Coulomb Blockade Electron Shuttle with Chemisorbed Au Nanodot

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1. Introduction

Nanomechanical Coulomb blockade electron shuttle devices have attracted considerable attention due to the interesting phenomena that they exhibit and are expected to become emerging devices in the field of nanoelectronics\cite{1}. We have demonstrated the Coulomb blockade electron shuttle phenomena in nanometer-sized double-barrier tunneling structures with scanning vibrating probe\cite{2, 3}, and have observed the Coulomb blockade electron shuttle phenomena in a cantilever-type nanomechanical electron shuttle device that consists of scanning tunneling microscopy (STM) probe/vacuum/octanethiol (CH\textsubscript{3}(CH\textsubscript{2})\textsubscript{7}SH, C\textsubscript{8}S)-protected Au nanodots (C\textsubscript{8}S-Au nanodots)/Au-Ti-coated SiO\textsubscript{2} cantilever/vacuum/Si back electrode under application of the RF signal with the frequency of $f$=86 MHz\cite{4}. In our previous results, C\textsubscript{8}S-Au nanodots as the Coulomb islands were physically adsorbed on Au-Ti-coated SiO\textsubscript{2} cantilever. It is well-known that the electron tunneling phenomena strongly depend on the tunneling distance. Essentially, nanomechanical Coulomb blockade electron shuttle devices have mechanical perturbations in their own driving mechanism, therefore, excessive mechanical oscillation results in an excessive increment of the tunneling probability and co-tunneling phenomena. These conditions are not suitable for observation of Coulomb blockade electron shuttle phenomena. Hence, a strong anchoring between the Coulomb islands and the cantilever is important to observe the stable tunneling current due to the electron shuttle phenomena. Hers, we demonstrate electrons transport through a chemisorbed Au nanodot under a nanomechanical vibration of an Au nanodot on cantilever that consists of STM probe/vacuum/chemisorbed Au nanodot/cantilever.

2. Experiments

The detailed description of the Au-Ti-coated SiO\textsubscript{2} cantilever fabrication technique on the Si substrate has been provided in our previous paper\cite{4}. The Au-Ti-coated SiO\textsubscript{2} cantilever was immersed in a solution of C\textsubscript{8}S in ethanol for 12 h to form C\textsubscript{8}S self-assembled monolayers (SAMs). After immersion, the cantilever was rinsed with ethanol and dried in nitrogen gas. Immediately after forming C\textsubscript{8}S SAMs, the cantilever was immersed in a solution of decanedithiol (HS(CH\textsubscript{2})\textsubscript{10}SH, C\textsubscript{10}S\textsubscript{2}) in ethanol for 7 h in order to partially substitute C\textsubscript{10}S\textsubscript{2} for C\textsubscript{8}S. Then, the cantilever was immersed in a solution of C\textsubscript{8}S-Au nanodots in chloroform for 7 h. A part of C\textsubscript{8}S molecules surrounding Au cores was expected to substitute with C\textsubscript{10}S\textsubscript{2} molecules on the cantilever, therefore, C\textsubscript{8}S-Au nanodots were anchored by C\textsubscript{10}S\textsubscript{2} molecules. Finally, the cantilever was rinsed in chloroform in order to remove physisorbed Au nanodots from the surface of Au-Ti coated SiO\textsubscript{2} cantilever. The diameter of the Au core was estimated to be 3.4±0.4 nm from the transmission electron microscope image.

Figure 1 shows the experimental setup of a cantilever-type nanomechanical Coulomb blockade electron shuttle device that consists of STM probe/vacuum/C\textsubscript{8}S protecting molecule/Au core/C\textsubscript{10}S\textsubscript{2} molecule/Au-Ti-coated SiO\textsubscript{2} cantilever/vacuum/Si back electrode. The three terminals of the STM probe, Au-Ti-coated SiO\textsubscript{2} cantilever, and Si back electrode were used for the observation of the probe tunneling current under the resonant vibration of the cantilever. The cantilever was oscillated by the application of an RF signal (frequency: $f$) and a dc substrate voltage $V_{\text{sub}}$ to the Si back electrode. The probe tunneling current between the STM probe and the Au-Ti-coated SiO\textsubscript{2} cantilever $I$ was measured.

