Conductance steps observed in adiabatic ferromagnetic quantum-dot point contacts made in the $In_{0.5}Ga_{0.5}As/In_{0.5}Al_{0.5}As$ heterojunction

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Clear $\sim 0.5(2e^2/h)$ conductance steps are observed in a quantum point contact (QPC) with a ferromagnetic (Ni) dot embedded in its center, which is made on the surface of a $In_{0.5}Ga_{0.5}As/In_{0.5}Al_{0.5}As$ heterojunction. Those steps are observed under no applied magnetic field. The interface between the embedded Ni dot and the heterojunction seems to become Ni-$In_{0.5}Ga_{0.5}As$ alloy due to the strong reactivity of Ni forming an adiabatic semiconductor-metal-semiconductor transient region, which has Ohmic and possibly ferromagnetic natures. The main origin of the $\sim 0.5(2e^2/h)$ steps thus could be a quasiballistic transport through the Ni dot and/or the transient region, which acts as a local spin filter at the QPC center.

I. INTRODUCTION

Fractional quantized steps, $f(2e^2/h)(0<f<1)$, in semiconductor quantum point contact (QPC) have so far been investigated and discussed from various points of view: For example, Wharam *et al.*[1] has already reported spin-split steps under a large parallel magnetic field. After finding half plateaus appearance depending on source-drain voltage by Patel *et al.*,[2] Thomas *et al.*[3] have pointed out that anomalous structure at $0.7(2e^2/h)$ evolved into $0.5(2e^2/h)$ step by increasing applied parallel magnetic field. Also recently, similar anomalies including $0.2(2e^2/h)$ step have been reported for a variety of structures and/or materials under zero magnetic field; Tscheuschner and Wieck[4] have found $0.5(2e^2/h)$ structure for zero bias in in-plane gate GaAs/AlGaAs transistors. Kane *et al.*[5] have observed $0.7(2e^2/h)$ steps in clean quantum wires of enhancement-mode field-effect transistor structures. Ramvall *et al.*[6] have reported $0.7(2e^2/h)$ and $0.2(2e^2/h)$ steps and their evolution into $0.5(2e^2/h)$ by applying strong parallel magnetic field in heterostructurely defined $Ga_{0.25}In_{0.75}As/InP$ quantum wire. As for the origins of the fractional steps with zero field, which are now believed to be universal, there have been a lot of theoretical contributions; one possible explanation has been given by the Luttinger-Tomonaga (LT) theory[7] for locally interacting ideal one-dimensional (1D) electrons. The theory claims that the conductance is renormalized as $K(2e^2/h)$ by the presence of mutual interactions, where the interaction-dependent parameter's are $K<1$ and $K>1$ for repulsive and attractive interactions, respectively. It seems, however, to have some difficulties such as finite-size and boundary effects to apply to the observed conductance anomalies. An alternative origin is a kind of spin effect suggested by Thomas *et al.*[3] There have also been reported some theoretical results[8,9] treating the problem from this point of view. Especially, Wang and Berggren[9] have shown the possibility of spontaneous local spin polarization occurring at the QPC center even under zero magnetic field.

Very recently, we have made a quantum wire with an embedded Ni dot in a $GaAs/In_{0.2}Ga_{0.8}As/AlGaAs$ heterojunction and observed Coulomb blockade effects modified by domain-wall dynamics in the Ni dot.[10] In the heterojunction, there have been thin Schottky barriers surrounding the Ni dot, through which electrons could pass by tunneling. However, spin-selective transport through the Ni dot has not been confirmed explicitly. In this paper, we report possible spin-selective transport in a QPC with an embedded Ni dot, which this time makes an adiabatic Ohmic contact to the $In_{0.5}Ga_{0.5}As/In_{0.5}Al_{0.5}As$ heterojunction. Moreover, the results described here might have an important meaning relating to the above-mentioned discussion about the origins of the fractional steps. The reason is that our structure could be regarded as a QPC which has a localized spin-polarized region not spontaneously but ''artificially.'' That is, the small Ni-$In_{0.5}Ga_{0.5}As$ alloy region which has Ohmic as well as possibly ferromagnetic natures is produced at the QPC center. In fact, two-terminal conductance exhibited clear $\sim 0.5(2e^2/h)$ steps for various pairs of gate voltages which made possible to sweep a constriction in the vicinity of the Ni dot.

