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MICROSCOPY WITH A SINGLE ELECTRON TRANSISTOR PROBE

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The coulomb blockade effect of a single electron transistor is harnessed to make an electrometer probe capable of imaging electric properties of a sample at 100 nm resolution. The sensitivity is such that it can image individual electrons that have been photoexcited, a sensitivity adequate so that a number of other mesoscopic phenomenon can be directly imaged.
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The quest to control and fabricate materials on ever smaller length scales has been greatly facilitated by many traditional forms of microscopy. Electron microscopy routinely resolves the atomic structure of many crystalline interfaces. Secondary ion emission microscopy can give chemical information at the sub-micron level. Optical microscopy, enhanced by spectroscopic and confocal techniques is another convenient commercially available technique. The full arsenal of such techniques are key to the continued advancement of the high technology sector such as the semiconductor or storage industries.

In the past decade there has been an explosion in research on a whole new microscopy technique called scanned probe microscopy [1]. The concept is to put a probe in close proximity to a sample surface to measure some local property. There are numerous varieties of such probes. The most prominent one, the scanning tunneling microscope or STM, measures the tunneling current between a metallic tip and the sample. This has enabled atomic level imaging of surfaces, their various reconstructions and individual molecules or atoms. Furthermore as a spectroscopic instrument it is also capable of measuring the density of states down to the atomic level, which can give direct insight into numerous

physical phenomenon. While ultimately very powerful, it is only measuring the surface properties, so that limits one to samples where both the physics is on the surface monolayer and one is capable of the extreme care required in the sample's surface preparation.

Most physical phenomenon do not conveniently reside on the top monolayer of the surface, yet local information about a phenomenon can penetrate through an otherwise nonideal surface. Examples include electromagnetic fields from buried fluorescent molecules, thermal fields of subsurface ohmic heating, static magnetic fields from nanometer scale domains or vortices of superconductors or electric fields from dopant distributions in semiconductors. This has motivated the development of new panalogy of local probes [1]. In the atomic force microscope (AFM) sharp tips can respond to force from the sample, not only as a result of friction or van der Waals attraction, but also from magnetic or voltage gradients whose source is below the surface. Because of their simplicity AFM tips are commercially available and have found wide spread use. Recently there has been a trend to structure the probes with increasing sophistication enabling new quantities to be measured. Apertures on metalized tapered glass fibers give access to optical properties below the diffraction limit. Others use microscopic hall bars or squids and thermocouples to measure local magnetic fields and temperatures. In particular surface electrical properties have been measured with noncontact techniques such as scanning capacitance microscopy [2], scanning Kelvin probe microscopy [3] and electric-field

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sensitive atomic force microscopy [4]. Indeed the last has in one instance [5] shown the remarkable ability to detect the presence of individual charges on insulators.

The exemplary focus here is the capabilities and promise of a probe microscope that operates on a different principle and can image electrical field and individual charges with a spatial resolution of better than 100 nm and two orders of magnitude greater charge sensitivity of 1% of a single electron. This probe, called a single electron transistor or SET is perched on the tip of a needle. The SET is a rather recent innovation in itself [6] and forms the active element of the microscope which we call the single electron transistor scanning electrometer or SETSE [7]. Because all of the important parameters are known, unlike earlier methods, one can assign a quantitative interpretation to the SETSE signal. Furthermore its high sensitivity allows it to be a very weakly perturbative probe, ideal for sensitive semiconducting systems.

The SET consists of a small (100 nm) island held in close proximity to the surface [Fig. 1(C)]. Source and drain leads attach on opposite edges of this disk shaped island through tunneling junctions. The current tunnels through the junctions at a rate determined by the island's electrostatic potential with respect to the source and drain. This potential is in turn controlled by the electric

field that the island experiences from external sources, such as fixed charges or capacitively coupled electrodes on a nearby sample (Fig. 1). At low temperatures and at proper voltage bias, the current flowing through the SET fluctuates periodically as this electric field increases. In fact, the current passes through the a full period each time the electric field lines terminating on the island induce a charge of exactly one additional electron [Fig. 1(A)]. This is a result of the coulomb blockade effect [6]. Hence, monitoring of the current through the SET as it is scanned over the sample provides a means of mapping the electric field emanating from the sample surface.

