Magnetic Domain Dependent Quantum Transport through a Ferromagnetic Dot Embedded in a Semiconductor Quantum Wire

Syoji Yamada,* Tomoyuki Kikutani, Nobuyuki Aoki, and Hidenobu Hori
School of Materials Science, JAIST-Hokuriku, 1-1, Asahi-dai, Tatsunokuchi, Ishikawa 923-12, Japan

Gen Tatara
Faculty of Science, Osaka University, 1-1, Machikaneyama, Toyonaka, Osaka 565, Japan
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Two unique quantum transport features, a clear appearance of Coulomb oscillations and a narrowing of Coulomb gap, are observed in an embedded ferromagnet (Ni) dot in a semiconductor wire after magnetic field application. Magnetic force microscopy analysis suggests the existence of a domain wall inside the dot before the field application, but it disappears after the field application forming a single domain in the dot. If we establish a transport model by assuming that the domain wall plays the role of a "resistive barrier," we can explain those unique transport features in terms of "Coulomb blockade effects modified by domain dynamics." [S0031-9007(98)07816-8]

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Recently, we have fabricated and proposed a ferromagnetic metal (Ni) dot structure embedded in a semiconductor quantum wire [1,2] as a new candidate for realizing spin-related quantum transports in mesoscopic electronics. Spin-related transports themselves, for example, spin-selected tunneling [3,4], spin-filter [5], and spin-valve [6,7] effects have already been studied extensively mainly by using all metal or metal-insulator multilayers. Our structure is a kind of heterogeneous small system composed of metal and semiconductor. But it can be regarded as a normal metal (2-dimensional electron gas, 2DEG)/ ferromagnetic metal/ normal metal (NM/FM/NM) junction with a reduced size so that transport features expected would be rather close to those of the spin-filtered Coulomb blockade effects. An alternative approach toward spin-dependent transport in a metal-semiconductor system is a spin field effect transistor (FET) proposed by Datta *et al.* [8]. Although there have recently been some related experiments [9], a full spin-dependent operation has not yet been confirmed.

On the other hand, the embedded ferromagnetic dot structure is interesting also from the viewpoint of recent mesoscopic magnetism [10]. If the dot size becomes smaller than about 1 μm, a quantum fluctuation [11] of domain walls is expected to occur, since it becomes large as the effective mass of the domain wall λL_p reduces. Here λ and L_p are the thickness and the cross-sectional length of the domain wall, respectively. Under such conditions, the domain dynamics would appear in magnetization and/or in macroscopic tunneling processes in mesoscopic samples [12]. As for magnetoresistance experiments, the case of thin transition metal *wires* has been extensively studied both in theory [13] and in experiments [14–16]. The domain wall has been believed to play a role of a scattering center and hence the (magneto-) resistance would increase due to the appearance of the wall [17]. However, it has recently been predicted that quantum correction gives the reduction of (magneto-) resistances due to its suppressive effect against weak localization. At present, complete agreements between the theories and several pioneering experiments are not attained. Moreover, transport problems for the *dot* sample with domain wall in its inside have not yet been studied.

Initially, we used conventional (GaAs/AlGaAs) high electron mobility transistor (HEMT) as a base semiconductor. However, probably due to the relatively thick depletion layer, transport we have observed was not that through the dot but rather that passing through the *sides* of the dot [1]. In this Letter, we then changed semiconductor to PM (GaAs/InGaAs/AlGaAs) -HEMT with a thinner depletion layer and hence succeeded to observe the transport *through* the dot, although the conductance was still very small. The features observed, the appearance of Coulomb oscillation and the reduction of Coulomb gap by magnetic field application, seem not to be explained by a simple picture excluding the domain wall in the dot. We concentrated our efforts here on establishing a new transport model of the ferromagnetic dot having a domain wall with its inside.

