

Tunneling images of a 2D electron system in a quantizing magnetic field

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Abstract

We have applied a scanning probe method, Subsurface Charge Accumulation (SCA) imaging, to resolve the local structure of the interior of a semiconductor two-dimensional electron system (2DES) in a tunneling geometry. Near magnetic fields corresponding to integer Landau level filling, submicron scale spatial structure in the out-of-phase component of the tunneling signal becomes visible. In the images presented here, the structure repeats itself when the filling factor is changed from $\nu = 6$ to $\nu = 7$. Therefore, we believe the images reflect small modulations in the 2DES density caused by the disorder in the sample.

Key words: 2D electron system; scanning probe imaging ; tunneling ;

Scanned probe techniques sensitive to electric fields can provide direct images of 2D electron systems [1]. Here, we present an extension of Subsurface Charge Accumulation (SCA) imaging [2], adapted to probe the 2DES interior in a novel tunneling geometry [3]. The measurement works as follows and is schematically shown in Fig. 1(a): A tunneling barrier separates the 2D layer and a parallel 3D substrate. An ac excitation voltage applied between the substrate and a sharp metal tip locally induces charge to tunnel back and forth between the 3D and 2D layers. The measured signal is the resulting ac image charge on the tip electrode, and no charge tunnels directly onto the tip. In this way, the experiment provides a local measurement of the ability of the 2D system to accommodate additional electrons.

The sample used for these measurements was an $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ / GaAs (001) wafer grown by molecular beam epitaxy (MBE), shown schematically in Fig.

1(a). The 2DES is located a distance of 60 nm below the exposed surface, and a distance 40 nm above a degenerately doped (10^{18} cm^{-3}) GaAs substrate (3D metal). The average electron density in the 2DES is $6 \times 10^{11} \text{ cm}^{-2}$, the low-temperature transport mobility is $\sim 10^5 \text{ cm}^2/\text{Vs}$ and the zero magnetic field 3D-2D tunneling rate is approximately 200 kHz. We position the tip to within a few nanometers of the sample surface using an innovative scanning head that provides a high degree of mechanical and thermal stability [4]. The image charge signal is detected using a circuit constructed from low-input-capacitance high-electron-mobility transistors. To acquire images, the tip is scanned laterally across the surface without the use of feedback. The data were acquired with the system immersed in liquid helium-3 at a temperature of 270 mK, with a 20 kHz applied excitation voltage of 8 mV rms.

Fig. 1(b) shows a simple equivalent circuit for the measurement: The local contribution to the signal is modeled as a tip-2DES capacitance C_{tip} in series with the tunneling barrier, represented as a capacitor C_T and resistor R_T in parallel. To account for phase shifts

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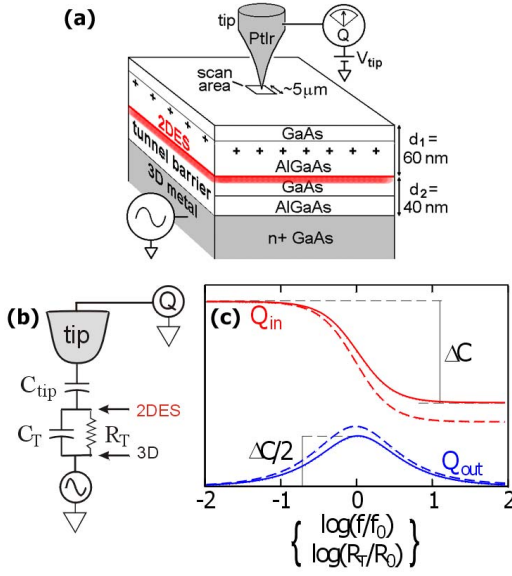


