Giant Magnetoconductance at an Interface between a Magnetic Semiconductor (Ga,Mn)As and a Two-Dimensional Hole Gas

Yoshiaki HASHIMOTO*, Toshiyuki YAMAGISHI, Shingo KATSUMOTO, and Yasuhiro IYE

Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Chiba 277-8581

(Received March 29, 2005)

We have observed huge (10000% at 0.07T) magnetoconductance (MC) in low temperature transport through an interface between a ferromagnetic semiconductor (Ga,Mn)As and a two-dimensional hole gas at a (Ga,Al)As/GaAs hetero-interface. The MC has a finite decay time and vanishes in a few seconds at 40mK while it rapidly recovers with a variation of magnetic field. The peculiar behavior is explained by the interplay between the Coulomb gap and disordered ferromagnetism. Sound evidence of the interpretation is obtained by introducing self-assembled InAs quantum dots at the interface, thus making the characteristic length of the disorder much longer.

KEYWORDS: tunneling magnetoconductance, Coulomb gap, single-electron charging effect

Large tunneling magnetoresistances in the junctions of ferromagnetic-ferromagnetic[1)] and ferromagnetic-nonmagnetic[2)] materials have been attracting attentions both from the application to so called spintronics and from the pure physics.[3)] Amplification of so called spin-valve magnetoresistance by single-electron charging effect was observed in the systems of normal metal - ferromagnet small junctions[4)] and theoretically explained.[5)] On the other hand, it was reported that Efros-Shklovskii's (ES) soft Coulomb gap[6)] is hardened by formation of magnetic polarons.[7)] The above two physical processes represent the two extremes in the spatial scale of disorder. Namely, in the former, the system contains only single charging site (Coulomb island)[8)] while infinite numbers of charging sites exist in the latter system and the disorder can be treated as continuous.[9)] There is another important difference that the long range nature of the Coulomb interaction is indispensable for the ES gap to emerge. The range of the interaction is determined by the ratio of the junction capacitance to the self-capacitance in few charging sites systems.

In this letter, we report huge hysteretic magnetoconducatance (MC) at an interface between a ferromagnetic semiconductor (Ga,Mn)As[10)] and a two-dimensional hole system (2DHS) at very low temperatures ($<$ 300mK). This MC has a peculiar property that it decays with a finite decay time. We show that this MC originates from transient softening of magnetically hardened ES gap at the disordered layer around the interface. We have also investigated a similar effect in a system with self-assembled InAs dots at the interface, which introduce a finite length scale of disorder. The result reveals a new aspect of the Coulomb gap from the time-domain, and at the same time shows crossover from single-electron circuits to disordered insulators.

The inset in Fig.1 shows a schematic cross sectional view of sample A, which is grown on a (001) semi-insulating GaAs substrate by molecular beam epitaxy (MBE). First an ordinal 2DHS structure with a thin (Al,Ga)As barrier layer on top was grown at 600C, then the substrate temperature was decreased to 270C and the top (Ga,Mn)As layer with a Mn concentration of 4.9% was grown. The hole concentration of the 2DHS was 1.0×10^{11}cm^{-2} and the Hall mobility was 9 m^2/Vs at 4.2K. These parameters were obtained by removing a part of the (Ga,Mn)As by selective etching. The top (Ga,Mn)As layer was metallic and had a Curie temperature of 110K after a low temperature annealing.[11)]

Another sample with InAs self-assembled dots grown under standard conditions[12)] just at the bottom of (Ga,Mn)As film was also prepared (sample B). The average diameter and height of the dots were 20 Åand 7Årespectively. The density of the dots was 1×10^{11}cm^{-2}.