In the following sections, after describing the sample structure briefly, the results from low-temperature transport measurements are addressed. We then discuss the possible structural and electromagnetic properties of the Ni-dot/$In_{0.5}Ga_{0.5}As$ channel interface on the basis of former and recent experiments for those material systems. Finally, several possible origins for the $0.5(2e^2/h)$ steps including the gate voltage sensing of the Ni-dot density of states are proposed.

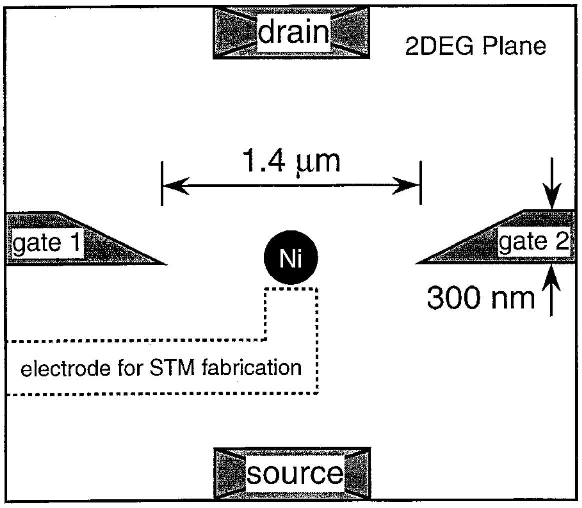

FIG. 1. Schematic top view of our sample. Dashed line shows a dummy Schottky electrode which was used by grounding only when the STM fabrication was done. Small positive voltage was applied to the electrode in low-temperature measurement.

II. SAMPLE STRUCTURE AND PREPARATION

In Fig. 1, a simple illustration of the top view of our sample is shown. This structure was fabricated by successively utilizing conventional electron beam (EB) lithography and two-step surface modifications using scanning tunneling microscope (STM) tips. The base heterojunction of $In_{0.5}Ga_{0.5}As/In_{0.5}Al_{0.5}As$ was grown on a semi-insulating GaAs substrate via $In_xAl_{1-x}As$ step buffer layers by molecular beam epitaxy (MBE).[11] Layer sequence from the top was as follows: 10-nm cap-$In_{0.5}Ga_{0.5}As$, 40-nm Si-doped $In_{0.5}Al_{0.5}As$, 20-nm undoped $In_{0.5}Al_{0.5}As$ spacer, 30-nm undoped $In_{0.5}Ga_{0.5}As$ channel, 820-nm $In_xAl_{1-x}As$ ($x=0-0.5$) step graded buffer and 30-nm GaAs buffer. Thus the two-dimensional electron gas (2DEG) plane is located 70 nm below the surface. The sheet electron density (n_S) and mobility (μ_e) of the wafer used were $1.31\times 10^{12}\,(/\mathrm{cm}^2)$ and 48 300 ($\mathrm{cm}^2/\mathrm{V\,sec}$), respectively at 77 K.

Split gate of width 1.4 μm and length 0.3 μm as well as a dummy electrode for STM fabrication were defined on a Hall bar using EB lithography and liftoff process. Embedding of Ni cluster was carried out by doing two-step STM process utilizing the dummy electrode; the first step is hole fabrication by tungsten (W) bare tip and the second is Ni cluster evaporation from the Ni-coated W tip both by applying single voltage pulse between the tip and the heterojunction surface at the tunnel conditions. Details of the STM fabrication process has already been reported elsewhere.[12] Typical hole size was 200–300 nm upper diameter and $\sim$100 nm depth and a diameter of the Ni-cluster was 100–200 nm. It is noted here that, as easily expected, a local heating is inevitably accompanied by the STM fabrication adopted here, since an applied electric field as high as $>\sim 10\,\mathrm{V}/5\,\mathrm{\AA}=20\,\mathrm{GV/m}$ is used in the electrical evaporation. Deposited Ni cluster thus immediately reacts with $In_{0.5}Ga_{0.5}As$ making some alloys and hence an electric contact to the $In_{0.5}Ga_{0.5}As$ channel almost in the perfect Ohmic regime is realized.