The starting base material is a pseudomorphic HEMT wafer composed of $Al_{0.25}Ga_{0.75}As/In_{0.2}Ga_{0.8}As/GaAs$ layers. Sheet electron density n_S and mobility μ at 77 K are 8×10^{11} cm^{-2} and 3×10^4 cm^2/V sec, respectively. On the top surface, a pair of split gates which defines a wire of 2 μm long and 1 μm wide was fabricated by electron-beam (EB) lithography and lift-off process. Between the split gates, Ni cluster was embedded by two-step surface modification using STM tips. The first is a conical hole fabrication by applying a single voltage pulse between a tungsten (W) tip and the HEMT surface. The second is an Ni evaporation also carried out by applying a single voltage pulse between a Ni-coated tip and the sample surface. Conditions of the pulse voltage

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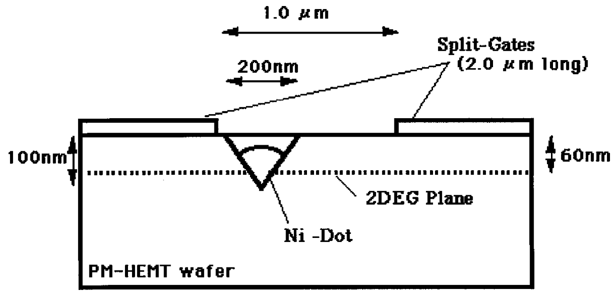

FIG. 1. Schematic cross section of the sample structure fabricated.

(peak and duration) were carefully chosen to make a hole of an optimum size (∼100 nm depth to reach the 2DEG plane) with no damage and to evaporate a small quantity of Ni (∼100 nm diameter) after hundreds of trials [18,19].

We have made magnetic force microscopy (MFM) analysis in an ambient condition, which has a Co-coated cantilever as a probe. Figures 2(a), 2(b), and 2(c) show typical line profiles of topographic and MFM images before and after field application, respectively. To magnetize the dot, we applied a magnetic field of 2000 G s perpendicular to the 2DEG plane. The form of the Ni dot here is slightly different from that in the sample (measured at low temperatures) shown in Fig. 1. The volume of Ni is almost twice or third and hence it forms a mound beyond the HEMT surface, which is suitable for MFM observation. Typical lifting height of the cantilever is within 60–80 nm. According to the profiles in Fig. 2(a), the mound has a 100 nm height and a 500 nm bottom diameter at the surface. It is clearly seen in Fig. 2(b) that before field application, we can find a negative peak followed by a positive one (indicated by arrows in the profile) in the corresponding region to the topographic image 2(a). In contrast, in Fig. 2(c), only a wide positive signal was recorded over the entire region of the dot. We adopted a cantilever of monopole type [20] to obtain better spatial resolution. It is, however, well known that a MFM signal reflecting the stray fields generally expands horizontally over the corresponding topographic signal. In fact, the signal expansion is almost 700 nm at the bottom in Fig. 2(c). If we apply the equal expansion width to Fig. 2(b), both the negative and positive peaks are included in the width, suggesting that they are coming not from the excursions on the right but from the dot itself.

The MFM data thus strongly suggest that there are mostly two domains within the dot before the field application, while they become a single domain after the field application. Since the spatial resolution in an MFM signal is generally limited to a few tens nm at most [20], the analysis of the signal especially as that in Fig. 2(b) should be done carefully. However, we believe our domain wall picture is reasonable, since recent micro-SQUID measurements [21] for similar size and various shape ferromagnetic dots suggest the possible formation of domain walls inside the dot before the field application. Additional and systematic analysis [22] of the magnetic domain structure for STM made and EB made Ni dots having various sizes also indicates the possibility of the appearance of domain walls inside the dots even when the lateral diameter is less than 200 nm.

Low temperature transport measurements have been done at 0.3 K with a superconductive magnet of 10 T. Figure 3 shows typical conductance traces against a gate voltage after a full pinch off of the wire taken with and without a magnetic field of 1600 G s. Here the full pinch off means the condition that depletion layers from the gates fully contact to the depletion layer surrounding the dot, which rigidly restricts electron transport paths only to that through the dot. As shown in the traces, the conductance oscillation with zero field seems aperiodic and not reproducible against gate voltage sweep direction. In contrast, the oscillations taken under the ± 1600 G s are periodic and reproducible against the directions of gate voltage sweep and of magnetic field. Here, the voltage (V_{g7}) of the gate close to the dot is fixed and only the voltage ($V_{g11} = V_g$ in the figure) of the opposite side gate was swept. These results suggest that the transport through the dot becomes simpler with an appropriate magnetic field application. The fact that the oscillation periods are almost equal for reversing the applied field indicates the realization of the dots with same effective size after the field application. In other words, it does not depend on the field direction but rather on the field strength. Note here that the observed tunnel conductance is very small due probably to the still thick depletion layers surrounding the dot (estimated to be several tens of nm).

In Fig. 4, typical current-voltage (I-V) characteristics are shown for the cases with and without magnetic field (± 5000 G s) application. Those traces are taken under the gate voltage (V_{g11}) just before the full pinch off condition.

