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Single Electron Tunneling Observed in a 1D Tunnel Junction Array at Room Temperature

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A 1D tunnel junction array has been constructed using liquid crystal molecules. The behavior of this junction can be described in terms of single electron solitons. By voltage sourcing this 1D array, it shows the DC i-v curve characteristic of single-electron tunneling. Since the capacitance is so small (~10^{-19}F), the Coulomb blockade can be observed even at room temperature, with a value of approximately 150 mV.

It is very interesting that although liquid crystal (LC) is an insulator, and consequently electrons cannot transfer from one molecule to another in the bulk state, electrons can transfer from one molecule to another via metal islands. When a molecule resides between the scanning tunneling microscope (STM) tip and a metal substrate, electrons can transfer from (to) the tip to (from) the substrate via this molecule. It has been confirmed that this situation is also valid when LC molecules are on metal islands. When metal islands are formed such that neighboring islands are separated by a distance comparable to LC molecular size, it is preferable for electrons to move not directly from one island to another, but via an LC molecule.

2D arrays were studied very early in 1960s, since it was easy to make disordered 2D systems. But they observed Coulomb blockade only at 4K. A 1D tunnel junction array has been studied by Geeligs, Delsing and Kuzmin [1-4] They estimate their electrodes capacitance as 3 x 10^{-16}F and Averin and Likharev estimate the stray capacitance of electrodes as 5 x 10^{-17}F. Again their capacitance was large, so that they have to reduce the temperature down to 4K.

Our previous study shows that the liquid crystal (LC) molecule acts as the central electrode in a double-tunneling junction. [5,6] It is straightforward to make the LC molecules act as electrodes in 1D array.

A mixture of Pt and Pd was deposited as islands on a quartz substrate using the DC-sputtering method.[9,10] The amount of the island is determined as follows:The sample is tilted during the deposition so that the density of islands vary across the plane of the substrate. The resistance was measured using the four terminal method. Island growth was stopped when the resistance across the islands was 7 x $10^7\Omega$ at one end of the sample surface, and the resistance of the other end was over the limit of the resistance meter (2 x $10^8\Omega$).

This resistance value across the surface was selected for the following reason. Since the LC molecule acts as the electrode, the electron should pass via molecules not directly from one island to the next island. The i-v characteristic is measured using a Scanning Tunneling Microscope (STM) (Nanoscope II) so that the STM tip acts as the outer-electrode. When the bias is applied, the tip immerses into the bulk LC. We believe that the tip pierces through LC molecules and stop piercing at the monolayer LC molecule. [11]

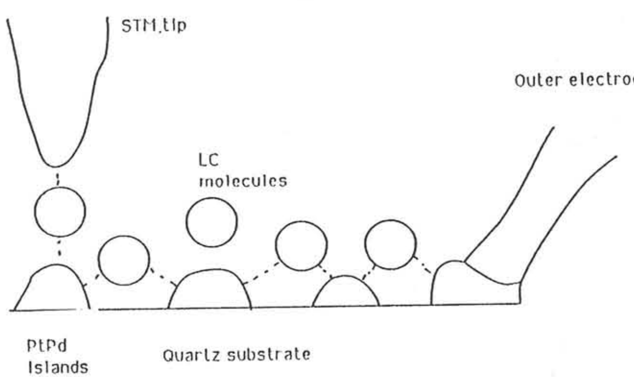

Fig.1 A schematic picture of the electronic circuit realized by molecule. PtPd islands were formed on a quartz substrate. LC molecules were put on this substrate and molecules occupy the position between islands.

The configuration near the edge electrode is STM tip - LC molecule - PtPd island. The STM bias voltage is set to 1V and set-current is 0.2 nA so that the tunneling resistance between STM tip and the island via a molecule is $5 \times 10^9 \Omega$. The resistance between one island and the neighboring island should be larger than $5 \times 10^9 \Omega$, unless the electron tunnel directly from one island to the next island. The sample area we used for our experiment is far from the area with resistance $7 \times 10^7 \Omega$.

A droplet of LC molecule (4'-n-heptyl-4-cyanobiphenyl, 7CB) was placed on these islands. Since the separation of islands is almost the same size as the molecules, where the size of the molecule is about 0.5 x 1.5 nm from nucleus to nucleus, we assume that the LC molecule resides between the islands and this forms the electro-circuit across the surface. Note that even if some islands would be large they do not affect the formation of the circuit since they simply form conduction sections.