III. RESULTS OF LOW-TEMPERATURE TRANSPORTS

Conductance measurements were carried out by constant voltage (<100 μV) ac lock-in technique at 0.3 K. Prior to measuring the ferromagnetic dot QPC's, we have first checked the properties of normal QPC, which has been simultaneously made on the same wafer with no embedded dot. The gate gap width and the length of the normal QPC was 0.5 and 0.3 μm, respectively. Figure 2(a) shows two terminal conductance of the normal QPC, where no anomalies or fractional steps were observed. Since the mean free path of this wafer was almost 1 μm at 0.3 K, the fact that only the first and second steps are able to be observed is reasonable. This result is similar to that of Schapers *et al.*[13] In contrast, QPC with an embedded Ni dot exhibits clear conductance steps at $\sim 0.5(2e^2/h)$ [accurately they are close rather to $0.4(2e^2/h)$] as seen in Fig. 2(b). In this figure, parameter is a fixed voltage (V_{g1}) applied to one side QPC gate (gate 1) and gate voltage (V_{g2}) applied to the opposite side (gate 2) was swept. Thus we scanned the ''constriction'' center in the vicinity of the Ni dot along the line perpendicular to the current direction.

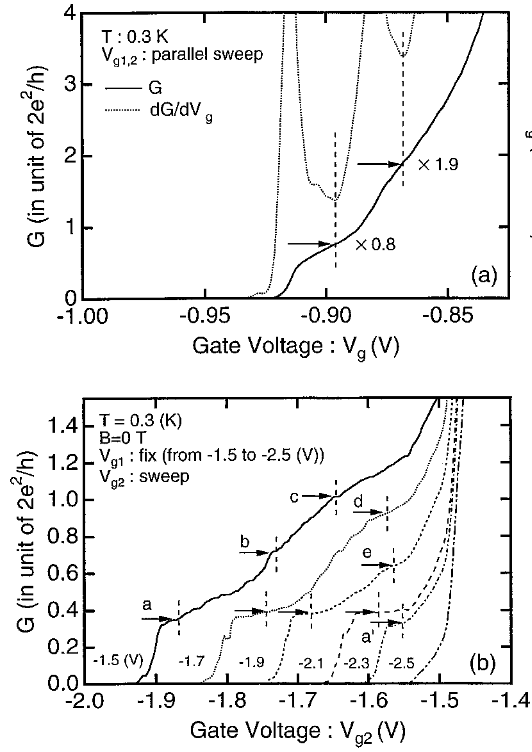

FIG. 2. Two terminal conductances of (a) normal (without ferromagnetic dot) and (b) ferromagnetic dot QPC's. Note here that the gap width is different between the normal (0.5 μm) and ferromagnetic dot (1.4 μm) QPC's.

In Fig. 3(a), our quantitative speculation about the lateral sweep of the constriction is shown by taking the structural and electrical asymmetries of the gate electrodes into account. In Figs. 3(a) and (b), also the expected feature of unreacted Ni dot and transition layer is illustrated schematically [Fig. 3(b) is a cross-sectional view]. From comparison of Fig. 3(a) with Fig. 2(b), the conductance trace corresponding to $V_{g1}=-1.9\,(\mathrm{V})$ seems to have its constriction center on that of the Ni dot. It is also noteworthy that the step heights for $V_{g1}=-1.5$ and -2.5 (V) (a and a') becomes slightly lower than those of other V_{g1} cases. This is probably because the constriction locates at the edge of the transition region where the motion of passing electrons is less affected

