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Scanning Probe Measurements on Semiconductor Nanostructures

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1. Introduction

The traditional techniques used to access electronic transport properties of semiconductor nanostructures use macroscopic ohmic contacts for applying external currents and voltages, and for measuring voltages. Microscopic properties of quantum systems, such as the probability density distribution of electronic quantum states inside a quantum dot [1] have, however, remained elusive. Here we use scanning gate microscopy (SGM) where the conducting tip of a scanning force microscope acts as a movable gate to study quantum dots realized in AlGaAs heterostructures. The technique has been applied to these systems by several groups in the recent past, and in general, similar experimental results were obtained [2–5]. However, little attention has been paid to the exact shape of the tip-induced potential and its implications for the interpretation of scanning gate measurements. We have therefore developed very sensitive techniques for measuring the tip-induced potential in real space using the quantum dot as a sensitive electrometer [6]. Our results clarify the origin of previous results that were not well understood, pinpoint limitations of the technique, and quantify the requirements needed for achieving reliable imaging of quantum states.

2. Measurement technique

For our measurements we use a home-built scanning force micorscope operated in a commercial dilution refrigerator with a base temperature below 100 mK [7]. The microscope is equipped with piezo motors for *in situ* lateral coarse positioning and tip approach. Tuning fork sensors with an electrochemically sharpened metallic tip are used as the surface imaging sensor in standard scanning force microscope mode. In scanning gate microscopy mode, the same tip is lifted above the surface and used as a scanning metallic gate that couples capacitively to the quantum dot under study.

In scanning gate microscopy, the conductance of a quantum device is measured as a function of lateral tip position. Conductance measurements are performed with standard low-frequency lock-in techniques. The result is a real-space conductance map which needs further interpretation in order to reveal physical properties of the system.

3. Sample and Fabrication

The samples used in our studies are based on Ga[Al]As heterostructures with a two-dimensional electron gas forming at the heterointerface 34 nm below the surface. Quantum dot structures were patterned by local anodic oxidation of the sample surface with a scanning force microscope at room temperature (type I samples) [8]. A particular device resulting from the application of this technique is shown in Fig. 1. Scanning gate images on such structures occasionally suffer from charge rearrangement induced by the scanning tip. While the charging traps can be located and their interaction with the dot can be characterized with the scanning gate technique, we will here focus on experiments where these effects were excluded by evaporating an additional 6 nm Ti top gate above the quantum dot structure [9]. This gate screened the interaction between the tip and charge traps. Above the quantum dot under study, the top gate was locally oxidized [9] in order to allow for electrostatic coupling of the tip to the quantum dot (type II sample).

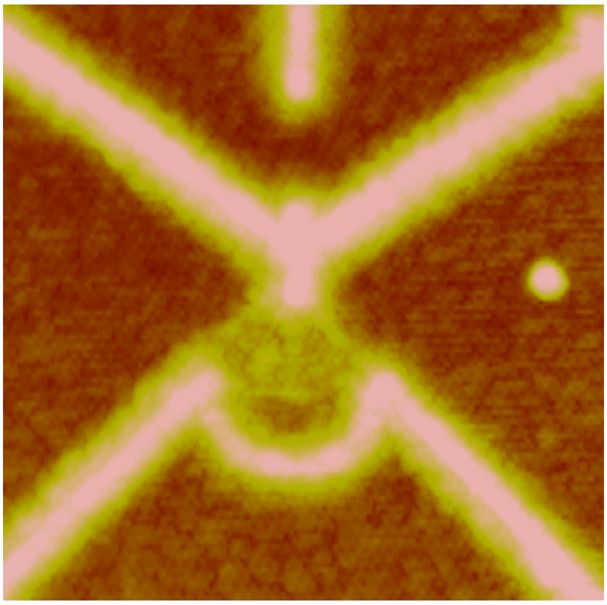

Fig. 1 Scanning force microscope image of a heterostructure surface patterned with local anodic oxidation to form a quantum dot structure. Bright lines are oxide lines depleting the subsurface electron gas.

4. Results on type I samples

On type I samples tuned to the Coulomb blockade regime, we find concentric rings of resonant conductance in the scanning gate images [3,4]. A representative image of this type is shown in Fig. 2. These rings follow equipotential lines of the tip-induced potential at the location of the quantum dot. We have extended such experiments at temperatures down to 100 mK to a quantum dot which is electrostatically coupled to a quantum point contact read-out [10]. In this case both the current through the dot as well as through the point contact are imaged as the tip scans across the sample. This way we identify the contributions of individual charging events of the dot as well as of neighboring impurity sites.

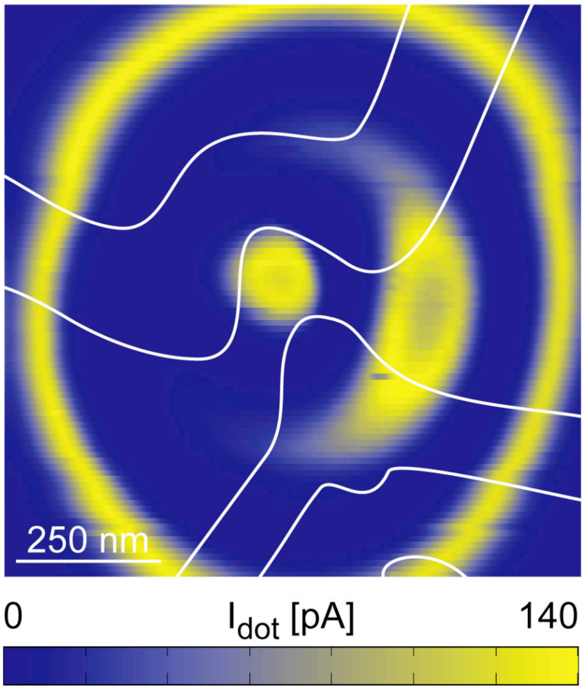

Fig. 2 Scanning gate image of a quantum dot structure. Bright rings of high current represent lines of constant potential at the location of the quantum dot. The measurement was taken in a dilution refrigerator at a temperature of 190 mK.

5. Results on type II samples

Type II samples minimize the influence of impurity charging events. Measurements with different voltages applied between the scanning tip and the quantum dot show that there exists no voltage at which the tip-induced potential vanishes completely [6]. As a working hypothesis we attribute this to the presence of charged regions on the surface of the scanning tip producing a contribution to the potential independent of the tip voltage.

We have used a novel feedback mechanism to map the potential induced in the dot by the tip with high resolution [6]. We find that the tip-induced potential consists of a repulsive part that depends on tip bias and an attractive part that is independent of tip bias, in agreement with our working hypothesis. We could also map the spatial variation of the tip's lever arm under least invasive conditions [6].

In addition, we were able to show that the tip-induced potential and with it the appearance of scanning gate images can be severely changed by an *in situ* treatment of the tip. Using such a treatment, the shape of the voltage-independent contribution to the potential can be greatly simplified and its magnitude can be reduced [11].

While scanning gate results for the tip-induced potential were independent of the quantum state used, the lever arm showed fine structure that could be the "quantum fingerprint" of a given state [6].

6. Conclusions

The scanning gate technique has now reached a degree of maturity to be successfully applied to the investigation of semiconductor nanostructures. We have shown that the tip-induced potential in the nanostructure can be more complicated than previously assumed. These results are of great importance for any qualitative and quantitative interpretation of scanning gate measurements.

Acknowledgements

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