Available online at www.sciencedirect.com
SCIENCE DIRECT
Physica E 32 (2006) 187–190
PHYSICA E
www.elsevier.com/locate/physe

Electron transport and shell structures of single InAs quantum dots probed by nanogap electrodes

M. Jung[a,*], K. Hirakawa[a], S. Ishida[b], Y. Arakawa[a,b], S. Komiyama[c]

[a]Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
[b]Research Center for Advanced Science and Technology, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
[c]Department of Basic Sciences, University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan

Available online 27 January 2006

Abstract

We have investigated electron transport and electron filling in single InAs quantum dots (QDs) using nanogap electrodes. Elliptic InAs QDs with diameter of ~60/80 nm exhibited clear shell filling up to 12 electrons. Shell-dependent charging energies and level quantization energies for the s, p, and d states were determined from the addition energy spectra. Furthermore, it is found that the charging energies and the tunneling conductances strongly depend on the shell, reflecting that the electron wave functions for higher shells are more extended in space.

PACS: 73.21.La; 73.23.−b; 73.23.Hk; 73.63.Kv

Keywords: InAs quantum dot; Shell structure; Single electron tunneling

As often referred as "artificial atoms" [1–3], nanolithographically defined quantum dots (QDs) exhibit many atom-like properties through transport experiments. For example, beautiful shell filling and the validity of Hund's rule have been demonstrated in vertical QDs fabricated with InGaAs/AlGaAs double barrier resonant tunneling structures [4,5]. Over the past several years, similar efforts have also been directed toward elucidating electronic structures of self-assembled InAs QDs. The first clue to the shell structures in InAs QDs was discovered in ensembles of InAs QDs by methods such as capacitance spectroscopy [6–8] and far-infrared magnetospectroscopy [9]. Although the capacitance spectroscopy provides valuable information on the electronic structures and the Coulomb interactions, detailed discussions on the shell structures were not possible due to inhomogeneous broadening that originates from size fluctuations of QDs. However, more recently, studies to clarify the electronic structures of single self-assembled InAs QDs have been started [10–12].

In this work, we have investigated electron transport and shell structures of single InAs QDs grown on the surfaces of GaAs by measuring tunneling conductances in a single electron transistor geometry using nanogap electrodes. Uncapped elliptic InAs QDs with diameter of ~60/80 nm exhibited clear shell filling up to 12 electrons before the gate leakage became significant. Shell-dependent charging energies and level quantization energies for the s, p, d states were determined from the addition energy spectra. Furthermore, it is found that the tunneling conductance strongly depends on the shell, reflecting the spatial size of the electron wave function in each shell.

Self-assembled InAs QDs were grown by molecular beam epitaxy on a (1 0 0)-oriented n^+-GaAs substrate. After successively growing a 100 nm-thick AlGaAs barrier layer and a 200 nm-thick undoped GaAs buffer layer, InAs QDs were grown at 500 °C. The n-type substrate was used as a backgate electrode. Patterns of metallic nanoelectrodes were defined by standard electron beam lithography. The metallic electrodes were formed directly on the uncapped QDs by successively depositing 10 nm-thick Ti and 10 nm-thick Au layers. Details of the nanofabrication process was reported elsewhere [13]. The inset of Fig. 1(a) shows a

*Corresponding author. Tel./fax: +81 3 5452 6261.
E-mail address: mjung@iis.u-tokyo.ac.jp (M. Jung).