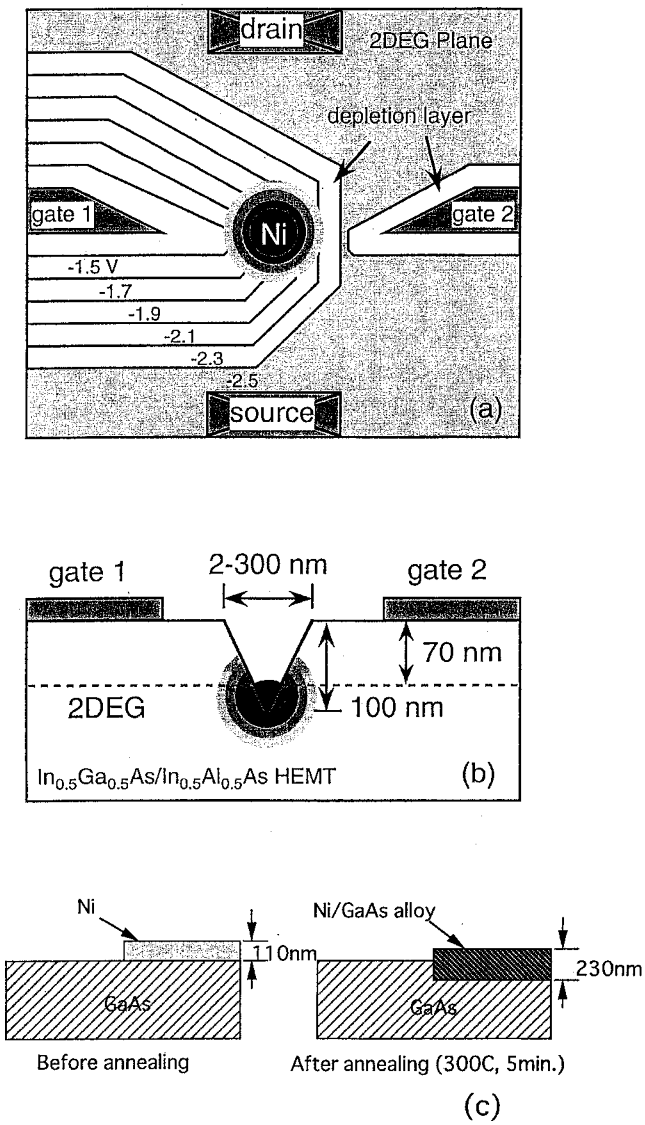

FIG. 3. Schematic (a) top view and (b) cross-sectional pictures of expected depletion layer expanding and Ni dot transition layer, illustrated by taking structural and electrical asymmetries of the gates into account. (c) Illustration of reaction process in thin Ni film/GaAs system after annealing from Ref. 15.

than in the dot center. Since the deviation of the constriction from the center is almost 200 nm for the two $V_{g1}s$, effective diameter of the Ni dot including the transition layer becomes almost 500 nm. It is also noted in Fig. 2(b) that conductance kinks corresponding to $\sim 0.75(2e^2/h)$ (b and e) and $1.0(2e^2/h)$ (c and d) were seen in the traces for $V_{g1} < -2.1$ (V). The origin of those steps, especially the one for $\sim 0.75(2e^2/h)$, is an open question at present.

IV. DISCUSSION

In order to explore the origin of the $\sim 0.5(2e^2/h)$ steps described above, we should discuss electrical and metallurgical structures of the interface transition region between the Ni dot and the $In_{0.5}Ga_{0.5}As$ channel. We first describe the speculation about the electrical properties of the interface. Kajiyama *et al.*[14] have given an empirical equation of $In_xGa_{1-x}As$ Schottky barrier height ϕ_{bn} against Au (curve *a*

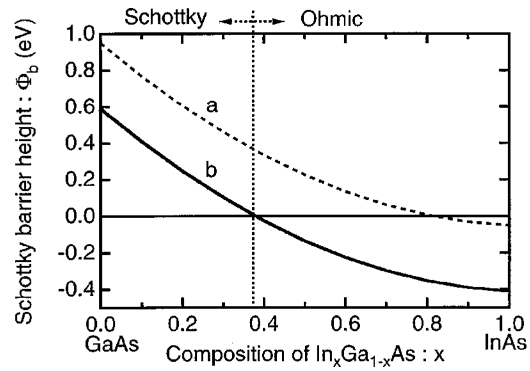

FIG. 4. Schottky barrier height dependency of Ni upon In content x, of $In_xGa_{1-x}As$, deduced from the empirical relation for Au by Kajiyama *et al.* (Ref. 14).

