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Observation of Negative Differential Resistance in Double Barrier Tunneling Junction

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1. Introduction

Electron transport in nanomechanical systems has attracted much attention[1-3]. In nanometer size double barrier tunneling junction (DBTJ) formed a center island and two electrodes, the electron transport is restrained due to Coulomb Blockade (CB) and is modulated by the mechanical oscillation, since the tunneling resistance strongly depends on a tunneling width. Recently, Gorelik *et al.* have proposed a novel electron transport mechanism; electron shuttle mechanism[1]. In this electron shuttle, the electrons transport from one electrode to the other in accordance with the mechanical vibration of the center island, if the center island can vibrate between electrodes. Therefore it is considered that the electron shuttle mechanism should involve the nanomechanical oscillator in the DBTJ such as quantum-bell oscillator[3] and soft organic molecular links between a center island and electrodes.

Recently, we have succeeded in observing the CB-based displacement current staircase in the DBTJs with scanning vibrating probe[4,5]. In this measurement, the colloidal gold particles on the top of the scanning probe are vibrated against the substrate by using a piezo scanner of the scanning probe. The displacement current due to the change in the number of electrons on colloidal gold particles in accordance with the vibration can be measured together with the tunneling current through the colloidal gold particles by using a 2-phase lock-in amplifier. The displacement current staircase indicates that the number of electrons on particles has been found to alternate periodically with the mechanical oscillation.

In this paper, we demonstrate an anomalous negative differential resistance (NDR) in DBTJs with the scanning vibrating probe, and discuss the mechanism of this anomalous NDR by introducing a resonant electron-shuttle model.

2. Experiments

Figure 1 shows a schematic diagram of the sample in this paper. To form a self-assembled dithiol-monolayer on gold substrate, an atomically flat gold substrate on cleaved mica is immersed in a solution of 1,6-hexandithiol (HS-(CH_2)6-SH, C_6S_2) in isopropanol. Then this sample is immersed in a solution of colloidal gold particles in toluene solution in order to bond gold colloids and form colloidal gold particle-insulator-gold structure. The average diameter of colloidal gold particle is 8 nm. With this sample, we make DBTJs consisting of tungsten scanning probe / vacuum / colloidal gold particles / C_6S_2 / gold substrate.

The tunneling and the displacement currents-voltage curves are simultaneously measured with vibrating probe by using the 2-phase lock-in amplifier[4]. The average tunneling current is also measured by using a d.c. voltmeter. The probe is vibrated at the frequency of 2632 Hz and the amplitude of 5 nm_{p-p}. All measurement is made at ultra high vacuum ($< 1 \times 10^{-9}$ Torr) and at temperature of 72 K.

3. Results and Discussions

Figure 2 (a) and (b) show the typical experimental

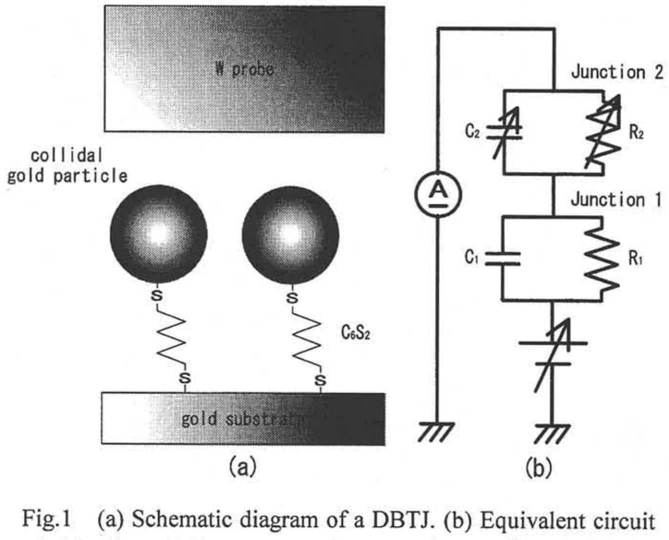

Fig.1 (a) Schematic diagram of a DBTJ. (b) Equivalent circuit of (a). C_1 and R_1 are capacitance and tunneling resistance between a gold particle and gold substrate, and C_2 and R_2 are between a gold particle and STM probe, respectively. Because of probe vibration, C_2 and R_2 are variable.

