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Coulomb blockade in arrays of quantum dots

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Abstract

We report current–voltage (I–V) characteristics of two-dimensional arrays of quantum dots fabricated from a GaAs/AlGaAs heterostructure. We designed the arrays for the self-capacitance of the dots to be comparatively low, in order to observe long-range interaction between the dots while keeping the tunability of the coupling by the gate voltage. The observed I–V characteristics showed no sign of charge injection threshold voltage scaled by the size of the array, which is theoretically predicted for disordered arrays without long-range Coulomb interaction. Instead, charge soliton injection in a much lower voltage region is observed indicating long-range interaction.

Keywords: Quantum dot arrays; Coulomb blockade; Soliton lattice

1. Introduction

Two-dimensional arrays of quantum dots which consist of metallic islands and oxide barriers have been studied extensively in the Coulomb blockade regime, while those that consist of two-dimensional electron gas (2DEG) at semiconductor heterointerfaces are far less explored although such systems have advantages of the tunability of the coupling through the barriers and of sensitivity to the external magnetic field.

One of the reasons is that in AlGaAs/GaAs, which is most commonly adopted to generate 2DEG, the self-capacitance of the dots tends to be large in the usual laterally confined systems [1] due to the surrounding metallic gates. This large self-capacitance absorbs most of the electric lines of force from the excess charges on the dot and thereby cuts off the long-range Coulomb interaction. Thus, anomalous properties predicted in 2DEG with long-range two-dimensional Coulomb interaction are difficult to observe in these systems [2].

Another reason is that disorder in such dot arrays in 2DEG is usually large due to the irregularity in the gate configuration. Such disorder is predicted to lead to a threshold voltage for conduction [3], which scales with the array size. Disorder also destroys the conduction properties peculiar to two-dimensional arrays.

In this article, we report the current–voltage (I–V) characteristics of two-dimensional arrays

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designed to make the self-capacitance and the disorder smaller than those by the usual lateral confinement method, keeping the tunability of the coupling by the gate voltage. The observed I–V characteristics does not show the threshold voltage behavior. Instead, charge soliton injection, which is an evidence of long-range Coulomb interaction, is observed.

2. Experiment

We prepared 2DEG with a carrier density of $2.2 \times 10^{15}\,m^{-2}$ and a mobility of $42\,m^2/Vs$ at 4.2 K by molecular beam epitaxy. The arrays were fabricated as follows. First, an "anti-dot" type lattice was prepared, i.e., $0.35 \times 0.35\,\mu m^2$ square holes were placed to constitute a square lattice with a lattice constant of 0.70 μm by electron-beam (EB) lithography and wet etching. Next a grid made of gold, which acts as a Schottky gate to separate each quantum dot, was placed upon the antidot lattice by EB lithography and lift-off technique. Fig. 1 shows a scanning electron micrograph and a schematic drawing of the sample structure.

The dots thus consist of mesa-etched quantum wires and Schottky gates. As reported in [4], the total capacitance of such a structure is much smaller than the case of the usual laterally confined structure. Since this decrease is mainly due to that in the self-capacitance, a larger ratio C/C_0 is expected in the present system, where C is the junction capacitance between dots and C_0 the self-capacitance. Hence, the charge soliton radius $\xi \equiv \sqrt{C/C_0}$ spans many dots and long-range two-dimensional Coulomb interaction may be recovered. Another advantage is that the dot size is comparatively well-defined by the etching and the irregularity in the dot size, i.e., the disorder in the array may be small.