Fabrication of the SET involves the evaporation of three separate areas of thin (10 to 20 nm) aluminium film onto a specially shaped glass fiber. The end of the fiber has a shallow conical taper that terminates at the tip in a flat, nearly circular area ~100 nm in diameter [Fig. 1(B) and (C)]. A circular patch of film covering the 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 source and drain leads are deposited first by separate evaporations from the side and rear. After an *in situ* exposure to oxygen that creates the oxide tunnel barriers, a final end-on evaporation deposits the island.

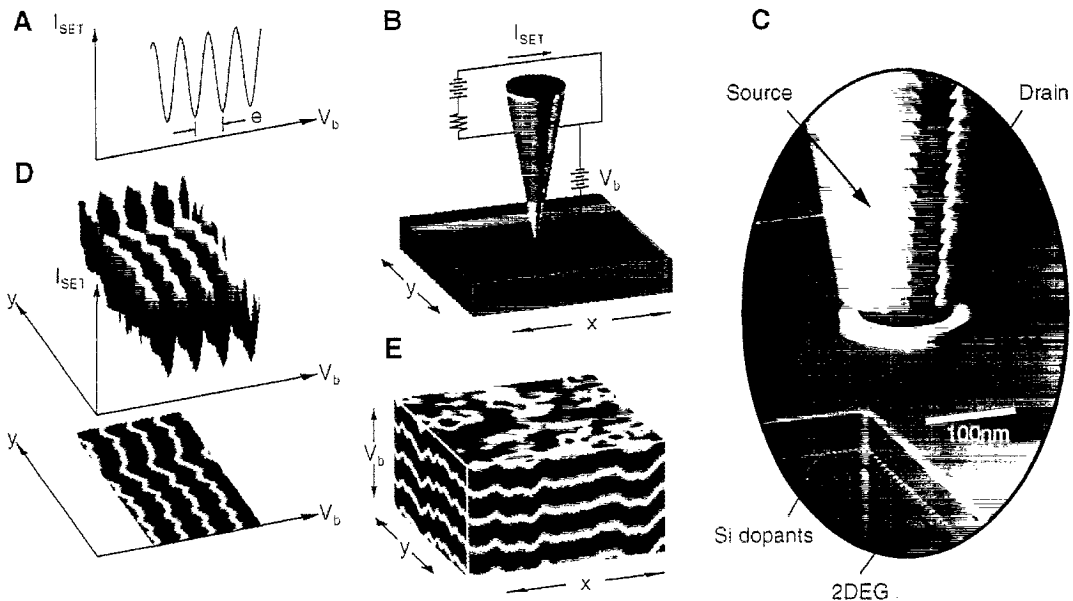


Fig. 1. (A) Typical current oscillations $I_{SET}(V_b)$ of a SET. (The zero of I_{SET} is offset, the amplitude is actually ~20% of the average). (B) Schematic depiction of the SET probe tip suspended above the GaAs/Al_xGa_{1-x}As heterostructure near a gate. (C) Magnified view of the tip and cutaway view of the sample. (D) $I_{SET}(V_b)$ vs y for a 2 μ m line scan: (Top) 3D representations after Fig. 1(A), (Bottom) 2D color representation of the same data. The wiggling of the stripes is caused by variations in the electrical charge density of the surface. (E) Color representation of a complete data set of $I_{SET}(V_b)$ vs x and y for a 2 μ m \times 2 μ m raster scan over a non-gated region. The top of the data block maps the electric field of the sample surface as detected by the SETSE. The side of the block is taken from Fig. 1(D).

All three electrode shapes are defined by natural shadowing.

The SET-tipped fiber is installed in a low-temperature scanning microscope probe stage, providing x - y - z positioning of the tip near the sample with sub-nanometer precision and stability. For best resolution and signal, the tip is held as close to the surface as possible without contact, typically at 25 nm height. Electrical contacts [see Fig. 1(B)] enable the application of a voltage V_b between the SET and the sample (or other electrodes) on the sample and also provide the means of biasing the SET and monitoring its current.

