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Scanning Single Electron Transistor Microscopy: Imaging Individual Charges

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1. Introduction

We report the development of a novel low-temperature electrostatic scanning probe microscope known as the single-electron transistor scanning electrometer (SETSE) [1]. The active element of this microscope is a metal thin-film single-electron transistor (SET) [2] fabricated at the end of a sharp glass tip. The SET is scanned in close proximity to the sample surface using a scanning probe microscope, and is used as an electrometer probe. The SETSE has demonstrated lateral spatial resolution of 100 nm and can detect ~1% of an electron charge (0.01e).

The SETSE was used to study the electric fields at the surface of a GaAs/$Al_xGa_{1-x}As$ two-dimensional electron gas (2DEG) sample. Images of the surface electric fields reveal fluctuations in the dopant and surface-charge distribution on 100 nm length scales, as well as individual photo-ionized charge sites. The SETSE has also been used to image and measure depleted regions, local capacitance, band bending, and contact potentials at submicrometer length scales on the surface of this semiconductor sample.

2. Microscope and Sample Description

The SET is a submicrometer-sized tunneling device whose current flow is governed by the Coulomb Blockade effect [2,3]. At low temperatures and proper voltage bias, the current flowing through the SET fluctuates periodically with increasing applied electric field. Hence, monitoring of the current through the SET as it is scanned over the sample provides a means of mapping the surface electric field.

Fabrication of the SET probe tip involves the evaporation of three separate areas of a thin (10 to 20 nm) aluminum film onto glass fiber with the shape of a truncated shallow cone. A circular patch of film covering the 100 nm diameter tip constitutes the field-sensitive island. The films for source and drain leads spread out from the edges of the tip and extend up the sides of the fiber to electrical contacts. The fabrication procedure has described elsewhere in detail [1]. The three electrode shapes are defined by natural shadowing, and require no lithographic processing.

The SET-tipped fiber is installed in a low-temperature scanning probe microscope stage, which allows three-dimensional positioning of the tip near the sample with subnanometer precision and stability. Electrical contacts allow measurement and control of the SET bias voltage, source-drain current, and voltage between SET and sample. Coulomb blockade was observed in the SET at temperatures below 4 K.

The semiconductor sample studied is a GaAs/AlGaAs 2DEG grown by molecular beam epitaxy. A δ-doped layer of Si donor atoms with density 5×10^{12} cm^{-2} is grown 22 nm below the sample surface. Most of the donor electrons are trapped in states at the GaAs surface, whereas a small fraction go to the GaAs/$Al_xGa_{1-x}As$ interface located 60 nm below the sample surface. Here they form a metallic two-dimensional electron gas with density 1×10^{11} cm^{-2}.

3. Charge, Field, Capacitance Imaging

Surface electric fields are imaged by recording the SET current as the probe is scanned without feedback in a plane at a fixed height above the sample surface (typically 25 nm). The local capacitance between tip and sample can be imaged simultaneously by measuring the periodicity of the SET response to applied tip-sample voltage.

Surface electric fields on short length scales are produced by fluctuations in the surface and dopant charge layers, modified by the dielectric response of the intervening semiconductor material as well as the presence of the conducting 2DEG sheet. These fluctuations have been imaged on the 100 nm length scale. Typically there are 300 surface and ionized dopant charges within the resolution limit of the SETSE. Numerical simulations indicate that a random placing of these charges would produce fluctuations in the surface potential nearly twice what are observed, which suggests a more uniform distribution.

Despite the resolution limits of the SETSE, individual charges can be imaged under appropriate conditions. At the low temperatures of these measurements, the surface electric field maps are stable to within 1%. Brief, low-intensity illumination of the sample by near-infrared light introduces permanent changes to the surface electric field pattern. The differences in the electric field maps before and after illumination reveal isolated 100 nm features which are consistent with the appearance of single positive and negative charges. These charges correspond to photo-induced charge transfer of electrons between dopants, surface traps, and the 2DEG.

Longer scale electric fields have also been imaged by the SETSE. Band bending at cleaved edges, as well as depletion fields produced by application of a bias voltage between the 2DEG and a metal gate evaporated upon the surface of the sample have also been observed by this microscope.

Local capacitance measurements provide topographic (and perhaps compositional) information complementary to electric field data. Changes in local tip-sample capacitance as small as 10^{-17} F are easily imaged with the SETSE, with much lower applied fields (10-100 V/cm) and frequencies (near dc) than those utilized in other capacitance microscopies [4].

4. Conclusions

Further improvement of the SETSE is likely to proceed along two fronts. The SETSE will be extended to the measurement of other electrostatic properties, such as local work function [1] or compressibility [5], or to measurement at higher frequencies [6]. At the same time, further development of SETs and probes with smaller dimensions will enhance spatial resolution and electrostatic sensitivity, while increasing operating temperatures. With good fortune, these developments will allow the SETSE to be applied to a wide variety of fundamental and applied problems.

References

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