Fig. 1. The experimental setup of a cantilever-type nanomechanical Coulomb blockade electron shuttle device that consists of STM probe/vacuum/C\textsubscript{8}S protecting molecule/Au core/C\textsubscript{10}S\textsubscript{2} molecule/Au-Ti-coated SiO\textsubscript{2} cantilever. The cantilever is oscillated by the application of an RF signal and $V_{\text{sub}}$ to the Si back electrode below the cantilever. The probe tunneling current between the STM probe and the Au-Ti-coated SiO\textsubscript{2} cantilever is measured by changing the distance between the probe and the cantilever at $V_{S}$. 
The application of an RF signal from the Si back electrode changes the distance between the probe and the cantilever. Measurements were carried out at 100 K.

Shuttle phenomena with a contribution of the integral applied and a cantilever oscillated at an amplitude of 0.28 nm and an eigenfrequency of 86.0 MHz. For the condition without the cantilever oscillation, the set point probe tunneling current was 5 pA, and the measurements were carried out at 100 K.

3. Results and Discussions

Figure 2 shows the experimental result for the relationship between normalized tunneling current I/ef and the distance between the probe and the cantilever d under the application of an RF signal from the Si back electrode in the cantilever-type nanomechanical Coulomb blockade shuttle devices with chemisorbed Au nanodots. In Fig. 2, the sample and substrate voltages of V_S=1.2 V were applied and a cantilever oscillated at an amplitude of 0.28 nm and an eigenfrequency of 86.0 MHz under the application of an RF power of 6 dBm to the Si back electrode [5]. We confirmed that the number of electrons on the Au core was -1 at the sample voltage of V_S=1.2 V from the tunneling current-sample voltage characteristic under the condition without the cantilever oscillation. Before measurement, the set point probe tunneling current was 5 pA. Then, the feedback circuit was turned off, and the probe approached the cantilever. In Fig. 2, several plateaus and kinks are observed, and the probe tunneling current at them are an integral multiple of 2e=27.6 pA. These phenomena were also observed in the cantilever-type nanomechanical Coulomb blockade electron shuttle devices with physisorbed Au nanodots [4]. Therefore, the plateau at the tunneling current of 2ef corresponds to one by one electron and hole transport per cycle of the oscillation of the Coulomb island, and the other plateaus whose value are an integral multiple of 2ef correspond to the single-electron shuttle phenomena with a contribution of the integral number of Au nanodots.

Furthermore, the other plateau with the tunneling current of ef=13.8 pA is also observed at the distance from 0.02 to 0.37 nm. Despite the set point current of 5 pA, the initial probe tunneling current increases to 13.8 pA and keeps the same value in the range of 0.37-0.02=0.35 nm. Similar plateaus also have been observed in the result of the tunneling current-distance characteristic with the physisorbed Au nanodots, however, the width of that plateau has been 0.07 nm and approximately is one-fifth part of that in chemisorbed Au nanodots. As discussed in the previous report, the magnitude of tunneling current at plateaus being an integral multiple of 2ef derives from the quantized number of Au nanodots which contributes to Coulomb blockade electron shuttle operation and makes parallel current paths from the STM probe to Au-Ti coated SiO2 cantilever. In the case of physisorbed Au nanodots, the Au nanodots were embedded in the Au-Ti coated cantilever by employing the Langmuir-Blodgett technique, therefore, a number of Au nanodots should be spread on all area of the Au-Ti coated cantilever with close-packed structure. Hence, the number of Au nanodots contributes to Coulomb blockade electron shuttle transport increased with the change in the distance of less than 0.1 nm.

On the contrary, in the case of chemisorbed Au nanodots, the Au nanodots were chemically anchored by C10S2 which partially exist on the Au-Ti coated cantilever, the density of Au nanodots should be smaller than that in the case of physisorbed Au nanodots. In this condition, the number of Au nanodots which contribute to Coulomb blockade electron shuttle transport scarcely changes because of their sparse density. Consequently, as shown in Fig. 2, the plateau width in chemisorbed Au nanodots is 0.35 nm and 5 times larger than that in physisorbed Au nanodots.

4. Conclusions

We have demonstrated Coulomb blockade electrons shuttle phenomena through a chemisorbed Au nanodot under a nanomechanical vibration of an Au nanodot on cantilever that consists of STM probe/vacuum/C8S protecting molecule/Au core/C10S2 molecule/cantilever. In the probe tunneling current-distance characteristics, a constant probe current of 2ef has been observed as a plateau region with an eigenfrequency of the cantilever of 86 MHz. Moreover, in spite of the change in the distance of 0.35 nm, a constant tunneling current ef due to electron shuttle has been observed. Coulomb blockade electron shuttle devices with chemisorbed Au nanodot are suitable for stable operation such as a standard current device.

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References