Detecting electrons on helium with a single-electron transistor (SET)

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Abstract

A superconducting single electron transistor (SSET) device has been designed and fabricated inside a ring which defines a shallow pool of liquid helium. The objective is to detect electrons trapped above the surface of the superfluid helium. Preliminary results are presented.

Key words: Single Electron Tunneling; Electrons on helium; Qubits

Phil Platzman and Mark Dykman have suggested [1][2] that surface state electrons on helium would be excellent candidates for qubits (quantum bits). The |0> and |1> states of the qubit would be the ground and first excited state (Rydberg states) in the potential well of an electron trapped on a helium surface on a micro-structured substrate [3]. The states would be coupled by resonant microwave excitation. A test qubit has been designed and fabricated, incorporating a single-electron transistor (SET) to detect the electrons. Preliminary results are reported here.

Single Electron Transistors can measure charge with a sensitivity of $6.3 \times 10^{-5} e/\sqrt{\mathrm{Hz}}$ at 10 Hz [4]. A metallic island is connected through two tunnel junctions to the source and drain leads and capacitively coupled to a gate terminal. The charging energy $E_{\mathrm{C}} = e^2/2C_\Sigma$ inhibits tunnelling below a threshold voltage $V_{\mathrm{C}} = e/C_\Sigma$, where C_Σ is the total island capacitance. The source-drain voltage is biased close to V_{C} and a gate electrode voltage V_{g} can modulate the current. The Coulomb blockade is effective at temperatures $T < E_{\mathrm{C}}/k_{\mathrm{B}}$ and for junction resistances larger than the quantum resistance $R_{\mathrm{Q}} = 25.6\,\mathrm{k}\Omega$. If aluminium is used for the island and leads then the superconducting energy gap modifies the tunnelling and can lead to enhanced sensitivity.

In order to make an electronic qubit on liquid helium, the electrons would be trapped over a thin film of helium, typically 0.5 μm thick. The electronic ground state "floats" above the helium at a mean height $z_0 =$ 11 nm. In the first excited state we have $z_1 = 43$ nm. If the electron is trapped above a metallic SET island, then the induced charge on the island will change as the electron is excited. The magnitude of the change is estimated as $\Delta Q \approx 0.04e$ depending on the coupling, well within the sensitivity of an SET. The aims of the current experiments are to trap and detect electrons using an SET and, if possible, detect their quantum state.

An SEM photograph of the SET device is shown in Fig.1 on a Si substrate with a SiO_2 buffer layer, made using e-beam lithography and shadow evaporation techniques inside an aluminum ring. The ring defines a helium pool 0.5 μm deep and 2.5 μm in diameter. The tunnel junctions $Al/Al_2O_3/Al$ have an area of 120 x 50 nm^2. All input leads to the SET were filtered with π-filters and thermo-coax cables. The dc source-drain characteristic (I-V) was measured as a function of temperature (down to 50 mK) and the gate modulation. In the superconducting state, the tunneling of normal quasiparticles starts at $V_t = (4\Delta + 2E_{\mathrm{C}})/e$ [6], where Δ is the superconducting energy gap (120 μeV).

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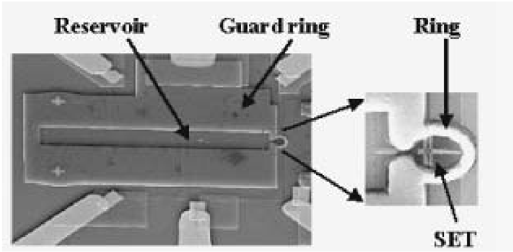

Fig. 1. Microscope photograph of a micro structure showing, at the left the completed SET design with all the electrodes and at the right SET inside the ring guard.

The charging energy was estimated to be $E_C = 100$ μeV with $C_\Sigma = 800$ aF . The normal resistance of the tunnel junctions was 22 kΩ, which is rather low.

The source-drain voltage was set at $V_{\rm bias}$ (typically 0.7 mV) and modulated with 5 μV at 30 Hz. The ac SET current was measured using a lock-in amplifier as the gate voltage was swept. Coulomb blockade oscillations (CBO) are shown in Fig.2. The gate period was $\Delta V_g = 11$ mV corresponding to a gate-island capacitance $C_g = e/\Delta V_g = 14$ aF. The micro-structure includes two other electrodes, the electron reservoir and the guard ring. Oscillations were observed by sweeping these electrodes, with voltage periods of 6 and 26 mV, giving capacitances to the island of $C_r = 27$ aF and $C_{gd} = 6$ aF respectively. The CBO were close to a fundamental sine wave. The phase ϕ of the oscillations can therefore be used to deduce changes in the island charge $\Delta Q/e = \Delta\phi/2\pi$ [5].

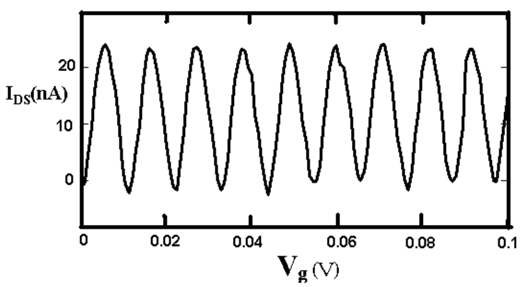

Fig. 2. The I-V_g Characteristics of the SET showing the modulation of current as a function of the gate voltage, with drain-source voltage biased at the onset of conduction. Each oscillation corresponds to one electron addition on the SET island.

The sensitivity of this SET is $\Delta Q = 10^{-2}$e. The cell is filled with pure ^{4}He so that the free helium level lies below the ring. The pool fills with superfluid helium by surface tension. We start by testing the SET response to changes in the island charge. At optimum gate and drain source voltage, we change the reservoir voltage by one period. The induced additional electron can be seen in the CBO by a phase shift $\Delta\phi = 2\pi$. Then we modulate the SET current by sweeping the gate voltage from 200 mV to 130 mV. At this point we optimise the SET for maximum sensitivity.

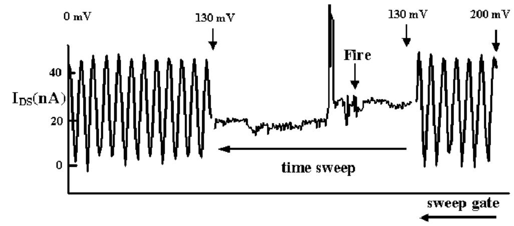

Fig. 3. This figure shows the I-V_g Characteristics of the SET current as a function of gate sweep from 200 mV to 0 mV. At 130 mV corresponding to the maximum sensitivity, electrons were generated by firing the filament. A π phase shift was recorded before and after firing.

Free electrons were generated using thermionic emission from a pulsed filament above the device. An increase in the SET current was immediately observed due to an increase in the working temperature produced by the hot electrons. The resistance increased dramatically, shown by a peak. After cooling again, the gate sweep is continued and the phase of the CBO has changed, by a phase shift of π, as shown in Fig.3, showing trapped charge has been detected.

In summary, we have designed and fabricated a microstructure for trapping electrons on helium, incorporating an SET. Preliminary experiments show that the device is sensitive to free electrons generated by a tungsten filament. Experiments are now in progress to control these electrons in the trap.

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