Detection of Single Electron Charging in individual InAs Quantum Dot by Nonconctact Atomic Force Microscopy

Romain Stomp[1], Yoichi Miyahara[1], Sacha Schaer[1], Qingfeng Sun[1], Hong Guo[1], Sergei Studenikin[2], Philip Poole[2], Andy Sachrajda[2] and Peter Grutter[1],
[1]Physics Department, McGill University, 3600 rue University, H3A 2T8 Montreal, Canada
[2]Institute for Microstructural Science, National Research Council of Canada, K1A OR6 Ottawa, Canada

E-mail: miyahara@physics.mcgill.ca

Quantum dots (QD) of various kinds are one of the most important entities in nanotechnology due to their potential applications as lasers, memory storage devices or building blocks for quantum computation. Understanding the electronic structure of QDs is not only important for such application, but also of great interest in fundamental physics. As a consequence, there have been a number of studies of electronic properties using mainly optical or capacitance spectroscopy techniques.

Investigating a single QD not fabricated by lithography techniques, such as a self-assembled semiconductor quantum dot or a nano particle, is challenging because of the extremely small dot dimensions. Spectroscopic techniques based on scanning probe microscopy (SPM) have been employed, in particular scanning tunneling spectroscopy (STS). The latter has been applied to the investigation of a single QD by measuring the tunneling current flowing in the double tunneling barrier junction which is formed by the tip, the QD and the back electrode.

In STS the acquired tunneling spectra feature the Coulomb staircase or/and the discrete energy states of the QD depending on the size of the QD and the tunneling barrier thickness [1-3]. However, these measurements are limited to substrates with adequate conductivity since a measurable tunneling current of typically 1 pA or more is usually required. Alternatively, the detection of the electrostatic force caused by the charging of QDs has also been tried with atomic force microscope (AFM). Single electron charging has thus been observed in small metallic islands [4-5] and in a discontinued single carbon-nanotube QD [6].

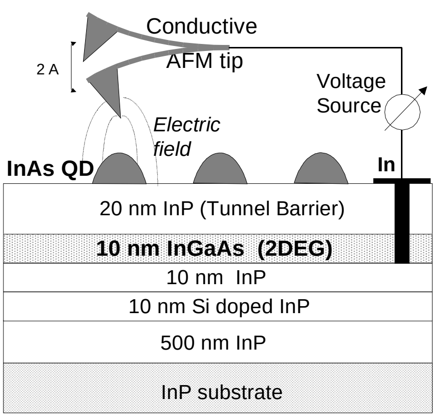

Fig. 1 Sample structure and experimental setup.

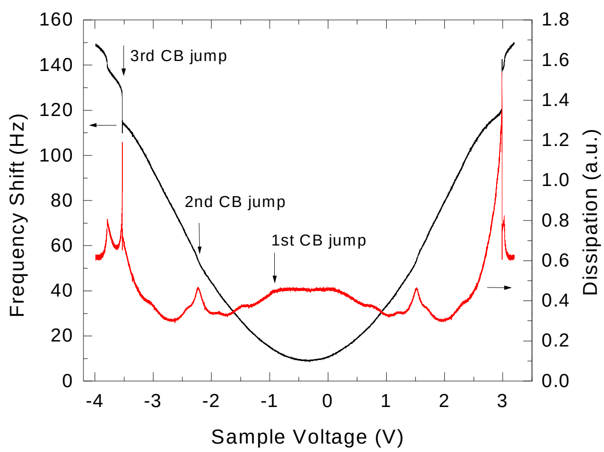

Fig. 2 Electrostatic force spectrum and dissipation-sample voltage curve over the QD.

We have been working on AFM based spectroscopy with the goal of observing the electronic structure of a single QD. In this paper, we report the first successful observation of the Coulomb blockade effect by electrostatic force measurement. The main experimental features agree well with a simple theory based on the semi-classical theory of the Coulomb blockade effect. These measured spectra can be thought as the "force version" of the Coulomb staircase.

In particular, we used a self-assembled InAs QD sample grown on a InP substrate by chemical beam epitaxy [7]. A two dimensional electron gas (2DEG) formed by a InGaAs quantum well was used as the back electrode. A 20nm InP layer serves as spacer layer and a tunneling barrier between the QD layer and the 2DEG layer (Fig. 1). QDs were imaged by noncontact AFM in vacuum at 4.5 K. The Pt coated conductive AFM tip was then positioned above a single InAs QD. The resonance frequency shift of the oscillating AFM probe was recorded as a function of the tip-back electrode bias voltage while the average tip-QD distance was kept constant (Fig. 1). The typical average tip-QD distance is 5-20 nm. We call this technique Electrostatic Force Spectroscopy (EFS).

The observed EFS spectra show several jumps on a parabolic background. The latter accounts for the capacitive interaction between the tip and the back electrode (Fig. 2). The jumps in the spectra can be interpreted by a series of single electron charging of the QD due to the single electron tunneling from the back-electrode to the QD. The condition for this tunneling to occur is determined by the change in the system's free energy, which includes the charging energy before and after the tunneling. This is identical to classical Coulomb blockade in double tunneling junctions. Simultaneously recorded dissipation show the peaks which appear at the corresponding positions to the jumps in EFS spectra. This can be understood in terms of the Joule dissipation of the electron energy [8].

Comparison of the experimental EFS spectra with the model calculation will be made and the possibility to observe the discrete energy states will also be discussed.

One of the important differences to STS is that there is no continuous current flowing in the system. As a consequence, EFS can detect single electron events. Furthermore, this implies that this technique can also be applied to the QDs embedded in other materials.

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