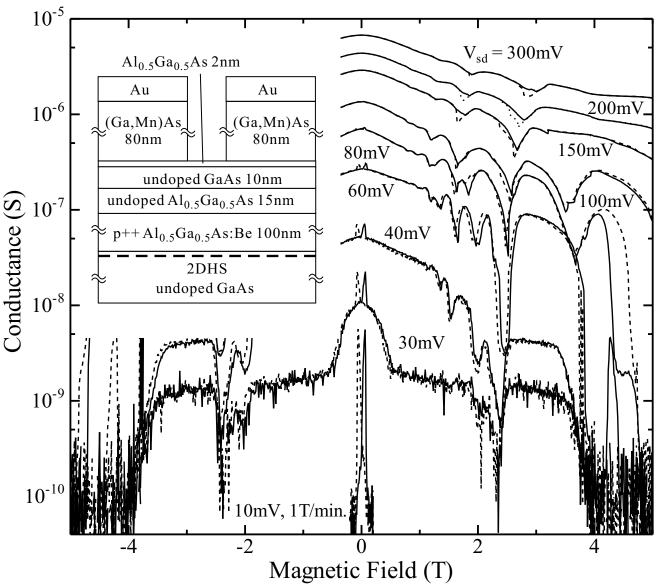


Fig. 1. Differential conductance as a function of magnetic field perpendicular to 2DHS for various bias voltages. Solid lines are for up-sweep while broken ones are for down-sweep. The sweep rate is 0.5T/minute except the lowest data (1T/min.). Inset: Schematic cross sectional view of sample A. In sample B, InAs dots are introduced between the (Ga,Mn)As layer and the $Al_{0.5}Ga_{0.5}As$ layer.

*E-mail: gensan@issp.u-tokyo.ac.jp

The structure is the same as sample A other than the introduction of InAs dots.

Two 300μm$\times$800μm Au electrodes were deposited on top of the substrate by lift-off technique. (Ga,Mn)As layer was selectively mesa-etched by using these electrodes as etching masks. We mainly measured conductance between these electrodes, that corresponds to the conductance of back-to-back junction conductance. This is only to enhance the visibility of the junction magnetoresitance and we confirmed that classical simple sum rule for series resistances holds in the present sample. The samples were set inside a mixing chamber of a dilution refrigerator and directly cooled by ^{3}He-^{4}He mixture down to 40mK. The conductance was measured by conventional DC technique under voltage-bias condition and magnetic field up to 7T was applied by a superconducting solenoid.

Because the 2DHS lies comparatively deep, the sample resistance is very high at low temperatures; it is about 1MΩ at 4.2K and reaches 10GΩ around zero-bias at 40mK. And at 40mK, it is strongly non-linear reflecting the tunneling nature of the conduction. Figure 1 shows the MC of sample A for various bias voltages under magnetic field up to 4.5T at 40mK. Large oscillations at high fields clearly reflect the Shubnikov-de Haas (SdH) oscillation in the 2DHS, *i.e.*, the conductance dips (resistance peaks) are explained by the formation of edge states around the electrodes. The hystereses accompanied with the peaks are simply due to the strongly non-linear tunneling resistance and the high, rapidly varying series resistance of 2DHS.

With decreasing the bias voltage, a sharp peaks in conductance grows around the zero-field. The MC is hysteretic for the field sweep and has a symmetry of $\varDelta_{\rm up}G(B) = \varDelta_{\rm down}G(-B)$, where G is the conductance, B the magnetic field, $\varDelta_{\rm up,down}$ mean variance due to the field up sweep and down sweep respectively. This is due to the ferromagnetism in the (Ga,Mn)As layer as shown later. Surprisingly, the faster the sweeping rate of the magnetic field, the higher is the peak height in the MC $\varDelta G_{\rm peak}/G(0)$. For the bias voltage of 10mV and the sweep rate of 1T/min., which is the fastest for our magnet, $\varDelta G_{\rm peak}/G(0)$ reaches 10^2 at 0.07T as shown by the lowest plot in Fig.1.

The sweep rate dependence is due to the finite decay time of the MC. Figure 2 shows time dependence of the conductance in sample A under finite bias voltage after stopping the field sweep for various target fields. In the beginning, the induced conductance decays exponentially with a decay time of about 1s. Interestingly, the conductance rapidly recovers with a restart of the field sweep as shown in Fig.3(a). Figure 3(b) shows the minor loop characteristics of the MC. The amplitude diminishes with decreasing the starting field strength. These two results manifests that the MC originates from random magnetization reversals of small magnetic domains, which occur around the zero-field.

Henceforth our discussion concentrates upon the microscopic mechanism of the giant MC. Here we propose a possible mechanism, which is supported by the successive experiment.