in Fig. 4). If the work function difference (0.35 eV) between Ni and Au is considered, we can deduce $\phi_{bn}(x)$ for Ni as shown in Fig. 4, curve *b*. From this curve, we can conclude that $\phi_{bn}(x) < 0$ for $x > 0.4$, which suggests an almost Ohmic property at the interface, even when no heat treatment is carried out. In our case, there should be some local heating when the Ni clusters are evaporated as described earlier. The full Ohmic nature could thus be guaranteed in our sample, but the metallurgical structure (what kind of transition or alloy layers are likely produced by the heating) seems rather more important to discuss the magnetic and/or spin-related transport properties. Note here that this reaction process is fairly different from a simple diffusion from surface as seen in thermal process of unreacted impurity metal, which might produce distributed impurity clusters (dots) in semiconductors.

Since there have been almost no works which deal with dynamics of (heat-treated) interface metallurgical structure between the two materials, we start our discussions from the pioneering work by Ogawa[15] concluding strong reactivity of Ni with GaAs. He has clarified interface alloy structure produced in thermally annealed Ni film (110 nm thick)/GaAs systems in detail, which varies depending on the anneal temperature, T_a; although there was no alloy layer when $T_a < 200\,°C$, monocrystalline hexagonal Ni_2GaAs and hexagonal NiAs+β-NiGa appeared as reaction products for $400\,°C > T_a > 200\,°C$ and $T_a > 400\,°C$, respectively. He also pointed out that the total alloy layer after the full reaction reaches to 230 nm. Figure 3(c) is a schematic illustration of the reaction of Ni thin film/GaAs system by heat treatment,[15] on the basis of which Fig. 3(b) was drawn.

Based on those results, we can speculate that Ni and Ni-related transition (reacted) layer, which is composed of $Ni_2In_{0.5}Ga_{0.5}As$ or NiAs, NiIn, and NiGa, could exist depending on the heated temperature in our case and they expand to about ~500 nm diameter at the QPC center. This diameter almost agrees with the value estimated from the transport measurement. The 2DEG's probably pass the region by adiabatically varying their Fermi wavelength. Although the magnetic properties of the Ni-related compounds are not known (related bulk materials such as Ni_3Ga usually exhibits paramagnetism), small structures of them such as films or clusters might have a ferromagnetic nature due to the size effects. These transition layers (together with the unreacted Ni dot) could then play a role of spin selector for the passing electrons. This picture simply explains the appearance of the $\sim 0.5(2e^2/h)$ steps observed in the constriction sweep measurement.

Very recently, Garcia *et al.*[16] and Ono *et al.*[17] have reported similar conductance quantization in thin Ni constriction at room temperature in the samples of very simple structures. Those results might observe the same phenomenon as ours reported in this letter. However, their samples seem to have sufficiently thin constriction compared with the electron mean free path $l_{e,\mathrm{Ni}}$ in Ni. In contrast, the transition region in our sample has too large diameter over the value $l_{e,Ni}$. But, we can point out that the region is not fully metallic and that only the restricted part (for example, one kind alloy such as NiAs) of the region might be ferromagnetic. In such a case, the mean free path could be larger than the size of the restricted part.

Finally we describe the speculation that gate voltage sweep is sensing density of states (DOS) at the Ni dot. This may be probable when the dot and/or the transient region has multiple domains. But the realistic microscopic structure of the transient region is still an open question and hence more detailed discussion seems not appropriate at present.

V. SUMMARY

In summary, we have made $In_{0.5}Ga_{0.5}As/In_{0.5}Al_{0.5}As$ QPC structure with a Ni dot embedded in its center. Low-temperature two-terminal conductance exhibited clear $\sim 0.5(2e^2/h)$ steps under zero magnetic field. Gate sweep experiment suggests the diameter of the interacting region of $\sim$500 nm, which almost agrees well with the value estimated from the interface metallurgical reactions between Ni and GaAs. The region consisted of Ni dot and transition alloy layer, which could have ferromagnetic nature and reveal artificial spin polarization, should explain the $\sim 0.5(2e^2/h)$ steps appeared in our transport measurements. In this sense, our result strongly support the spin-related origin for the fractional steps so far observed in a variety of clean OPC's, although there remain possibilities of some other origins such as gate voltage sensing of DOS at the Ni dot.

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