Erasable Electrostatic Lithography

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We report a revolutionary lithography called Erasable Electrostatic Lithography (EEL) where patterns of charge are drawn on a GaAs surface with a scanning probe. The charge locally depletes electrons from a subsurface 2D electron system (2DES) to define any quantum component. Crucially, EEL is performed in the same low-temperature high-vacuum environment required for measurement, so patterning, measurement, and device modification are made during a single cool down. This vastly reduces the measurement-lithography cycle time compared to other lithographic techniques such as electron-beam and local oxidation by atomic force microscopy [1,2]. EEL is particularly productive where device geometry is of interest, such as investigations of the 0.7 anomaly [3] and chaotic electron trajectories in quantum billiards [4].

Spots of charge drawn with a probe bias less than -5 V deplete underlying 2DES electrons. The charge is erased locally with a probe bias of +3 V, or globally by illuminating the sample with a red light emitting diode. Charge patterns drawn with a negative probe bias persist unchanged for at least one week, whereas patterns drawn with a positive bias decay in a few hours. This electrostatic behaviour is similar to that of surface electrodes, which suggests the EEL mechanism is the charging of GaAs surface states.

We demonstrate the unique productivity of EEL by drawing, characterising, and then erasing a series of quantum components, all during a single cool down. The device incorporates a 2DES, with electron mobility $5\times10^{6}\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ and density $3.1\times10^{11}\,\mathrm{cm}^{-2}$, formed at a GaAs/AlGaAs heterojunction 97 nm beneath the surface. Electron-beam fabricated metal surface electrodes are biased to -1 V to define a 5 μm long quantum wire. EEL components are then drawn on the GaAs surface between the electrodes, and characterised by plotting the wire conductance G against the electrode bias V_g. Figure 1 (a) illustrates the EEL fabrication of a point contact. Two spots of charge are drawn laterally about the wire centre with a probe bias of -6 V. The dashed line outlines the electron depletion showing how a narrowing, or point contact, is formed. Figure 1 (b) plots G against V_g before and after the EEL fabrication. Before fabrication, the wire potential is evidently disordered as no conductance plateaus are seen. After EEL fabrication, plateaus are observed quantised in units of $2e^2/h$ showing that a 1D electron system has been created by a point contact. Barriers, antidots, and large and small quantum dots were later drawn within the quantum wire.

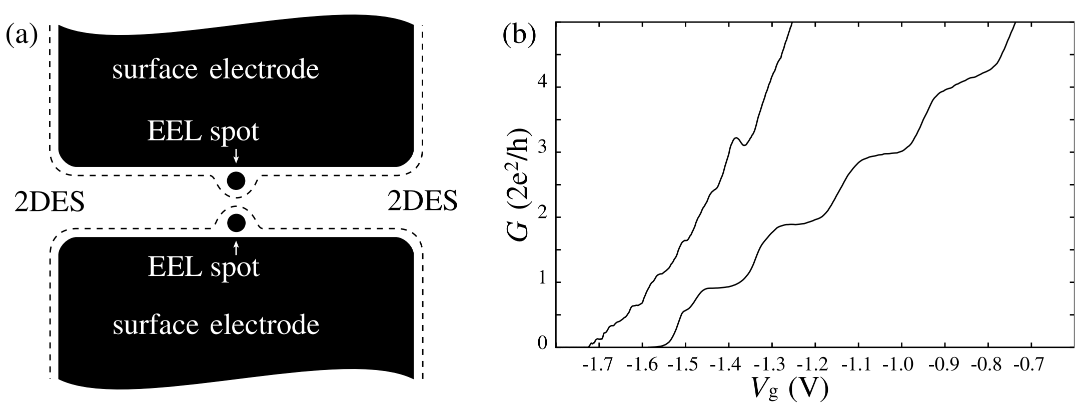

Figure 1. (a) Point contact fabricated by EEL at the centre of a quantum wire. The dashed line outlines the 2DES electron depletion. (b) Plots of quantum wire conductance against electrode bias. The leftmost plot characterises the original wire (offset by +0.6 V). The rightmost plot characterises the EEL fabricated point contact. A 1 kΩ series resistance has been subtracted from both plots.

