Imaging Electrons in a Single-Electron Quantum Dot

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Abstract. A scanning probe microscope (SPM) can be used to image a single-electron quantum dot at liquid-He temperatures by recording the Coulomb blockade conductance as a charged SPM tip is scanned above. The Coulomb blockade produces a ring in the image as the first electron is added to the dot. If the tip is sufficiently close to the surface, simulations show one may be able to extract the shape of the electron wave function inside the dot from Coulomb blockade conductance images with a resolution exceeding the size of the tip perturbation.

INTRODUCTION

A scanning probe microscope (SPM) can be used to image the flow of electron waves in a two-dimensional electron gas (2DEG) at liquid He temperatures [1] and to obtain information about the wavefunction in nanostructures [2]. A cooled SPM can image quantum dots in a carbon nanotube [3] and a single-electron dot in a GaAs/AlGaAs heterostructure [4] in the Coulomb blockade regime. This will help in the development of single-electron quantum dots and dot circuits for quantum information processing, by providing ways to image the location of electrons and to locally probe the circuit. Single-electron quantum dots have been proposed as spin qubits [5], and single dots and tunnel-coupled double dots of this type have been built and characterized [6]. Here we propose a technique that will allow SPM imaging in the Coulomb blockade regime to determine the shape of the electron wavefunction inside a quantum dot.

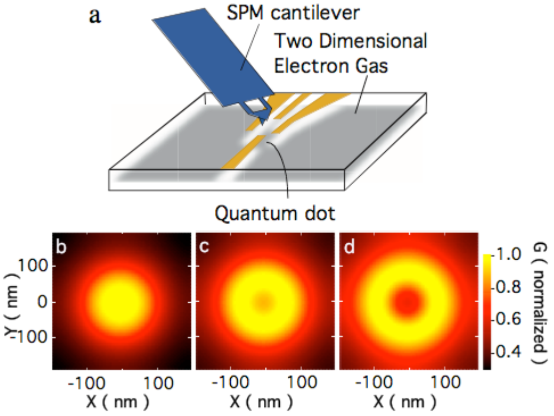

FIGURE 1. (a) Experimental set up for Coulomb blockade imaging of a quantum dot. (b)-(d) Simulated images of Coulomb blockade conductance of a single-electron quantum dot vs. tip position for tip voltages V_{tip} (b) –15mV, (c) –18mV and (d) –21mV; see Fig. 2 caption for dot and tip parameters. A less negative tip voltage causes the ring to shrink.

COULOMB-BLOCKADE IMAGING

Figure 1a illustrates the experimental set up used for Coulomb-blockade imaging of a single-electron quantum dot [4]. The dot was patterned by surface gates on a GaAs/AlGaAs heterostructure containing a 2DEG. A liquid-He cooled charged SPM tip was scanned at a fixed height above the surface of the heterostructure. The charged tip induces a perturbation, shifting the potential forming the dot as well as the energy levels inside the dot, thereby changing the dot conductance in the Coulomb blockade regime. Images are obtained by recording the dot conductance as a function of tip position.

Figures 1b-d show simulated SPM images of a single-electron quantum dot. For these simulations, the tip was located 50nm above the 2DEG, half the spacing used in the experiment [4]. A smaller tip height enhances the imaging resolution, allowing for the extraction of information about the electron wavefunction inside the quantum dot.

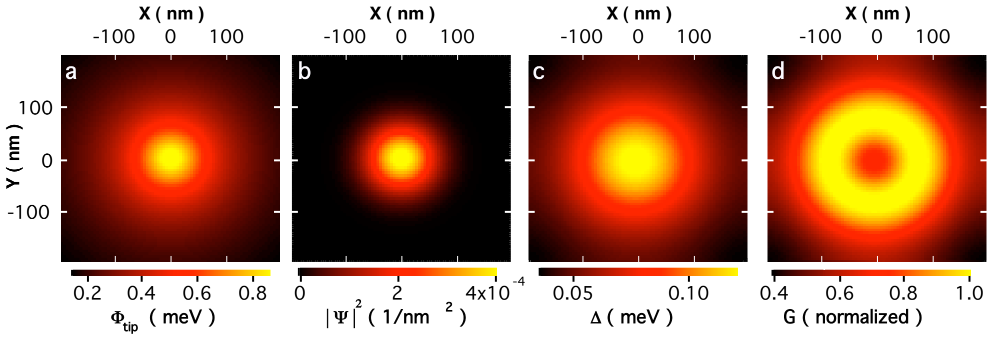

FIGURE 2. (a) Tip perturbation for a tip 50nm above the 2DEG with radius 30 nm and voltage 20 mV. (b) Calculated wavefunction of the single-electron ground state of a quantum dot with a harmonic potential with $\hbar\omega = 0.31$ meV. (c) Calculated shift of the lowest energy level in the dot vs. tip position. (d) Dot conductance vs. tip position at 0.3K.

Figure 1d contains a ring of high conductance corresponding to a Coulomb-blockade resonance through the lowest energy level in the dot. Inside the ring, there are 0 electrons in the dot; outside there is 1. Making the tip voltage V_{tip} less negative alters the size of the ring as demonstrated in Figs. 1b-d. Similar rings were observed in the experimental images, and the adjustability of the ring diameter with tip voltage was demonstrated [4].

The shift Δ in the energy level inside the quantum dot as the tip is scanned above the dot is a convolution of the tip perturbation Φ_{tip} on the potential energy that forms the dot and the square of electron wavefunction amplitude $|\Psi|^2$ from first order perturbation theory. If Φ_{tip} is known and it is comparable in width or narrower than $|\Psi|^2$, one can extract the shape of $|\Psi|^2$ by deconvoluting Δ with respect to Φ_{tip}. The energy shift Δ can be extracted from the line shape of the resonance peaks forming the rings in the conductance images [4]. In the resonant tunneling regime where only one energy level contributes to the dot conductance, the line shape of Coulomb blockade peak is given by [7]:

$$G = G_{\max}\left[Cosh(\Delta/2k_BT)\right]^{-2} \qquad (1)$$

where G_{max} is the dot conductance at resonance determined by the tunneling rate through the quantum dot and the temperature T. The values of Δ can be extracted using the inverse of Eq. 1.

Figure 2 shows simulations of the Coulomb blockade conductance G (Fig. 2d) and the energy shift Δ (Fig. 2c) vs. tip position based on first order perturbation theory for a quantum dot formed by a parabolic potential with single electron ground-state wavefunction $|\Psi|^2$ (Fig. 2b). The tip perturbation Φ_{tip} in Fig. 2a is from a small conducting sphere located above the sample, using a simple model that neglects the effects of metal gates. We can deconvolute the calculated Δ with respect to Φ_{tip} to reproduce the wavefunction in Fig. 2b.

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