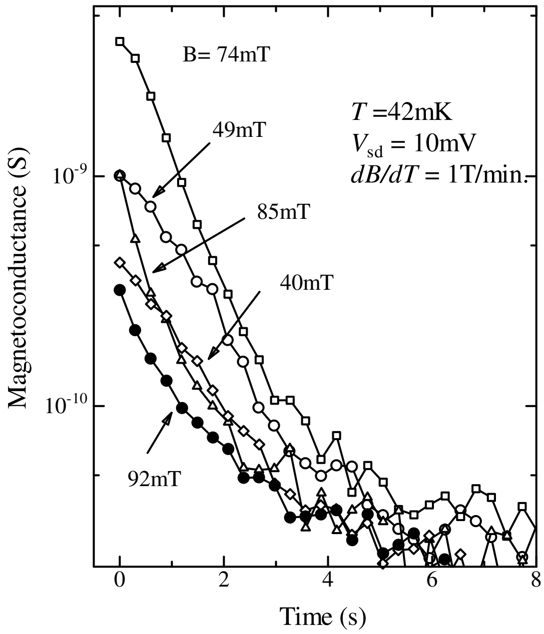
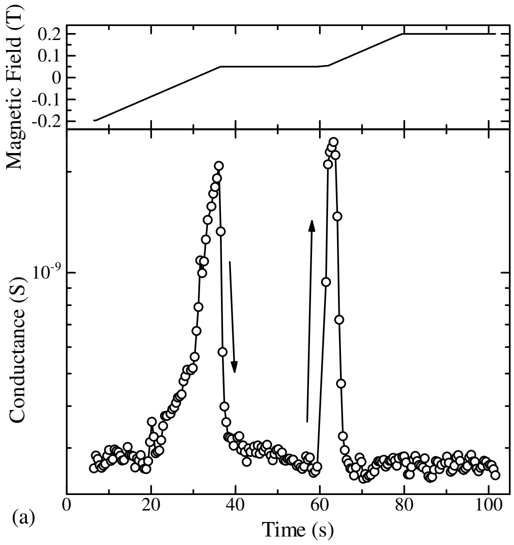


Fig. 2. Time decay of the magnetoconductance in sample A after stopping the variation of magnetic field. The field was swept to the target fields indicated in the figure with a sweep rate of 1T/min. from -0.2T. Then the current was measured as a function of time at the targets.

The interface between the (Ga,Mn)As and the 2DHS should have significant disorder due to the lattice mismatch and the inevitable growth interruption. There should occur, then, the localization of holes, which leads to the formation of interface magnetic polarons. The polarons make a hard gap at the Fermi level as reported by Terry et al.[7] and the large series resistance due to the interface becomes large. Under a fixed magnetic field, the spatial distribution of the holes is determined so as to minimize the sum of the inter-site Coulomb energy and the *p-d* exchange energy. The latter is strongly affected by the random distribution of the magnetic domains in (Ga,Mn)As). A finite energy is needed to change the distribution, which forms the hard gap. Now, when the magnetic field is varied, the domain structure changes causing some shift in the most stable hole distribution through the exchange energy. However, the real charge distribution does not catch up the change immediately because the intermediate distributions need high energies, which form an effective barrier for the transition. This results in transient softening of the gap and causes the observed MC with a finite time constant.

The gap can be easily overcome by applying small bias voltage, which appears as the bias dependence shown in Fig.1. Most part of the bias is, however, still applied to the thick tunnel barrier and we cannot discuss the size of the gap quantitatively from the data. If the above hypothesis is the case, then, the decay time measured in Fig.2 directly corresponds to the relaxation time of the localized hole spatial distribution.

Here we define the characteristic length scale of the disorder as the inverse of a peak position in the Fourier spectrum of disorder potential. The ES Coulomb gap is



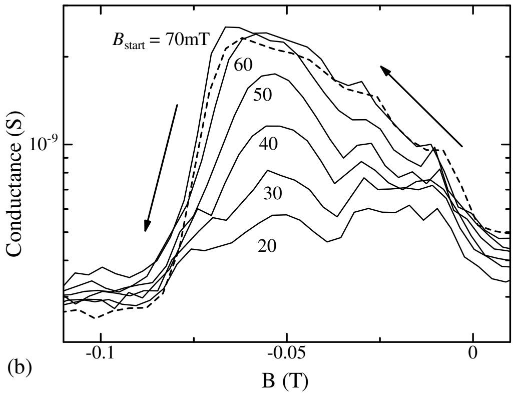
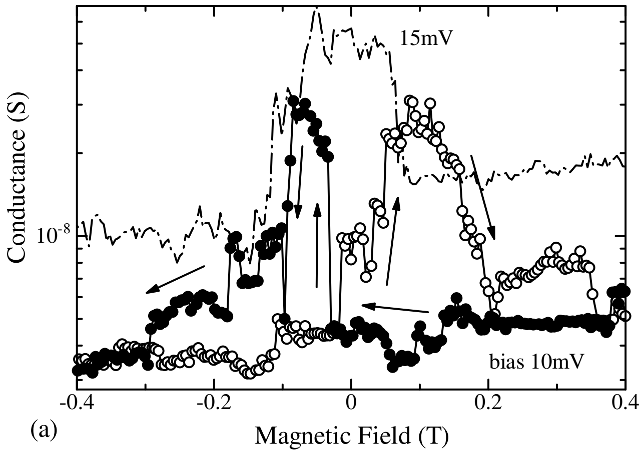