We measured the characteristics of arrays with sizes 5 × 5 and 50 × 50. The sources and drains of the arrays were symmetrically biased by a DC voltage source up to 20 mV and the current was detected by a current amplifier. The differential conductance of the devices was measured by an AC lock-in technique (22 Hz, 50 μV). The gate voltage

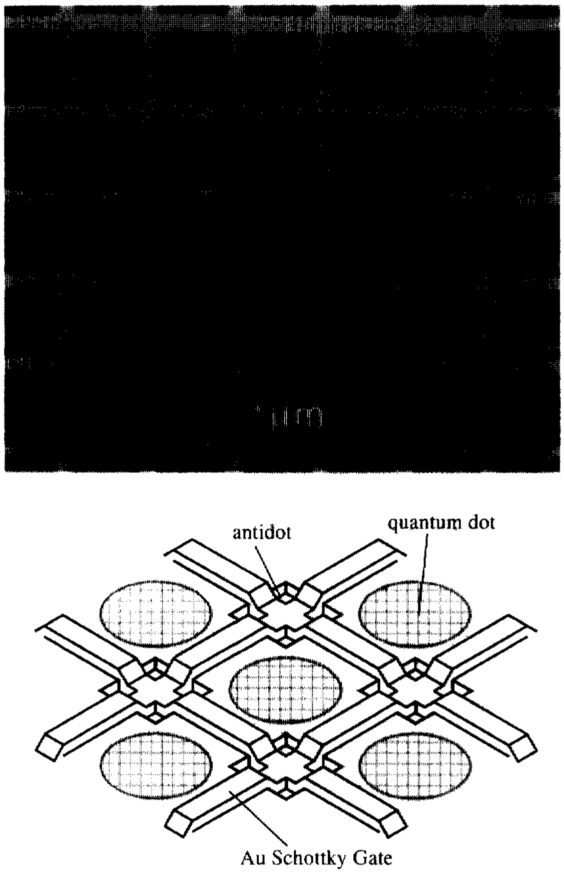

Fig. 1. SEM image and a schematic drawing of the sample structure in the 5 × 5 array with the lattice constant 700 nm. Electron gas beneath the Au gate (appears white) can be depleted with an appropriate gate voltage and forms a quantum dot array.

was applied by another voltage source to bring the samples from anti-dot regime to dot-array regime. Each dot is about 150 nm in radius and has about two hundred electrons. The samples were directly cooled in liquid ^3He down to 0.4 K.

3. Results and discussion

First, in order to demonstrate that the anti-dot lattice is certainly formed in the sample when the Schottky gate is open, we measured the magnetoresistance in the anti-dot regime. When the

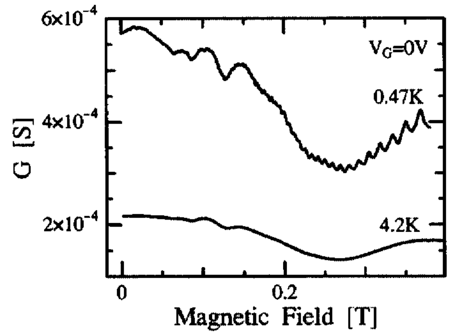

Fig. 2. Magnetoconductance of the 5 × 5 array at $V_G = 0$ V after illumination, where the junction resistance is low and a few conductance channels are preset between dots.

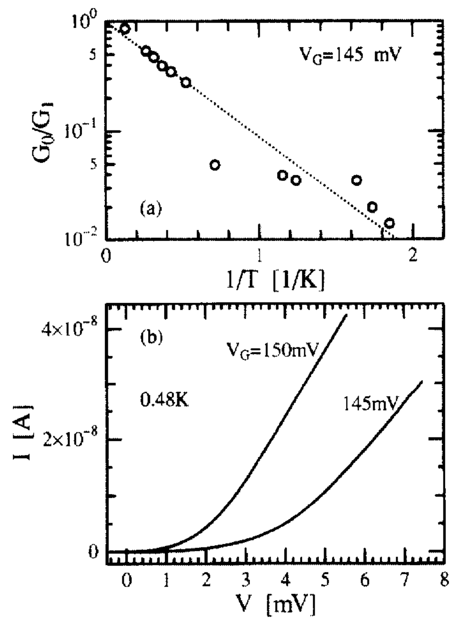

Fig. 3. (a) Temperature dependence of the normalized zero-bias conductance of the 5 × 5 array at $V_G = 145$ mV in the dark. The dotted line corresponds to the activation energy 0.21 meV. (b) I–V characteristics of the 5 × 5 array at 0.48 K in the dark for $V_G = 150$ and 145 mV, respectively.