The electric field between tip and sample is monitored by recording the SET current I_{SET} as the probe is scanned without feedback in a plane at a fixed height z above the planar sample surface. Collection of a typical data set involves positioning the probe over the surface and sweeping the sample bias voltage V_b by an amount sufficient to cause the induced charge on the island to vary by several electrons. This in turn causes the SET current $I_{\text{SET}}(V_b)$ to oscillate through several full cycles, one for each electron [see Fig. 1(A)]. A sequence of such curves taken as the tip is scanned along a line in the y direction is illustrated in Fig. 1D by two equivalent plots, representing the magnitude of $I_{\text{SET}}(y, V_b)$, first by height and then more compactly by a colored gray scale. Finally, a raster scan in x and y results in a complete $I_{\text{SET}}(x, y, V_b)$ data set [Fig. 1(E)]; contour lines of constant color in the x - y plane indicate lines of constant electric field, with successive contour lines representing electric fields that differ by a fixed amount corresponding to an induced charge of one electron. Because the SET current I_{SET} varies nearly sinusoidally with the sample bias voltage V_b , we can characterize I_{SET} at each point in our data set by a period and a phase. The period [e/C_s , see Fig. 1(A)] is determined by the capacitance C_s between the tip and the sample electrode and varies primarily with height z . The phase, which essentially counts the number of electrons induced on the tip, contains most of the information about the spatial distribution of electric fields. It forms a direct and calibratable measure of the effective surface potential V_s .

A simple scan of the SET conductance across a 2×2 micron area of GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ heterostructure grown by molecular beam epitaxy is shown in Fig. 2. It has a δ -doped layer of Si atoms of density $5 \times 10^{12} \text{ cm}^{-2}$ is grown 22 nm below the sample surface within an $\text{Al}_x\text{Ga}_{1-x}\text{As}$ region. Many of these Si atoms ionize and act as electron donors. Most of the electrons are trapped in states at the (GaAs) surface, while a small fraction go to the GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ interface located 60 nm below the sample surface. Here they form a metallic sheet, a two-dimensional electron gas (2DEG) [10]. To describe its electrostatic behavior, the sample may be regarded as

a conductor (the 2DEG) topped by 60 nm of insulator containing the donor and surface charge layers. Potential fluctuations on short length scales are produced by these charge layers. The potential change required in the sample to induce a single coulomb blockade oscillations in the SET is about 30 meV. For the probe geometry of this image that corresponds to about 15 electrons on the sample. Typically there are about 300 surface and ionized dopant charges underneath the tip. We believe the statistical fluctuations in this number across the sample are imaged in Fig. 2. However, numerical simulations indicate that a random placing of these dopants and trapped charges would produce fluctuations in V_s nearly twice as large as observed in Fig. 2, which suggests a more uniform distribution. Such fluctuations in the potential play an important role in limiting the mobility of the underlying 2DEG and give a new means of characterizing the disorder.

The SETSE can be used to image individual electron charges on and within the semiconductor sample (Fig. 3). In the absence of light, maps of the effective surface potential V_s as in Fig. 2 are repeatable to within 1%. This allows one to subtract maps made before and after brief, low intensity illumination. The differences show up as a few small circular spots whose size (~ 100 nm) is limited by the spatial resolution. These are images of isolated photo-ionized or neutralized sites, presumably donor atoms or traps. Figure 3 shows such a "difference" map. Sufficiently energetic photons create free carriers that can transfer electrons between various sites, primarily the silicon dopants and the surface traps, converting some neutral sites into charged ones and

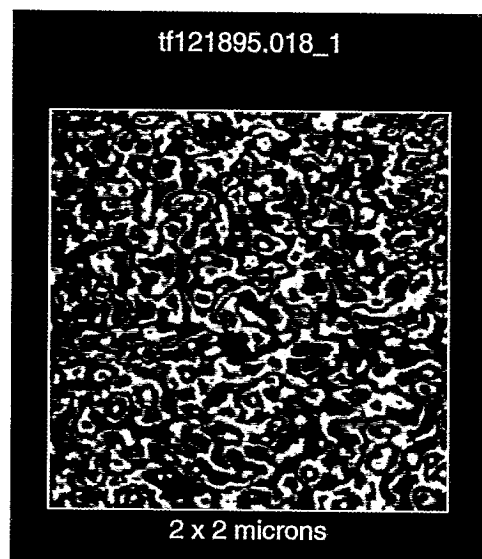


Fig. 2. x - y map of the SET current I_{SET} showing fluctuations in the potential from dopants and surface charges.