Fig. 3. (a) Upper panel shows the magnetic field sweep. Corresponding variation in the device conductance is plotted in the lower panel. The left arrow indicates time-dependent decay when the field sweep is stopped while the right one does the fast recovery due to the re-start of the sweep. (b) Minor loop characteristics of the magnetoresistance. The magnetic field is cycled as $-0.2\text{T} \rightarrow B_{\text{start}} \rightarrow -0.2\text{T}$. The arrows indicate the direction of the field sweep. The broken line is for $B_{\text{start}} = 0.5\text{T}$. The temperature is 60mK both for (a) and (b).

soft in the absence of magnetic interaction as long as the spatial scale of the disorder is infinitesimally small, in other words, the disorder is "continuous". That is, there is a different distribution with infinitesimally small excitation energy though the ground state distribution has no degeneracy. When the characteristic length scale of the disorder is finite compared with the system size, the lowest excitation energy is generally finite hence the gap becomes hard. The limit of this direction is a "Coulomb island" in single-electron circuits. The amplification of spin-valve magnetoresistance by Coulomb blockade is thus related with the amplification of tunneling magnetoconductance by ES Coulomb gap.

Next we describe an experiment to examine the above hypothesis. If we intentionally introduce a characteristic length scale of the disorder at the interface, the relaxation time of the MC should be significantly modified. We have attempted to carry out the plan by introducing self-assembled InAs dots into the interface. It is well known that such dots distribute randomly at the growth



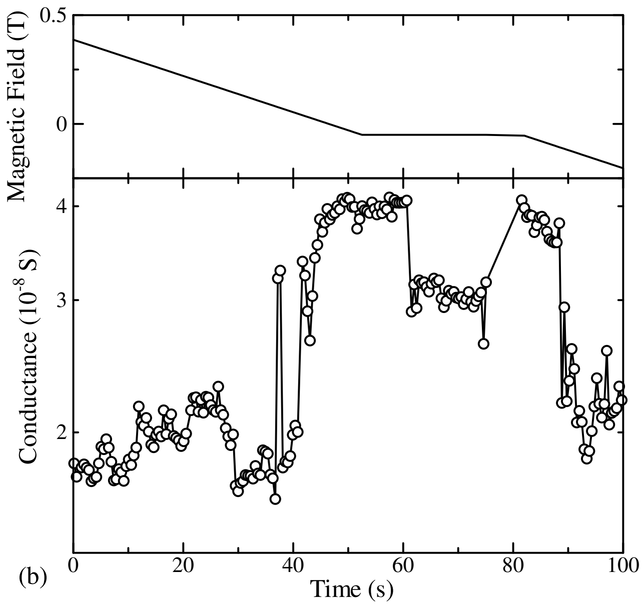


Fig. 4. (a) Conductance peaks around the zero-field in sample B with self-assembled InAs dots. Solid circles correspond to a down sweep of magnetic field while open ones are for up sweep for a bias voltage of 10mV. Dotted line represents data for a bias voltage of 15mV and for up sweep. Arrows indicate the direction of the field sweep. (b) Time dependence of the sample conductance. The top panel shows the trace of the magnetic field and the bottom one shows the variation of the sample conductance.

surface and the sizes of them also have a distribution though they have a characteristic average spacing and the size distribution is narrow. Hence the introduction of the dots makes the characteristic length of the disorder at the interface much longer through strain and dielectric inhomogeneity and the system approaches to a large scale single-electron circuits from a disordered insulator. Here we do not consider the charging/discharging effect of InAs dots themselves. The charging energy of the dots is much higher than the energy scale of the present experiment and the charge distribution of the dots is fixed.

