FILLING OF FEW ELECTRON QUANTUM DOTS IMAGED AND CHARACTERIZED BY SCANNING FORCE MICROSCOPY

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The ability of quantum dots to confine single charges at discrete energy levels makes them a promising platform for quantum computation where the intrinsic properties of single electrons, such as spin, act as the conventional 1 and 0 bit in a classical computer. In order to control initialization and to scale up the number of bits, an understanding of both the energy levels of single quantum dots and the variation between dots need to be characterized.

Self-assembled quantum dots are of considerable interest in this field because their size, shape, and material can be controlled during the growth process. Controlling these properties is important as these influence the confinement potential, thereby controlling the energy levels of the dot. However, the method of growth does not allow for positioning of the quantum dots which end up randomly distributed over the sample surface. This makes it difficult for lithography techniques to access the quantum dots to perform either charge transport or charge sensing measurements so that the dot properties can be measured.

An atomic force microscope can be used to spatially access the dots, and by applying a voltage between cantilever tip and back-electrode (beneath the dot), the energy levels of individual dots can be probed (see figure 1). At low temperatures the dots are in the Coulomb blockade regime and individual electrons can be controllably added by applying a sufficient bias voltage to overcome this electrostatic repulsive energy. The oscillating cantilever in these experiments is responsible for both loading/emptying the dots through electrical gating and also detecting tunneling events through a change in resonant frequency and/or the amount of energy required to maintain a constant oscillation amplitude. Electrical leads are not required in this experiment which not only leaves the surface electrostatically intact but also gives us the freedom to investigate any dot on the surface.

Using an atomic force microscope we demonstrate the ability to probe the electron levels in few electron self-assembled InAs quantum dots. The charging energy, level spacing, and shell structure of single dots are extracted and supported theoretically (see figure 2). In this contribution, we present the mechanism of the dissipative electrostatic interaction due to the tunneling single-electrons in detail. In essence, this dissipative interaction arises from the delayed response of a single tunneling electron to the oscillating chemical potential induced by the oscillating tip. The delay is due to the finite tunneling rate which is determined by the tunnel barrier. We developed a theoretical model for this dissipation process and obtained a very good agreement between the theoretical dissipation versus Vbias curve and the experimental one (Fig. 2). Multi-dot complexes are also investigated and pairs of dots which are either capacitively or tunnel coupled are observed (figure 3). Finally, we show how by increasing the oscillation amplitude of the cantilever we can probe the excited states of the dot similar to excited state spectroscopy.

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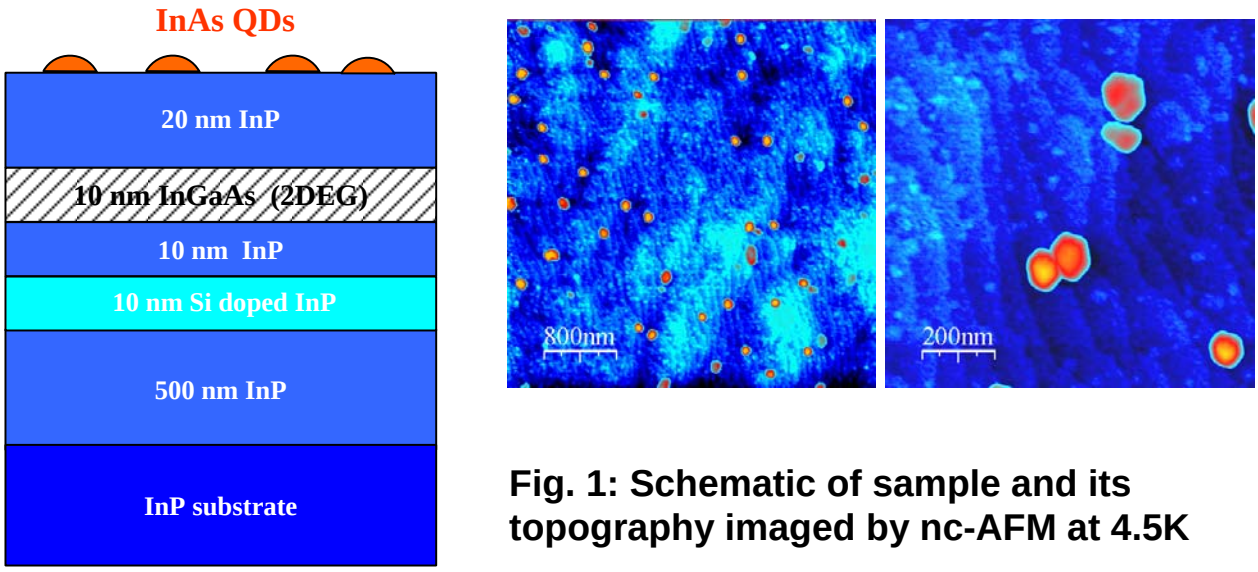

Fig. 1: Schematic of sample and its topography imaged by nc-AFM at 4.5K

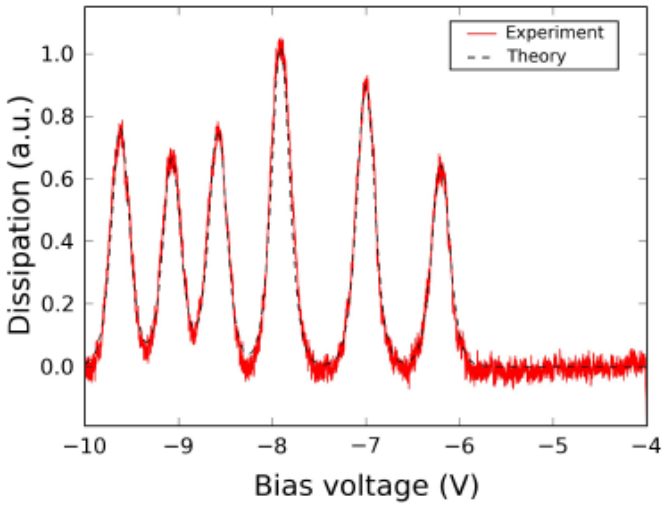

Fig. 2 Theoretical (solid) and experimental (dashed) dissipation versus bias voltage curves. (*T* = 30 K, *A*=0.5 nm, Tip-QD distance = 15 nm)

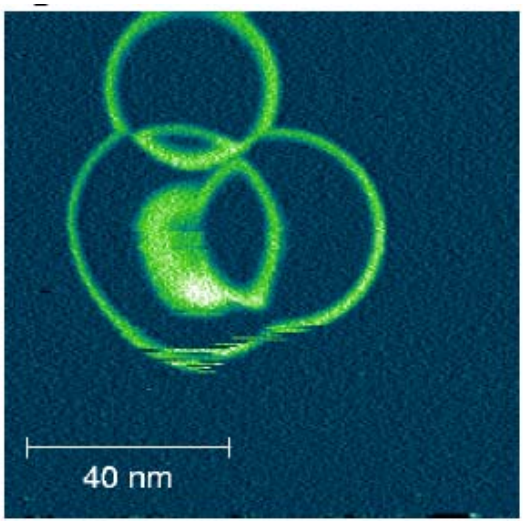

Fig. 3 Multiple qdots interacting. 4.5 K nc-AFM dissipation image