Fig. 1. (a) Schematic of heterostructure sample and SCA measurement. The 2DES forms in the potential well at the GaAs/AlGaAs interface from electrons provided by silicon dopants (+'s). An AlGaAs tunneling barrier separates the 2DES from a 3D substrate. (b) Equivalent circuit of the sample-tip system. (c) In-phase and 90° out-of-phase signals (Q_{in} and Q_{out}) versus frequency f and tunneling resistance R_T . The charging has identical functional dependence on f and R_T , with characteristic values of $f_0 = [2\pi R_T (C_T + C_{tip})]^{-1}$ and $R_0 = [2\pi f (C_T + C_{tip})]^{-1}$, respectively. The magnitude of the curves is set by the tip-sample capacitance difference ΔC between a fully charging and locally non-charging 2DES. The dashed curves qualitatively show the enhancements in Q_{in} and Q_{out} as the in-plane relaxation rates approach the tunneling rate.

we define two amplitudes Q_{in} and Q_{out} , representing respectively the in-phase and 90° out-of-phase (lagging) components of the image charge per unit excitation voltage, typical units being aF. Fig. 1(c) shows the charging characteristics of the circuit. In zero magnetic field, the tunneling rate across the barrier f_0 is about ten times higher than the 20 kHz excitation frequency. In this frequency range, the out-of-phase component is more sensitive to variations in the local tunneling resistance. In contrast, the in-phase component is mostly sensitive to capacitance variations. More rigorous models show an enhancement in the charging characteristics as the 2DES becomes an increasingly poor conductor, i.e., as the system approaches integer filling, as indicated qualitatively by the dashed curves in Fig. 1(c).

As the magnetic field approaches integer fillings $\nu = 6$ and $\nu = 7$, we observe an increase in Q_{out} , corresponding to an increase in R_T , as shown in the fixed-tip signal of Fig. 2(a). Clear and reproducible features appear also in image scans, as exemplified in Fig. 2(b).

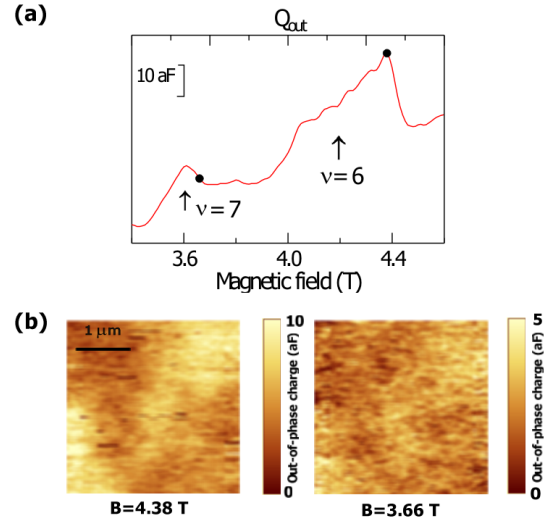


Fig. 2. Out-of-phase data near $\nu = 6$ and $\nu = 7$. (a) A fixed-tip Q_{out} curve displaying the $\nu = 6$ and $\nu = 7$ peaks, acquired near the upper right corner of the imaged area. (b) Two $3\mu\text{m} \times 3\mu\text{m}$ images with values of B indicated as dots in (a). All data was acquired with the tip bias adjusted to equal the contact potential [5], so that the tip itself does not produce a dc perturbation of the 2DES, as determined by in situ Kelvin probe measurements. Charge sensitivity calculated from this data is $\sim 0.06 e/\text{Hz}^{1/2}$. Topographic component of Q_{out} has been subtracted [3].

As one lowers the field the structure appears at around $\nu = 6$, then disappears and again reappears at around $\nu = 7$. This re-emergent behavior likely originates from density modulations induced by the static disorder potential, consistent with the interpretation in [2]. Structure is seen down to a length scale of few hundred nm; the spatial resolution of our technique is set by the radius of curvature of the tip, nominally 50 nm in this case. More surprisingly, structure also exists in length scales $\sim 1\mu\text{m}$, in contrast to the expectation that the disorder length scale is set by the distance to the donors and to the 3D layer (both 15 nm in our case).

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