Figure 4 (a) shows the MC of sample B, in which the InAs dots are introduced at the (Ga,Mn)As/2DHS interface. Peaks in the MC around the zero field similar to those in Fig.1 are observed though with significant amplitude of "noises". Also the magnetoresistance curve is more telegram-like than those of sample A shown in

Fig.1 and Fig.3. An important difference is in the time dependence shown in Fig.4(b). The MC does not show smooth decay but telegram-like random jumps appear. This is the origin of "noises" in Fig.4(a).

The result is naturally explained within our picture. The main feature of the ES Coulomb gap properties still remain in sample B with the disordered interface, the giant MC thus appears through similar mechanism. The enlargement of the characteristic length of disorder kills soft paths to relax to the ground state and the smooth decay disappears. As is often observed in single electron circuits, the background charge fluctuation due to some defects, noises from the circuits, etc., causes rapid change in the electrostatic energy and also change in the hole distribution resulting in the jumps of the MC. Besides the charge fluctuation, it is difficult to explain such flip-flop type telegram noise because the flip of magnetic domains, the other candidate for the origin of the noise, is hysteretic in the external magnetic field and cannot cause a flip-flop instability.

The successful qualitative explanation of the two experiments with different appearances manifests the basic legitimacy of our model. At present no theoretical calculation has been done for such systems and quantitative examination is difficult. Proposals of quantitative models and more direct experiments in, *e.g.*, systems in which the non-magnetic and the ferromagnetic layers are closer are required. We believe essentially the same explanation is applicable to the extremely large tunneling magnetoresistance reported in a similar system,[2] which is explained by the conservation of hole momentum in the report. What we have observed here can be summarized as the interplay of Coulomb interaction and the p-d exchange interaction in a system with the intermediate scale of disorder between the continuous disorder limit and the discrete charging circuit limit.

In summary, we have found huge (10000% at 0.07T) MC in low temperature transport through an interface between a ferromagnetic (Ga,Mn)As and a 2DHS. The MC has a finite decay time while it recovers with starting a variation in magnetic field, which is explained along the interplay between the Efros-Shklovskii Coulomb gap and disordered ferromagnetism. An experimental support of the interpretation is obtained by introducing self-organized InAs quantum dots at the interface, thus making the characteristic length of the disorder much longer.

Acknowledgement

This work is supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

1) S. Yuasa, A. Fukushima, T. Nagahama, K. Ando and Y. Suzuki: Jpn. J. Appl. Phys. **43** (2004) L588.
2) C. Rüster, C. Gould, T. Jungwirth, J. Sinova, G. M. Schott, R. Giraud, K. Brunner, G. Schmidt, and L. W. Molenkamp: Phys. Rev. Lett. **94** (2005) 027203.
3) For review, see *e.g.* I. Zutic, J. Fabian, and S. Das Sarma: Rev. Mod. Phys. **76** (2004) 323.
4) K. Ono, H. Shimada and Y. Ootuka: J. Phys. Soc. Jpn. **66** (1997) 1261.
5) X. H. Wang and A. Brataas: Phys. Rev. Lett. **83** (1999) 5138.
6) A. L. Efros and B. I. Shiklovskii: J. Phys. C **8** (1975) L49; B. I. Shklovskii and A. L. Efros: *Heavily Doped Semiconductors*, (Springer, 1984).
7) I. Terry, T. Penney, S. von Molnar, and P. Becla: Phys. Rev. Lett. **69** (1992) 1800.
8) D. V. Averin, K. K. Likharev: *Single-Electronics* in *Mesoscopic Phenomena in Solids* eds. B. L. Altshular, P. A. Lee and R. A. Webb (North Holland, 1991).
9) N. F. Mott, *Metal-Insulator Transitions 2nd ed.* (Taylor & Francis, 1990).
10) H. Ohno, A. Shen, F. Matsukura, A. Oiwa, A. Endo, S. Katsumoto and Y. Iye: Appl. Phys. Lett. **69** (1996) 363.
11) T. Hayashi, Y. Hashimoto, S. Katsumoto and Y. Iye: Appl. Phys. Lett. **78** (2001) 1691.
12) K. Hirakawa, S. -W. Lee, Ph. Lelong, S. Fujimoto, K. Hirotani and H. Sakaki: Microelectronic Engineering **63** (2002) 185.