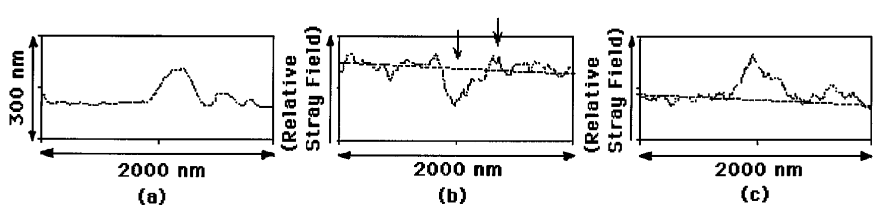

FIG. 2. Line profiles of (a) topographic image and MFM images of (b) before and (c) after the field application. Vertical axes are "height" for (a) and "stray field strength" for (b) and (c), respectively. Line profiles are taken horizontally at the image centers. Other profiles taken horizontally at the vertical positions of almost ± 130 nm, from the image centers give similar results.

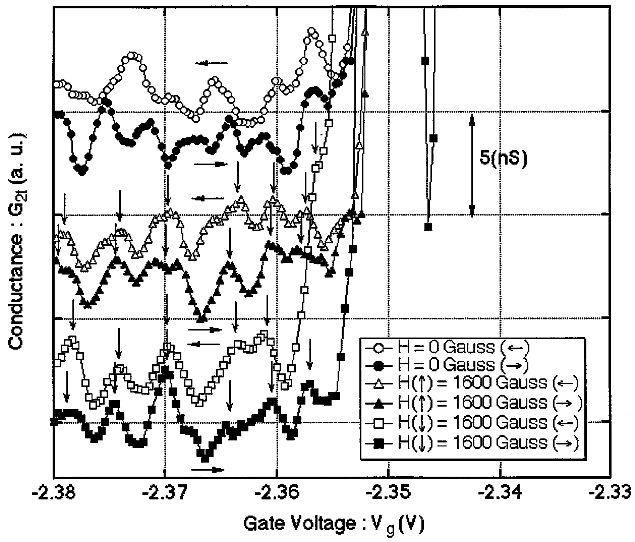

FIG. 3. Typical two terminal conductances ($G_{2t}s$) against the gate voltage $V_g = V_{g11}$ without and with magnetic field application. The gate voltage V_{g7} of the opposite gate was fixed to create the depletion layer which is enough to contact to the one surrounding the Ni dot.

In order to deduce Coulomb gap values unambiguously in Fig. 4, several sets of parallel tangent lines to the large $|V|$ regions of the I-V traces are written (thin lines in the figure) and the cross points with the voltage axis were determined as usual. There are then clear differences between the Coulomb gaps before and after the field application: The Coulomb gap at zero field of 8–9 mV likely decreases to about a half (5–6 mV) by applying the fields of -5000 G s (downward) or $+5000$ G s (upward). Those results suggest that the Coulomb gap likely reduces to about a half as sufficient strength fields are applied. Since also the gap is roughly related to the effective "dot" size, the gap reduction is considered to mean an effective expansion of the dot size.

Let us have some quantitative discussion here. We can assume $E_c = e^2/8\pi\varepsilon_0 a$ as a charging energy for a metal fine particle of radius a. If the features mentioned above are those of Coulomb blockade effects, the oscillation period in gate voltage ΔV_g and the Coulomb gap $V_{\rm gap}$ are represented as $\Delta V_g = e/\alpha C$ and $V_{\rm gap} = e/2C$, respectively, where C is a total capacitance of the dot and equals $4\pi\varepsilon_0 a$, and α is a parameter related to the capacitance between the dot and the gate. If we adopt the values $\Delta V_g \sim 4$ mV and $V_{\rm gap} \sim 4$ mV for the case of after the field application, they give the same $a \sim 180$ nm when $\alpha = 2$. As a result, the dot diameters of 180 and 360 nm are obtained for the cases of before and after the field application, respectively. Those values are somewhat larger than the expected structural sizes of >50 and >100 nm, respectively, although realistic values are not accurately estimated at present. These discrepancies seem, however, within the allowance from the approximations in the equations used.