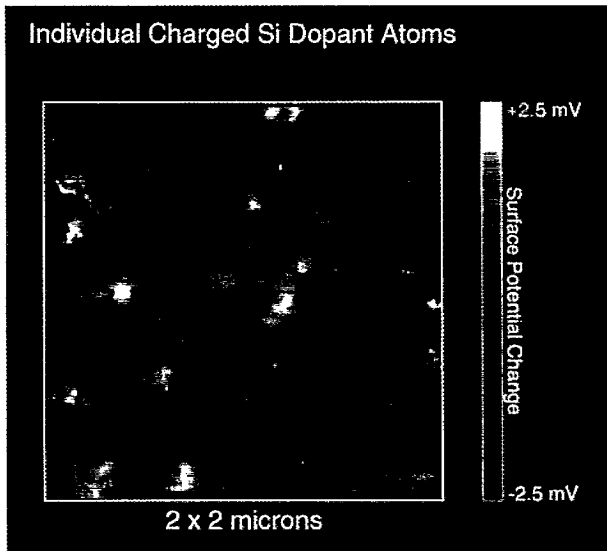


Fig. 3. Photoactivity of single dopant atoms and surface traps shown in x - y maps of the surface potential V_s , induced by exposure to light. Individual photo-ionized (neutralized) sites with a single electron charge are seen as light (dark) spots.

vice-versa. In this image, the light spots mark new positive charges and the dark spots new negative charges. The more intense signals are likely from higher (surface) sites and the weaker changes from lower (donor layer) sites. Simulations of the charge-coupling fraction f for a single charge of $\pm e$ buried at these levels predict changes in V_s of approximately 1.5 to 2.5 mV, as observed. Such measurements can be performed at different wavelengths to perform a very local photoionization spectroscopy.

In the future the physics of a number of fundamental problems particularly in mesoscopics can now be addressed with the SETSE. For example the depletion length and structure at the edge of a side gateable 2D electron gas has been predicted [8] and be directly imaged by the SET probe by several alternate techniques: The reduced capacitance over a depleted area can be measured, also the electric potential may well be different from the undepleted 2DEG, finally the screening to oscillating sidegate or backgate potentials can also be measured and for the basis of a depletion image. This becomes even more interesting when a magnetic field quantizes this gas into various Landau levels which imposes further structure on the depletion region [9] which too could be imaged with the SETSE. These include edge states and strips of compressible and incompressible electron gas which should have distinct potentials and also varying abilities to screen electric fields, both measurable quantities for the SET probe [10].

There is a long standing controversy about the current and potential distribution of the quantum hall state [11–13], with arguments ranging from “the current is carried uniformly across the hall bar” to “all the current flows at the edges of the hall bar”. In the classical limit the hall voltage between left and right edges of a current carrying strip in a magnetic field should change linearly with position. However at the various integer filling factors when the 2DEG is in a magnetic field, this is not the case, since here the screening ability of the electrons is modified leading to varied slow divergences of the potential at the edge. Again the SETSE could be an ideal noninvasive probe for such a system.

The contact potential or difference in work function between sample and tip has also been measured by the SETSE [7] and this too has implications. Consider the cross-section of a simple p - n diode. As one crosses the junction the bands bend to accommodate the redistribution of charges and reflecting the dopant distributions also. Understanding and maintaining tight control over the profile of these dopant distributions is a key factor in decreasing the size of modern transistors. In principle the SETSE could even monitor this on commercial semiconductors especially if the resolution can be further improved by another order of magnitude and a way can be found to expose such a junction without intervening surface effects on the charge distribution. The same sensitivity to the band potential could enable it measure and map various quantum hall states. As a magnetic field is increased on a 2DEG, the bands shift in energy in a sawtoothed pattern as the various Landau levels cross the Fermi level. This effect has been detected already with a fixed SET lithographically patterned onto a spot over a 2DEG [14]. Any related spatial structure can be imaged with the SETSE, for example strong density fluctuations in the 2DEG could have multiple coexisting Landau levels.

Sometimes devices can exhibit nonreproducible or hysteretic effects. This can happen if a high gate voltage permanently transfers electrical charge onto a surface or into a dopant layer. The source, magnitude and extent of such nonequilibrium effects can be mapped and quantified with a SETSE. Such effects might also be observed in regions of high current density such as near a constriction of a current path.

The scope of physics issues that might be addressed by the SETSE can be broadened if it can be designed to give higher spatial resolution and operate at higher temperature. Both occur naturally when the island size of the SET is decreased and an order of magnitude improvement is quite reasonable. The challenge will then focus on samples that can maintain interesting physical phenomenon close enough to the surface to take advantage of the SETSE's capabilities. Finally

new extensions to the SETSE could be implemented in the future such as single-electron capacitance spectroscopy [15] which is a powerful new technique to record the complete electron energy structure of mesoscopic systems.

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