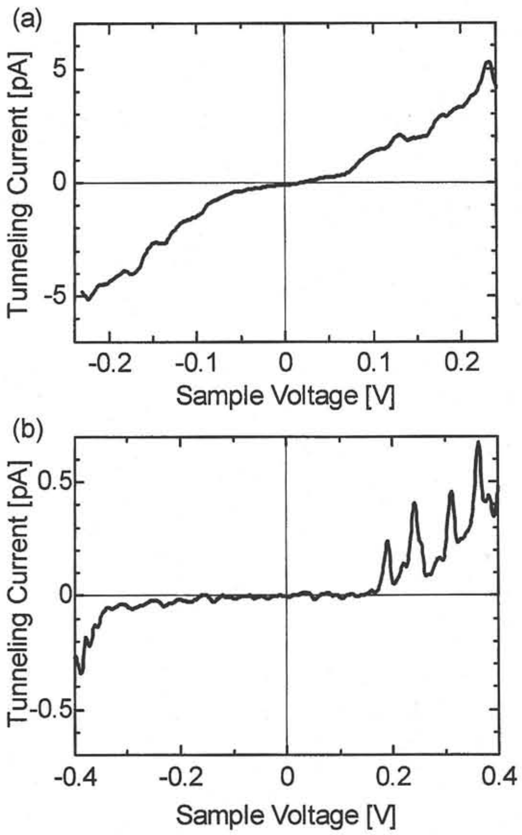

Fig.2 (a) Experimental result of tunneling current – sample bias voltage curve. We find Coulomb staircase about 90 and 170 mV. (b) Tunneling current – sample bias voltage curve with probe slightly apart from colloidal gold particle compared to that in (a). In Fig. 2 (b), anomalous NDRs are clearly observed.

results of the tunneling current-the sample voltage curves. In Fig 2 (a), Coulomb staircase is observed at the sample voltages of about 90 and 170 mV. It should be noted that the displacement current-voltage curve was simultaneously measured with the tunneling current-voltage curve and that the displacement current tends to increase at the beginning of the plateau (not shown). The average distance between the sample and the probe can be controlled by changing the piezo voltage of the z-axis piezo scanner, which control the distance between the probe and the sample. Figure 2 (b) also shows the tunneling current–the sample voltage curve at slightly large the average distance compared to that in Fig. 2 (a). In Fig. 2 (b), anomalous NDRs are clearly observed. Peaks are observed at the sample voltages of 189, 241, 312, and 363 mV with the peak-valley ratios of 4.4, 4.7, 2.0 and 1.6, respectively. These anomalous NDRs should not due to the resonant tunneling but due to Coulomb blockade, since the center particles and electrodes are made of gold; the diameter of gold particles are too large to occur resonant tunneling. It should be noted that the NDRs should have not been observed in the static DBTJs.

We think some resonant phenomenon occurs at the current peaks. Here we briefly demonstrate a "resonant electron shuttle model" as follows: The center particles tend to vibrate at a proper oscillation frequency, since the colloidal gold particles are connected to the gold substrate via the elastic C_6S_2. When the electron shuttle occurs, the center particles tend to vibrate due to the change in Coulomb force during the one by one electron transport. If this shuttling frequency meets the proper oscillation frequency, the vibration amplitude of the center particle should increase. At this resonant frequency, the electron shuttling should be promoted. It should be noted that the tunneling current-voltage curve is measured with vibrating the probe. The electron shuttle frequency can be modulated by this probe vibration, since the tunneling rate depends on the tunneling resistance. As a consequence, the NDR should have clearly observed in this experiment.

4. Conclusions

We find the anomalous NDRs in DBTJ consisting of the tungsten probe / vacuum / colloidal gold particles / C_6S_2 / gold substrate. To explain this NDR, we proposed "resonant electron shuttle model".

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