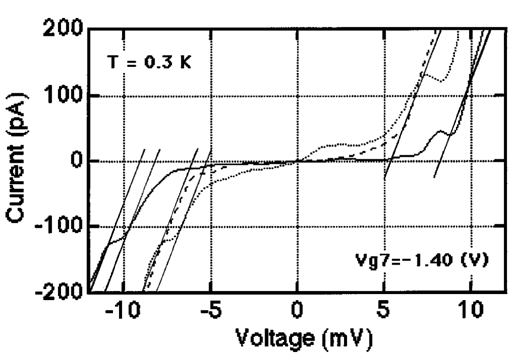

FIG. 4. Field-dependent I-V characteristics of the Ni-dot structure for $V_{g11} = -2.07$ (V). Solid lines are those without magnetic field. Dotted and dashed lines are the cases of $+5000$ G s (upward) and -5000 G s (downward) applications, respectively.

Based on the results of MFM analysis and low temperature transports, we can now propose a transport model for our Ni-dot structure embedded in the HEMT based quantum wire. Before the field application, there seem to exist two domains in the dot. If we assume the domain wall as a "resistive barrier," the dot could be regarded as two subdots divided by the "barrier" having an opposite magnetization direction. In the problem of electron transport through the dot, therefore, we should consider the following two typical cases as for barrier/current direction: In the case as shown in Fig. 5(a), electrons with down (majority) -spin pass through the series subdots by crossing (or tunneling) the barrier, since down-spin electrons have a higher density of states (DOS) at the Fermi level of the Ni dot. Another case is that the barrier is parallel to the current direction [Fig. 5(b)]. In this case, two subcases of barrier /sample surface alignment [the barrier is parallel or perpendicular—Fig. 5(b)—to the surface] could appear and also mainly down-spin electrons pass through both of the subdots simultaneously. In the case of oblique barrier alignment, parallel but unbalanced conduction through the two subdots, depending on the obliquity, would occur.

After the application of enough fields, however, MFM analysis indicated the disappearance of the domain wall, i.e., the "barrier" in the dot. The full dot is then realized (not shown), and the dot size becomes almost twice as large as that before the field application. This size change should be the main origin for the Coulomb gap narrowing observed in Fig. 4, although identical gap value is not attained against the reversal of the field direction. Besides the size change, a simpler transport path has to be realized in this case, which could be responsible for the appearance of the clear Coulomb oscillation after the field application seen in Fig. 3. One important thing to be noted is that, in all the cases, spin-selective transport would occur due to the DOS imbalance in the Ni (sub-) dot(s) between up- and down-spin electrons. Unfortunately, this selectivity is not confirmed within this work. One possible method is to use spin-split edge states in 2DEG as an injector and a collector of spin-polarized electrons. This is the main

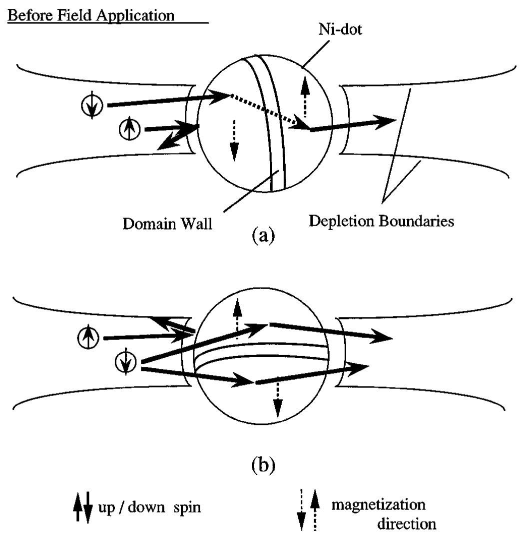

FIG. 5. Possible transport models for the Ni dot before the field application. Note that dashed arrows attached to the dot(s) indicate the directions of *magnetization*, while those attached to electrons (circles) indicate the directions of spin (up or down).

reason that we adopted the high mobility 2DEG as a base material, although it still plays only a role of leads to the dot.

We have investigated ferromagnetic (Ni) dot structure embedded in HEMT-based quantum wires. Preliminary MFM observation suggests domain wall formation inside the dot before the field application. It then disappeared after the field application, forming a single domain in the entire dot. In low temperature transport measurements, we observed two distinct field-dependent features: a clear appearance of Coulomb oscillations and a narrowing of Coulomb gap after the appropriate magnetic field application. On the basis of MFM and transport results, we propose a transport model, in which the domain wall inside the dot plays a role as a resistive barrier. In other words, the domain wall splitted the original dot into the two subdots and then it changed drastically the effective "dot" size and the Coulomb blockade-related transport features.

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*Email address: shooji@jaist.ac.jp

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