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Single Electron Transport through Single InAs Quantum Dots Probed by Nanogap Electrodes

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1. Introduction

The electronic and optical properties of self-assembled InAs quantum dots (QDs) have attracted a great deal of interest during the past several years. Research has been directed towards both their fundamental physics and device applications, such as quantum dot memory devices, lasers, and infrared photodetectors. Although electron transport through QDs have been investigated, it has been difficult to probe them at the single dot level due to the lack of spatial resolution.

A few different approaches have been tried to investigate the electrical properties of single InAs QD. In particular, a scanning tunneling microscopy (STM) has been utilized to probe InAs nanocrystal suspended on the gold surface [1]. Although STM is a very powerful tool to investigate the electronic structures, the major obstacle is the lack of mechanical and electrical flexibility. Other works have been reported on the tunneling transport in a vertical quantum dot structures, in which a layer of InAs QDs was located in the center of a GaAs quantum well [2,3]. This structure has a drawback of rather small compatibility with further device applications.

In this work, we have investigated the electron transport through single InAs SAQDs with and without GaAs capping layers by metallic leads with nanogaps.

2. Sample preparation

InAs QDs were grown by molecular beam epitaxy on semi-insulating (100) GaAs. After a growth of a 300-nm-thick GaAs buffer layer at 600 °C, the InAs QDs were grown at 500 °C. The average base diameter and height of the grown QDs was about 30 nm and 10 nm, respectively. The areal density was 4×10^{10} cm^{-2}. In order to investigate electrical properties of single QD, we grew two kinds of QDs. In one kind of samples, InAs QDs were grown on GaAs surfaces without GaAs capping layers. In the other type of samples, QDs were capped with thin GaAs layers. Metallic electrodes with gaps of 15~20 nm was fabricated by standard electron beam lithography and subsequent deposition of 5 nm-thick NiCr and 25 nm-thick Au.

3. Electron transport through exposed InAs QDs and wetting layers

Typical scanning electron microscopic (SEM) images of fabricated nanogap samples are presented in Fig. 1(a) and 1(b). As seen in Fig. 1(a), nanogap electrodes with 20 nm separation, which touches only one uncapped InAs QD, was formed. Figure 2 shows current versus voltage (I-V) curves measured at 4.2 K for a sample fabricated on uncapped InAs QDs. Quasi-ohmic I-V characteristics with resistance ~ 4 kΩ were observed, indicating that even the InAs QDs exposed on GaAs surfaces are not depleted. The measured resistance is much smaller than the quantum resistance e^2/h ~ 26 kΩ and, consequently, obscures the Coulomb blockade effect. On the contrary, no current flows through the wetting layers.

4. Electron transport in QD single electron tunneling structures

In order to observe single electron tunneling effect, a tunneling barrier was inserted between the QDs and the nanogap electrodes. Figure 3 shows the I-V curve measured at 4.2 K for a typical nanogap sample fabricated on InAs QDs capped with a 30 ML-thick GaAs layer grown at 300 °C (see Fig. 1(b)). With the low-temperature grown tunneling barrier, the tunneling resistance was increased up to 10 MΩ.

A clear Coulomb blockade and Coulomb staircase characteristics were observed. The right hand side of Fig. 3 shows the tunneling conductance obtained by numerical differentiation of the I-V curve. I-V curves were highly reproducible as long as the junction remained stable. The Coulomb gap of ~ 25 mV was observed, which is slightly larger than the value reported from capacitance measurement (~ 17 meV for 20 nm QD) [5].

5. Conclusions

In summary, we have found that the uncapped InAs QDs grown on the GaAs surfaces show metallic conductivities, indicating that even the exposed SAQDs are not depleted. The measured resistance was ~ 4 kΩ, which is much smaller than the quantum resistance R_Q ~ 26 kΩ. On the contrary, it was found that no current flows through the exposed InAs wetting layers. For the nanogap samples fabricated on QDs covered with thin GaAs capping layers grown at 300 °C, a clear Coulomb gap of ~ 25 mV and Coulomb staircase were observed at 4.2 K.

References

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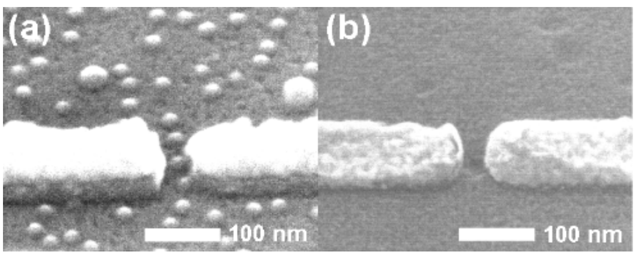

Fig. 1. (a) SEM image of a typical nanogap sample fabricated on uncapped InAs quantum dots. Average gap width was 15 ~ 25 nm. (b) SEM image of a typical device fabricated on quantum dots capped with 30 ML-thick GaAs layer grown at 300 °C.

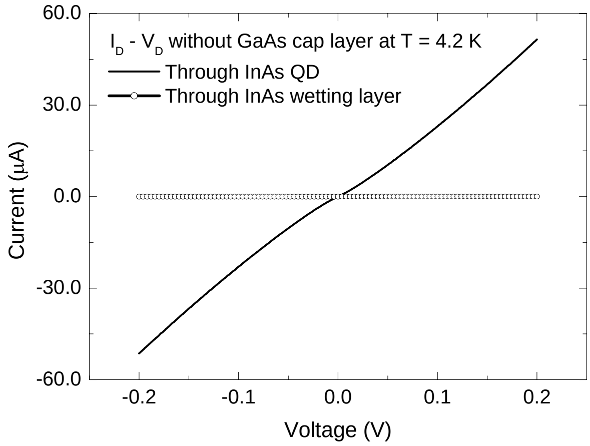

Fig. 2. Current-voltage curves measured at 4.2 K on a nanogap sample fabricated on uncapped InAs quantum dots (solid line). No current flows through InAs wetting layers (open circles).

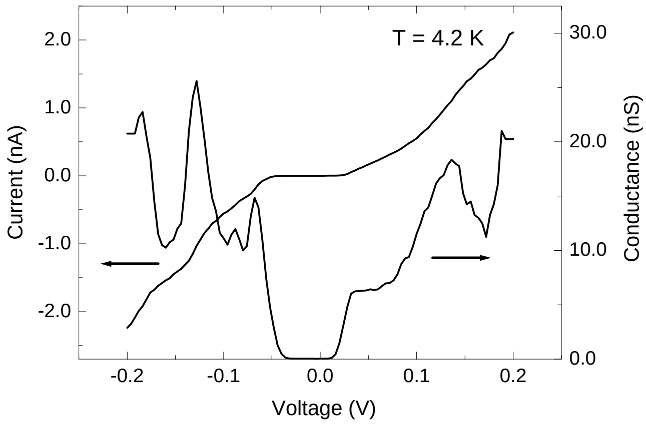

Fig. 3. Current-voltage curve (left axis) and tunneling conductance spectrum (right axis) measured at 4.2 K on a nanogap sample fabricated on QDs covered with thin GaAs capping layers grown at 300 °C.