gate voltage (V_G) was zero, the resistance of the 5 × 5 array was very high and we needed to apply positive V_G or illuminate the sample to open some conducting channels between the dots. We show in Fig. 2 the weak field magnetoconductance at $V_G = 0$ V after illumination, where the junction resistance is low and a few conductance channels between the dots are present. Clear resistance peaks due to the well known commensurability effect appeared indicating the formation of a high-quality anti-dot lattice [5].

Next, we discuss the conduction in high-resistance regime. All the results discussed henceforth were taken in the dark. Fig. 3a shows the temperature dependence of the normalized zero-bias conductance of the 5 × 5 array at $V_G = 145$ mV. The conductance rapidly decreased with the decreasing temperature. At the lowest temperature (0.48 K), we measured the I–V characteristics, the results of which are shown in Fig. 3b. A clear blockade is observed and the extrapolation from the high-voltage linear region to $I = 0$ gives the offset voltage $V_{off} = 3.86$ mV and 1.98 mV for $V_G = 145$ and 150 mV, respectively. If we assume that the linear region corresponds to the state in which each dot contains one excess electron, $V_{off} = Ne/2C_{tot}$, where C_{tot} is the total capacitance per dot, that is the sum of C_0 and $4C$, and N the size of the array [6]. This results in $C_{tot} = 0.125$ and 0.24 fF for $V_G = 145$ and 150 mV, respectively.

The single-electron charging energy E_C obtained from the above values of C_{tot} is 0.33 and 0.64 meV and roughly agrees with the activation energy of 0.21 meV obtained from the temperature dependence shown in Fig. 3a. Hence, we conclude that the appearance of blockade shown in Fig. 3b is due to the single-electron charging effect. The increase in C_{tot} with the increase of V_G is probably due to the decrease of the width of the depletion layers between the dots. This sensitivity of C_{tot} to V_G indicates that C is comparable to or larger than C_0 because the shape of the dot is comparatively well defined in the present structure and C_0 should be insensitive to V_G.

Fig. 4a shows the I–V characteristics of a 50 × 50 array at the lowest temperature. The characteristics are qualitatively similar to those of the 5 × 5 array, though negative gate voltage was necessary in order to enter the high-resistance region in this sample. The reason for this difference in the gate characteristics is not known at present. In this sample, V_{off} was accordingly much higher than that of 5 × 5 array and the Joule heating prevented us

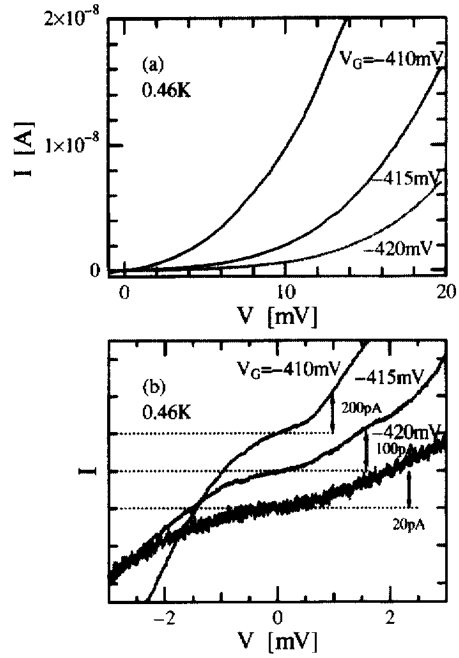

Fig. 4. (a) I–V characteristics of the 50×50 array at 0.46 K in the dark at gate voltage $V_G = -400$, -415 and -420 mV, respectively. (b) I–V characteristics around the origin. Note that the current scale is different for different curves.

from the direct observation of V_{off}. Instead we estimated V_{off} as follows. By linear scaling of V and I, the I–V curves can be almost identical to that in the 5×5 array. Assuming that V_{off} also scales in the same way as the curves, we simply multiply V_{off} of 5×5 array with the scaling coefficients. Thus, we estimated V_{off} to be 9.7, 12.7 and 14.0 mV for $V_G = -410$, -415 and -420 mV.