The one edge of the 2D array of islands is connected to the outer- electrode and biased by voltage V. The STM tip which is held in the middle of the 2D array corresponds to the other outer-electrode. Since the tip apex plays an important role in our configuration we used a chemically etched PtIr wire. [12] This is the reason why we treat this circuit as a 1D array of islands, since the tip apex acts as a source of electrons which pass through the lowest resistance path towards another outer electrode. An operational-amplifier circuit with virtual grounded input terminals, connected to STM tip, in series with voltage source and sample, was used to measure the current.

The current across the 1D array vs. the voltage across the 1D array was obtained (Fig.2). Coulomb blockade is observed in the small voltage range.

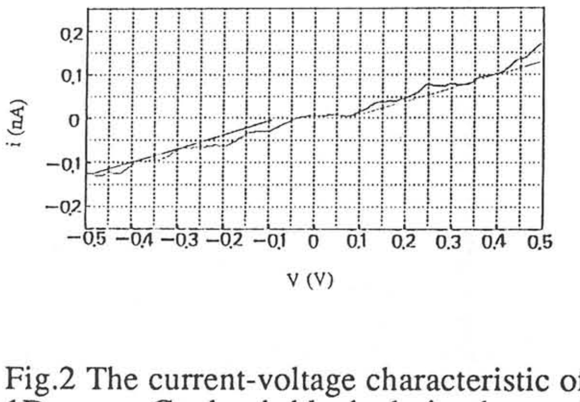

Fig.2 The current-voltage characteristic of 1D array. Coulomb blockade is observed and the first step in the i-v curve occurs at 150 mV. After bringing the tip to the tunnel regime (the bias voltage is 1V (sample positive) and set point current is 0.2 nA), the feedback was cut, the bias voltage was ramped and the current was measured.

The threshold voltage of Coulomb blockade is given by eq. [7]

$$V_t = \frac{e}{C_0}[\ln(C/C_0)]^{-1} \qquad (1)$$

The first point at which di/dv changes abruptly is at about 150 mV in our system. From this value, C_0 is calculated as 5 x10-

19 F. C is calculated to be 5 x 10^{-18} F from eq. (1) and by the previous value which was obtained at the double-tunnel junction. [5]

Since the distance between the outer-electrode and STM tip is about 10 mm and the length of the molecule is about 2 nm, the number of electrodes is about 5 x 10^6. The i-v characteristic of this kind of long array is calculated using a simulation program SETCAD. [13] (Fig.3)

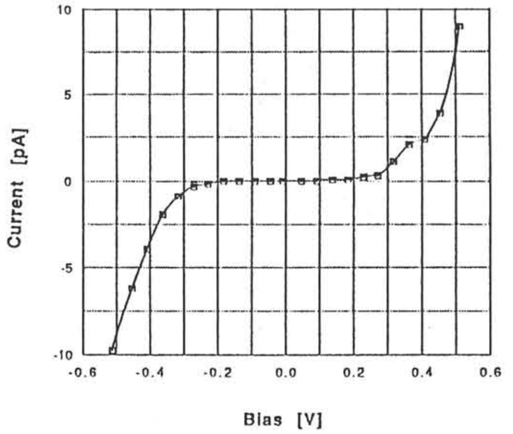

Fig.3 The calculated i-v curve using SETCAD program. The number of tunnel junctions is 14. There is a Coulomb gap and it agrees well with the experimental result (Fig.2).

Since the i-v characteristic represents a large number of tunnel junctions, it is necessary to simulate if a large number of junctions give a such i-v characteristic. We consider an array of 14 junctions for the simplicity. Since the capacitance is small ($C=10^{-18}$ F), a Coulomb gap appears even at 300 K in the simulation. The calculated i-v curve agrees well with the measured i-v curve (Fig.2).

The size of the individual island and the average distance between them is critical for this experiment. In that area of the sample where the resistance between the islands would be smaller than about 5 x $10^9 \Omega$, electron could tunnel directly from one island to the next island. Since the size of individual islands is larger than the molecule, their capacitance is large, and consequently the electrostatic energy between them is small so that the single electron tunneling cannot be observed at room temperature. The effect manifests itself, however, in the region where the resistance between the islands is larger than 5 x $10^9 \Omega$.

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