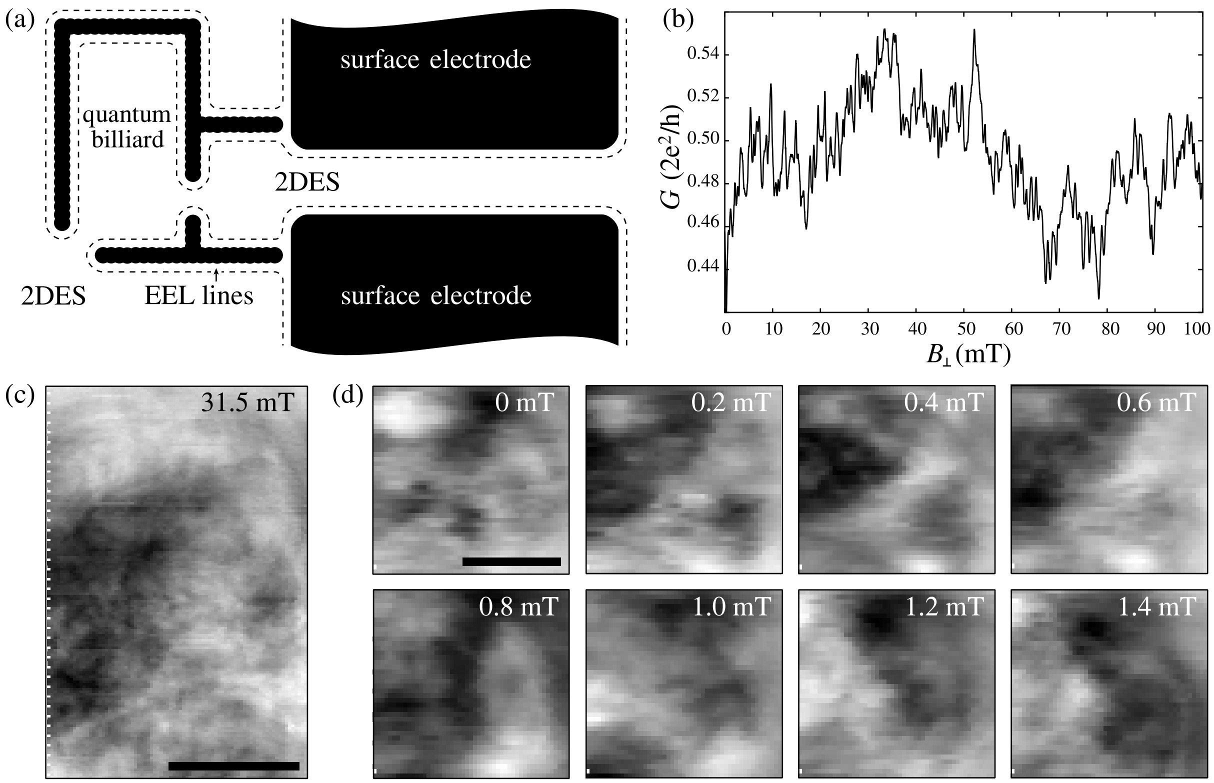

Figure 2. (a) Quantum billiard fabricated by EEL adjacent to a quantum wire. The dashed line outlines the 2DES electron depletion. (b) Plot of device conductance against perpendicular magnetic field. A 1 kΩ series resistance has been subtracted. (c) High resolution conductance image of the quantum billiard in 31.5 mT. (d) Series of low resolution conductance images of the top half of the quantum billiard, from 0 mT to 1.4 mT in 0.2 mT increments. Scale bars are 1 μm.

A row of closely spaced EEL spots defines a linear barrier, or line, in the 2DES. We demonstrate EEL lines by drawing the 1.4 μm by 2.2 μm quantum billiard illustrated in figure 2 (a). The EEL spots are separated by 100 nm and drawn with a probe bias of -6 V. Further EEL spots tune the billiard entrance and exit to each transmit one degenerate 1D subband ($n = 2$) which maximises the fractal dimension [4]. For the duration of the experiment, the surface electrode bias is taken to -1 V to deplete underlying electrons and so separate the billiard source and drain 2DES regions. Figure 2 (b) plots billiard conductance against perpendicular magnetic field. Note that the structure is reproducible and is not noise. Broad structure seen in figure 2 (b) is caused by classical trajectories between the entrance and exit, while fine structure is caused by chaotic trajectories. The minimum period in conductance is 2 mT, corresponding to a change of one flux quantum h/e through an area 2 μm^2. Figures 2 (c) and (d) present conductance images, made by scanning the probe 50 nm above the sample surface while the billiard conductance is recorded to determine the colour of the associated image pixel. During imaging the probe bias is small, so the wealth of detail seen in figure 2 (c) is interpreted as interference due to wavelength-scale modifications to electron paths. Figure 2 (d) presents a series of eight lower resolution conductance images of the top half of the billiard. The magnetic field is increased by 0.2 mT between images, which is chosen to be less than the minimum period seen in figure 2 (b). Some structure is unique to an image, while other features evolve. We do not yet have a complete understanding of the structure or the length scales involved.

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[4] A P Micolich *et al.*, *Phys. Rev. Lett.* **87**, 036802 (2001).