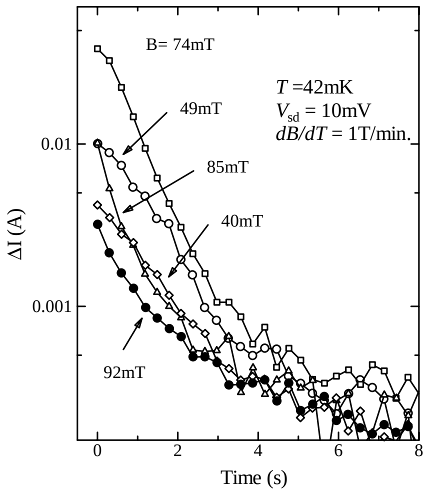


Figure 2. Left panel: temperature variation of the differential resistance of the sample as a function of the bias voltage. Right panel: Magnetoresistance of the sample for various bias voltages. The seep rate of the magnetic field is 0.5T/min. except the topmost data for the bias voltage of 10mV (1T/min). Solid curves are for up-sweeps of the magnetic field and broken ones for down-sweeps.



(a)



(b)

Figure 3. (a) Sweep rate dependence of the hysteretic MC around zero field. The bias voltage is 10mV. (b) Time dependence of the sample current for the fixed bias $V_{\rm sd}$= 10mV. The parameter is the destination of the field sweep and the origin of the time is taken as the stopping time of each sweep.

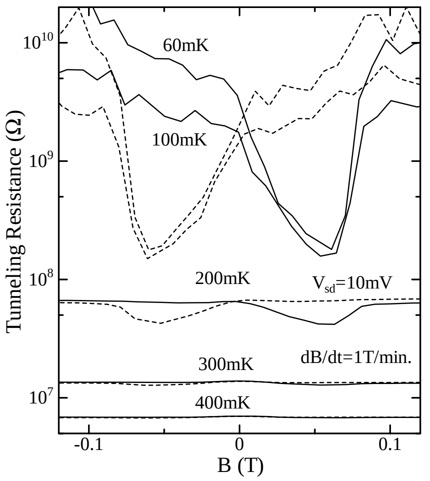
lowering $V_{\rm sd}$, and as described in the next subsection, with increasing the sweep rate of the magentic field. As shown in the top of the right panel of Fig.2, the amplitude of the hysteretic magnetoresistance reaches more than two orders of magnitude for 0.07T.

3.2. *Time-dependent MC*

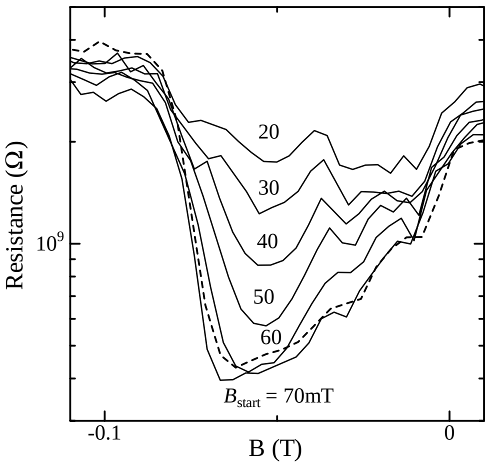
The giant hysteretic MC around zero field has sweep rate (dB/dt) dependence as shown in Fig.3(a). The faster the sweep rate, the larger the MC. As expected from this behavior, the MC has a finite decay time of a few seconds as shown in Fig.3(b), in which the device current after stopping of the manetic field sweep is plotted as a function of time. The decay time is almost independent of $V_{\rm sd}$ around the zero bias, which means the MC cannot be attributed to a simple variation in the circuitry. An important point in the decay is that even after a complete decay of the MC at a field B_0, a restart of the sweep causes sudden recover of the MC as long as $|B_0|$ <0.07T. The boundary is close to the cohersive force of the (Ga,Mn)As.

On the other hand, the resistance of the sample is almost the sum of those of two junctions and the MC is not coming from the spin-injection effect but from some intrinsic nature in the (Ga,Mn)As-2DHS interface.

Figure 4(a) shows the temperature dependence of the hysteretic MC. As expected from the temperature dependence of the I-V characteristics and the bias dependence of the MC, the amplitude rapidly diminishes with increasing temperature and it can hardly be observed above 600mK. Minor loop magnetoresistance is



(a)



(b)

Figure 4. (a) Temperature dependence of the hysteretic MC. The solid curves are for down-sweeps of the magnetic field and the broken ones are for up-sweeps. (b) Minor loop magnetoresistance for down-sweeps. The parameter is the turning magnetic field (in mT). The bias is 10mV and the temperautre is 60mK. The magnetoresistance curve from 0.5T is indicated by broken curve.

displayed in Fig.4(b), which shows decrease in amplitude with decrease in the value of magnetic field at the turning point.

3.3. *Possible Origin of the Giant MC*

Though we do not have a concrete idea on the origin of the giant MC at present, here we discuss possible mechanisms. The characteristic teperature of the MC is too low to be attributed to the thermal activation over the barrier of $Al_{0.5}Ga_{0.5}As$. Apparently we cannot attribute it either to ordinal selection rules in tunneling through heterostructures (*i.e.*, matching of the in-plane momentum and perpendicular kinetic energy). We experimentally confirmed that by replacing the (Ga,Mn)As layer with an ordinal highly doped GaAs layer. The interface resistance is not so high also for the combination of a (Ga,Mn)As and an almost symmetric quantum well.

The fact that the temprature region for the hysteretic MC is close to that for the SdH and the quantum Hall effect indicates that the coherence in the 2DHS plays an important role for the presence of a new selection rule. Hence we should consider the braking of the inversion symmetry in 2DHS and the ferromagnetism in (Ga,Mn)As. It is well known that the inversion symmetry breaking lifts the Kramers degeneracy of the subbands may give an additional selection rule for the tunneling from half-metallic materials. A change in the magnetization in (Ga,Mn)As produces a non-equilibrium trangent state which opens a transport channel. According to this interpretation, the decay time is the time for the recovery of the equilibrium.

Another possible origin is the charging up of the interface states. Due to the lattice mismatch between the 2DHS and (Ga,Mn)As or some contamination introduced during the substrate-temperature lowering process, comparatively shallow localized interface states may exist. Due to the Coulomb blockade in these states[a] and the half-metallicity in (Ga,Mn)As, the spin blockade effect may take place. The inversion in the magnetization breaks up the spin blockade until a "sooer or later" spin blockade[5] for the new spin configuration occurs, which gives the finite decay time of the MC.

4. Summary

We have found extremely large MC in the conduction through the interface between a (Ga,Mn)As and a 2DHS. The MC clearly is the consequence of the ferromagnetism though the detail of the mechanism is still unclear.

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[a]The blockade is probably supported by the triangular shape of the potential of 2DHS.