1386-9477/$ - see front matter
doi:10.1016/j.physe.2005.12.068

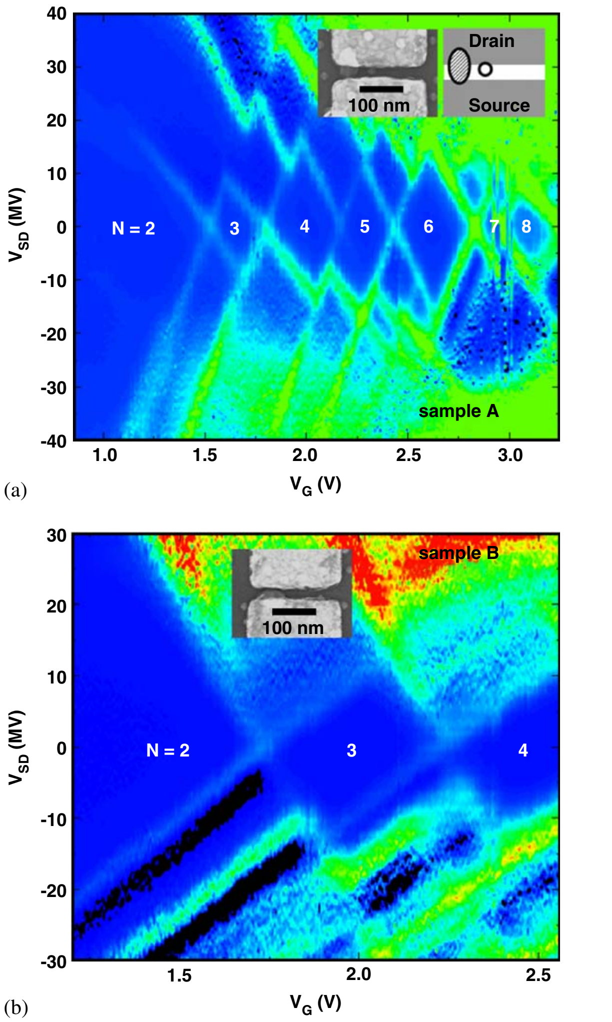

Fig. 1. (a) Contour plot of the differential conductance, dI/dV_{SD}, of a single electron transistor which contains a single elliptic InAs QD with 60/80 nm diameter (sample A) is plotted as a function of the source-drain voltage, V_{SD}, and the gate voltage, V_G. Bright areas correspond to high values of dI/dV_{SD}. The inset (left) of (a) shows a scanning electron microscope (SEM) image of the fabricated device and the right is a sketch of the fabricated device. (b) The Coulomb stability diagram of the sample B.

typical scanning electron microscope (SEM) image (left) and its schematic sketch (right) of the fabricated nanogap structure. As seen in the figure, metallic electrodes with 30–40 nm-wide nanogap separation were formed. All the measurements were done at 4.2 K.

In this paper, we will focus ourselves on two samples (samples A and B) which contain a single elliptic QD of a similar size (diameter of ~60 nm (short axis)/~80 nm (long axis)). Figs. 1(a) and (b) show the Coulomb stability diagrams of samples A and B, respectively, obtained by plotting color-coded differential conductance, dI/dV_{SD}, as a function of V_{SD} and V_G. Coulomb blockade takes place in the dark-colored diamond-shaped areas, each of which is associated with a well-defined number N of confined electrons. The Coulomb diamond for $N = 1$ does not show up in Fig. 1 because the contrast is too weak in the color scale of the figure. For sample A, it should be noted that the Coulomb diamonds for $N = 2$, 4, and 6 are unusually larger than other diamonds, indicating that the system is more stabilized at these fillings. Similarly, shell filling up to 6 electrons was observed for sample B, as shown in Fig. 1(b).

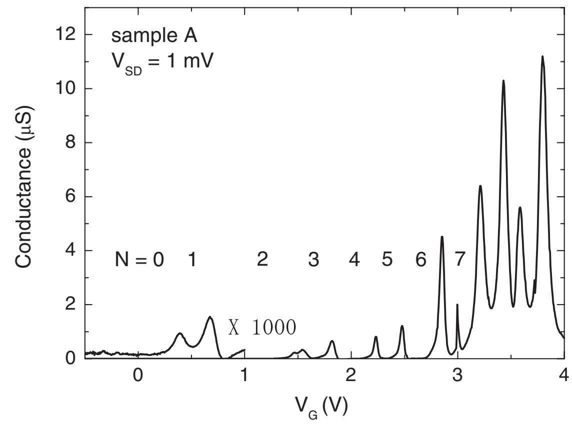

Fig. 2. Linear conductance spectrum taken on sample A by applying $V_{SD} = 1\,mV$ as function of the back gate voltage, V_G.

Fig. 2 shows the linear conductance spectrum of sample A taken by applying $V_{SD} = 1\,mV$ as a function of V_G. The sample A exhibited clear Coulomb peaks up to 12 before the gate leak current became significant. Since no conduction was observed below $V_G = 0\,V$, the observed two peaks around $V_G = 0.5\,V$ can be assigned to the filling of the ground states in the dot. For higher V_G region, four bunched peaks are observed for $1.4\,V < V_G < 2.6\,V$ and six bunched peaks are seen for $2.7\,V < V_G < 4\,V$. (Slightly deformed peaks at $V_G = 1.5$ and 3.0 V are due most likely to temporal fluctuation in the electrostatic environment around the dot during the measurement.) We attribute the observed bunching of the Coulomb peaks to the shell structure in the QD, since the observed peak numbers are consistent with the level degeneracy of the two-dimensional QD systems (2, 4, and 6 for the s, p, and d shells, respectively). Interestingly, the magnitude of the conductance for each shell is extremely different. This point will be discussed later.

Since the difference in the electrochemical potential between the source and drain electrodes where the tunneling-in line and the tunneling-out line of a Coulomb diamond crosses (i.e., $e|V_{SD}(\text{apex})|$ at the apex of each Coulomb diamond) is equal to the addition energy [5,14,15], we plotted in Fig. 3 the addition energy of electrons in sample A (full circles) as a function of the number of electrons in the QD. Here, e is the elementary charge. When $|V_{SD}(\text{apex})|$ depends on the polarity of V_{SD}, which is often the case as seen in Fig. 1, the full circles were put at the average values of the two. In the same figure, the addition energy spectrum for sample B obtained in the same manner is also plotted by triangles. As seen in the figure, the two samples exhibit similar addition energy spectra.