Spin transport through a single self-assembled InAs quantum dot with ferromagnetic leads

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(Dated: March 23, 2022)

We have fabricated a lateral double barrier magnetic tunnel junction (MTJ) which consists of a single self-assembled InAs quantum dot (QD) with ferromagnetic Co leads. The MTJ shows clear hysteretic tunnel magnetoresistance (TMR) effect, which is evidence for spin transport through a single semiconductor QD. The TMR ratio and the curve shapes are varied by changing the gate voltage.

PACS numbers:
while the other was formed to be 200 nm-wide and 20 µm-long, giving rise to different switching fields for each lead. Since there exists a natural oxide layer formed on the InAs surface, the Co/InAs interface layers act as tunnel barriers. Thus, the device used in this study is a lateral double barrier MTJ, Co/InAs/Co. A scanning electron micrograph of the Co/InAs/Co MTJ is shown in Fig. 1(b). A single InAs QD with a size of ∼ 80 nm is located between the two Co leads. Transport measurements were performed by the dc method in a 3He−4He dilution refrigerator at ∼ 50 mK.

The current vs source-drain voltage ($I-V_{SD}$) characteristics of the Co/InAs/Co MTJ at 50 mK are shown in Fig. 2(a) for various backgate voltages ($V_G$). These curves are measured under an external magnetic field of ∼ 0.2 T parallel to the long axis of the Co leads, where the magnetizations of both leads become nearly parallel. The $I-V_{SD}$ characteristics clearly show the zero conductance in the vicinity of $V_{SD} = 0$ V, indicating Coulomb blockade. Also, step-like $I-V_{SD}$ structures, so-called Coulomb staircase, can be seen. It should be noted that the resistance jumps of ∼ GΩ are much larger than the quantum resistance of $h/e^2 \sim 25.8$ kΩ, and the junction resistance is very large compared to the previous studies by Jung et al. [17] who used nonmagnetic Au leads. Thus, the couplings of the dot to the Co leads are very weak and sequential tunneling processes are likely to be dominant for our sample. Furthermore, the $I-V_{SD}$ curves show asymmetric features about the polarity of $V_{SD}$. This means that in our device the two tunnel barriers is asymmetric. In Fig. 2(b) we also measure the differential conductance, $dI/dV_{SD}$, as functions of $V_{SD}$ and $V_G$. Unfortunately, since the accessible range of the $V_G$ is very narrow, we observe only one diamond-like shape of the $dI/dV_{SD}$ in Fig. 2(b). However, these operations verify that our device is working as a single electron transistor, as well as nonmagnetic Au leads. [17] We also emphasize that this is the demonstration of Coulomb blockade effects for a single semiconductor QD with ferromagnetic leads.

Figure 2(c) shows the magnetic field dependence of the tunnel resistance for $V_{SD} = 22.5, 32.5,$ and 41 mV at $V_G = 200$ mV, measured at 50 mK. The magnetic field ($H$) is applied parallel to the long axis of the wires. The data traces are recorded for two sweep directions of the magnetic field: the blue curves are up-sweep from −0.2 to +0.2 T, while the red curves are down-sweep from +0.2 to −0.2 T. Here, the TMR ratio (%) is defined as $\{(I_H-I_{-0.1T})/I_{-0.1T}\} \times 100$, where $I_H$ and $I_{-0.1T}$ are the tunnel currents for magnetic field of $H$ and for $H = -0.1$ T, respectively. First, we focus on the data for $V_{SD} = 41$ mV. When the magnetic field is swept from +0.2 T toward negative fields (red curve), the magnetizations of the two Co leads are changed from a parallel configuration into an approximately anti-parallel configuration, as
Co/InAs/Co junction measured at $V_G = 600$ mV [Figs. 3(a)-(d)], the change in the TMR ratio is small but slight variation in the shape of the TMR curve is seen with decreasing $V_G$. These features are reproduced qualitatively. Surprisingly, the shape of the TMR curve and the TMR ratio change markedly at $V_G = 50$ and 0 mV [Figs. 3(e) and 3(f)].

One of the possible mechanisms of the spin-dependent transport presented here is spin accumulation in a single InAs QD by injecting spin-polarized electrons from one ferromagnetic Co lead. 

In theoretical studies based on the spin accumulation, 

the bias dependence and the gate-voltage dependence of the TMR ratio have been predicted. By means of optical measurements, the spin relaxation time in self-assembled InAs QDs was deduced to be ~1 ns at low temperature, 

which is long enough to induce a nonequilibrium spin accumulation. However, the unexpected large TMR ratio, shown in Figs. 3(c) and 3(f), can not currently be explained by previously reported theoretical predictions. 

Also, the origin of the shape change in the TMR curve is unclear yet. In this regard, we speculate that the influence of complicated domain structures in the wider lead and/or the magneto-Coulomb effect on the tunnel conductance should also be taken into account.

Recently, for PdNi/CNT/PdNi systems, the gate-dependent TMR was reported, in which the dependence may originate from the discrete energy level depending on the gate voltage and the spin orientation of the ferromagnetic leads. In our case, the influence of the discrete levels in the QD, which may have the spin splitting due to spin accumulation, should also be considered.

In summary, we have fabricated a double barrier MTJ which consists of a single self-assembled InAs QD in contact with ferromagnetic Co leads. Clear Coulomb blockade effects and TMR effects are demonstrated and they can be varied by changing the gate bias voltage.

K. H. and T. M. thank Prof. S. Tarucha and Dr. J. Martinek for helpful discussions. This work is supported by the Special Coordination Funds for Promoting Science and Technology, and Collaborative Research Project of Materials and Structures Laboratory, Tokyo Institute of Technology. K. H. acknowledges JSPS Research Fellowships for Young Scientists.

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