According to the theory in Ref. [3], when the array is disordered and does not have the long-range interaction, a threshold voltage $V_{th} = \alpha Ne/C_{tot}$ exists for the current flow below V_{off}, where $\alpha = 0.338$ for 2D. In the voltage range above V_{th} and below V_{off}, the current obeys the power law:

$$I \propto (V - V_{th})^{\zeta} \tag{1}$$

with $\zeta = \frac{5}{3}$. Duruöz et al. claimed observation of this behavior in a laterally confined quantum dot array though the results are not perfectly consistent with the result for the single-dot system [7].

In the present case, however, the observed I–V characteristics cannot be explained within this theory for the following reasons. First, although V_{th} is estimated from V_{off} to be about 9 mV, the current increases smoothly as shown in Fig. 4 a and no special kink or anomaly is observed in the curves around the voltage. Second, the exponent ζ becomes larger than 2 if we assume some appropriate value of V_{th}.

On the other hand, in the case of $C \gg C_0$, the charge-soliton picture predicts the threshold voltage of the soliton injection as [6,8]

$$V_{th(s)} = \frac{e}{2C_0}\left(1 - \frac{2}{\pi}\right)\left(\frac{C_0}{C}\right)^{1/2}, \tag{2}$$

which is independent of N and hence is usually much smaller than V_{off}. Fig. 4b shows a blowup of Fig. 4a around the origin. Clear rise of the current was observed at about 0.5 mV. The voltage at this rise increases with the negative gate voltage and about twice of the threshold voltage per dot $e/2C_{tot}$. These features strongly suggest that the observed I–V characteristics corresponds to the injection of the charge-soliton.

The above comparison clearly shows that the charge-soliton picture better fits to the present results. In other words, quasi-uniform quantum dot lattice with $C_0 \simeq C$ are realized in our sample. In such "two-dimensional Coulomb gases", charge Kosterlitz–Thouless (KT) transition is predicted to take place [9]. In real systems, however, we can only observe the precursor effect of charge KT transition because of the finite logarithmic interaction range. Such a precursor effect appears in characteristic temperature dependence and is found in a metallic junction array [10].

Then why do we not observe the precursor effect in the present system? This is probably due to the small value of ξ in the present system. In the present experiment, C/C_0 was estimated to be about 1 from the comparison with the numerical calculation by Bakhvalov et al. [8]. The fact that no qualitative difference is observed between 5×5 and 50×50 arrays also suggests ξ must be smaller than 2–3. In order to observe the clear precursor effect, ξ should be larger than about 10.

An achievement of such a large soliton radius requires improvement in the sample structure. For example, in the present structure many electric lines of force between the dots are cut off by the grid gate. A thinner and narrower gate is undoubtedly more effective for the purpose. Also the "floating" gate technique introduced in Ref. [11] may be useful to avoid this problem. These improvements would decrease C_0 of our dots, because the bare self-capacitance is about 0.2 fF in an even larger quantum dot of 300 nm in radius in AlGaAs/GaAs 2DEG. Hence for further decrease, decrease in the dot size is indispensable. Another way to see such a many body effect of a charge soliton is to increase the concentration of solitons by applying an uniform gate voltage to the array besides the grid gate. This results in the decrease in the average distance of the solitons and gives rise to the logarithmic interaction rather than the exponential one.

To summarize, we measured I–V characteristics of two-dimensional arrays of quantum dots fabricated from a GaAs/AlGaAs heterostructure. The charge-soliton picture better fits the observed I–V characteristics indicating the presence of long-range Coulomb interaction.

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