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Huge Magnetoresistance Effect in Semiconductor based Nanostructures with Zinc-blende MnAs Nanoparticles

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1. Introduction

Ferromagnetic nanoparticles that can be embedded in semiconductor materials (granular materials) are attractive for semiconductor-based spintronic applications, since they have features that can not be obtained by either ferromagnetic metal or ferromagnetic semiconductor alone. Among them, their good compatibility with semiconductor materials and high Curie temperature (T_C) are practically important [1-2]. Zinc-blende (ZB) type MnAs nanoparticles embedded in a GaAs matrix (referred to ZB GaAs:MnAs) is prospective, since it is expected to be haft-metallic [3-4]. Here we report on the huge magnetoresistance (MR) effect in MBE-grown magnetic tunnel junctions (MTJs) with ZB GaAs:MnAs as ferromagnetic electrode. Our results demonstrate the potential of granular materials as important resources for semiconductor-based spintronics.

2. Device structure

The studied magnetic tunneling junctions consist of ZB MnAs nanoparticles as the bottom electrode, a 2.1 nm-thick AlAs tunnel barrier followed by a 1 nm-thick GaAs spacer, and a 20 nm-thick NiAs-type hexagonal MnAs thin film as the top electrode. The MTJs were grown by molecular beam epitaxy (MBE) method. The ZB MnAs nanoparticles with 2-3 nm in diameters are formed by annealing low-temperature grown GaMnAs at 480°C. Figure 1 shows a transmission electron microscopy (TEM) image of the MTJ. Dark areas indicated by while circles correspond to zinc-blende MnAs nanoparticles in which high concentration of Mn atoms precipitates. In this structure, spin-dependent tunneling process occurs between the nanoparticles and the top film through the AlAs tunnel barrier.

3. Magnetotransport characteristics

After the growth, circular mesa diode structures with 200 μm in diameter were fabricated by standard photolithography and chemical etching for transport measurements. Figure 2 shows the magnetoresistance of the sample measured with a bias voltage of –1 mV. The magnetic field was applied in plane along the GaAs[110] azimuth. A huge magnetoresistance up to 100,000% was observed. This huge magnetoresistance can not be explained by the conventional Jullier model. We found that this huge magnetoresistance is a consequence of the Coulomb blockade effect of the ZB MnAs nanoparticles and an electromotive force (emf) emerging from the MTJ. The inset in Fig. 2 shows that the resistance of the MTJ increased sharply when $|V| < 50$ mV, revealing a Coulomb energy of $U = 50$ meV for the nanoparticles. At small negative bias, the resistance of the MTJ is quite large, since electron tunneling to the nanoparticles is blocked by the Coulomb blockade effect. Under a magnetic field, the MTJ is self-biased by the induced emf in the same direction with the applied bias voltage, thus its effective resistance is drastically reduced.

4. Origins of the emf

The macroscopic mechanism for this emf is the conservation of energy [5]. When a spin magnetic moment μ_B with direction anti-parallel to the field B flips to the parallel direction, it must give its magnetic energy $g\mu_B B$ to other system, where g is the effective g-factor of the material in which the spin is embedded. Barnes and Maekawa proposed that this energy could be transferred to electronic system and manifested itself as an emf that could drive an external load [6-7]. The induced emf in our MTJs exists for a time scale of 10^2 seconds, allowing observation of the emf by dc transport measurements. A possible microscopic mechanism of the observed emf with long life-time is that the zinc-blende MnAs nanostructures are super-paramagnetic molecular magnets that undergo quantum tunneling of magnetization as observed in the well-studied Mn_{12} molecular magnet system [8]. Further theoretical studies are needed to construct a microscopic theory for the emf induced by a static magnetic field observed in our zinc-blende MnAs nanoparticles system.

5. Conclusion

We have observed a huge magnetoresistance effect up to 100,000% in MTJs with ZB GaAs:MnAs electrode. The huge magnetoresistance is the consequence of the Coulomb blockade effect of nanoparticles and the electromotive force emerging from the MTJ. Utilizing this effect can help us to develop magnetic sensors with ultra high sensitivity. Our results show that granular materials are important resources for semiconductor-based spintronics.

Acknowledgements

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References

[1] P. N. Hai, M. Yokoyama, S. Ohya and M. Tanaka, Appl. Phys. Lett. **89** (2006) 242106.

[2] P. N. Hai, K. Takahashi, M. Yokoyama, S. Ohya and M. Tanaka, J. Magn. Magn. Mat. **310** (2007) 1932.

[3] M. C. Quian, C. Y. Fong, W. E. Pickett and H. Y. Wang, J. Appl. Phys. **95** (2004) 7459.

[4] M. Shirai, T. Ogawa, I. Kitagawa and N. Suzuki, J. Magn. Magn. Mat. **177** (1998) 1383.

[5] S. E. Barnes, J. Ieda and S. Maekawa, Appl. Phys. Lett. **89** (2006) 122507.

[6] S. E. Barnes and S. Maekawa, Phys. Rev. Lett. **98** (2007) 246601.

[7] S. E. Barnes, J. Magn. Magn. Mat. **310** (2007) 2035.

[8] S. E. Barnes and S. Maekawa, private communication.

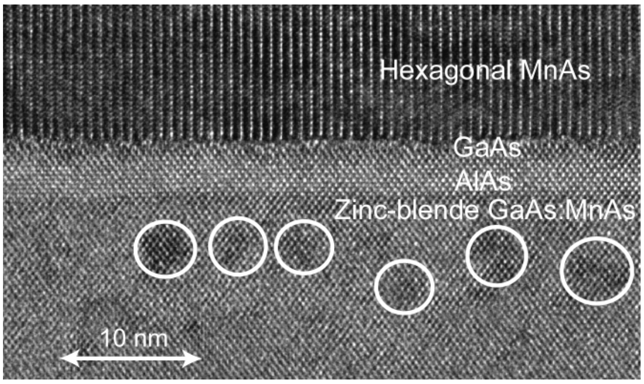

Fig. 1. Transmission electron microscopic (TEM) image of a MTJ consisting of MnAs thin film (20 nm) / GaAs (1 nm) / AlAs (2.1 nm) / Zinc-blende (ZB) GaAs:MnAs (10 nm) grown on a p+GaAs (001) substrate. The white circles indicate the areas with zinc-blende MnAs nanoparticles.

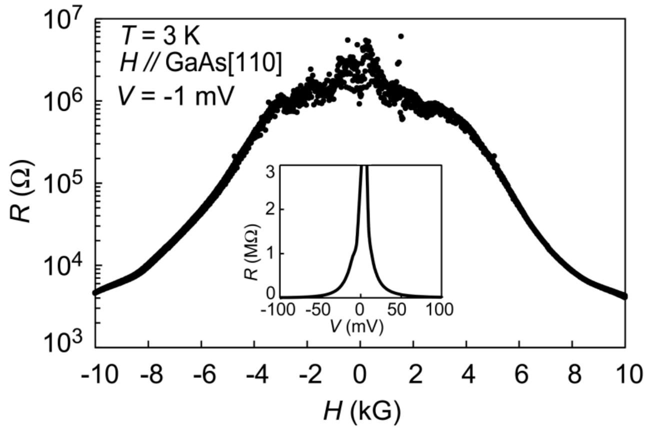

Fig. 2. Magnetoresistance of the MTJ measured at – 1mV. A huge magnetoresistance up to 100,000% was observed. The huge MR is a consequence of the induced emf combined with the Coulomb blockade effect. The inset shows the voltage dependence of the MTJ resistance at zero-field. Coulomb blockade of U = 50 meV was observed.