Counting Individual Trapped Electrons on Liquid Helium

G. Papageorgiou, P. Glasson, K. Harrabi, V. Antonov, E. Collin, P. Fozooni,
P. G. Frayne, M. J. Lea,[a] and D. G. Rees
Department of Physics, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, United Kingdom

Y. Mukharsky
CEA—DRECAM, Service de Physique de l'État Condensé, Centre d'Études de Saclay, 91191 Gif-sur-Yvette Cedex, France

(Received 30 November 2004; accepted 1 March 2005; published online 5 April 2005)

We show that small numbers of electrons, including a single isolated electron, can be held in an electrostatic trap above the surface of superfluid helium. A potential well is created using microfabricated electrodes in a 5 μm diameter pool of helium. Electrons are injected into the trap from an electron reservoir on a helium microchannel. They are individually detected using a superconducting single-electron transistor as an electrometer. A Coulomb staircase is observed as electrons leave the trap one–by–one until the trap is empty. A design for a scalable quantum information processor using an array of electron traps is presented. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1900301]

The smallest element for electronic quantum information storage would be a single electron in a quantum dot. Two quantum states form the basis $|0\rangle$ and $|1\rangle$ for a quantum bit, or qubit, while interacting qubits enable quantum information processing.[1] The trapping, control, and detection of single electrons are major technical challenges. Single electrons, and a positron named Priscilla,[2] have been held in a Penning trap and detected by resonant interactions. In the solid state, electrons have been trapped in a chain of tunnel junctions;[3] one-electron quantum dots have been made in self-assembled structures,[4] etched vertical pillars,[5] and lateral quantum dots;[6] single[7] and double[8] dots have incorporated a quantum point contact electrometer. Here we show that surface-state electrons can be held in an electrostatic trap on a pool of superfluid helium, 5 μm in diameter and some 0.8 μm deep. Individual localized electrons, including a single electron, are detected and counted by a single-electron transistor (SET) electrometer beneath the helium. This leads to a design for a quantum processing device using a linear array of trapped electronic qubits on helium.[9]

Surface-state electrons on liquid helium[10] are attracted by a weak positive image charge in the liquid and are held by a vertical pressing electric field E_z. This produces a vertical potential well with a series of excited states, similar to the Rydberg states in a hydrogen atom. Below 2 K, the electrons are in the quantum ground state, "floating" about 11 nm above the surface. Excited Rydberg states can be populated by microwave absorption at frequencies above 125 GHz.[11] An electronic qubit[9] would have the ground state as $|0\rangle$ and the first excited state as $|1\rangle$. The electrons are well decoupled from the environment, interacting only weakly with thermal vibrations, or ripplons, on the atomically smooth superfluid helium surface. Electron–electron Coulomb interactions are important and a two-dimensional (2D) electron Wigner crystal forms at low temperatures.[10] These unique properties make electrons on helium excellent candidates for qubits, with long decoherence times.[9] An essential requirement is to trap and control individual localized electrons, as reported here.

The devices[12] are shown in Fig. 1. Free electrons are generated by thermionic emission from a pulsed filament. The electrons are stored on the helium surface in an electron reservoir, Figure 1(a), which consists of a 10 μm wide helium microchannel,[13] depth $d \approx 0.8$ μm, above an electrode

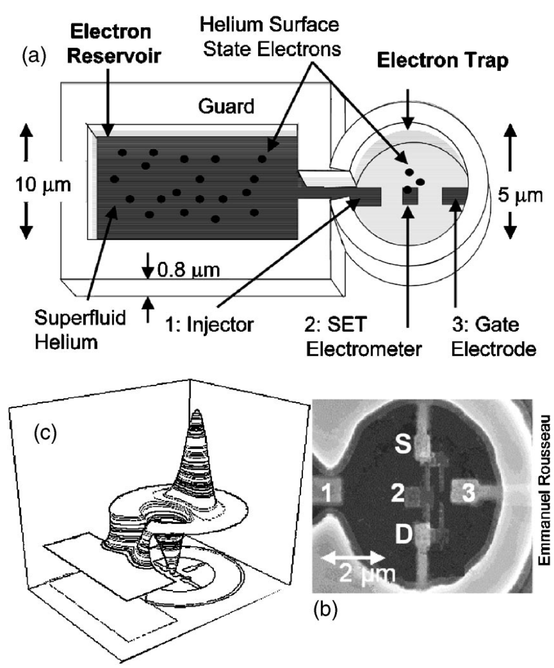

FIG. 1. Microelectronic devices with Al, Au, and Nb electrodes (Ref. 12) on a Si/ SiO_2 substrate. (a) A Nb guard electrode defines an electron reservoir and a helium pool (the electron trap), filled with superfluid helium. (b) Photograph of the trap, injector (1), electrometer [SET island (2)] and gate (3) electrodes. Source (S) and drain (D) electrodes are connected to the SET island through Al/A_2O_3/Al tunnel barriers. The SET operates below 0.5 K in the superconducting state at the Josephson-quasiparticle peak in the I–V characteristic, with a source-drain voltage bias of 0.55 mV and a source-drain current $I_{SD} \approx 5$ nA. (c) Electrostatic model showing an electronic trap between a repulsive gate potential and an attractive electron reservoir potential.

[a]Author to whom all correspondence should be addressed; electronic mail: m.lea@rhul.ac.uk

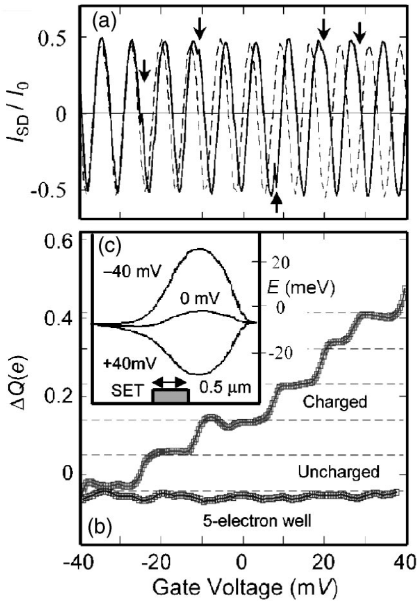

FIG. 2. Counting individual electrons. (a) Coulomb blockade oscillations in I_{SD} (mean amplitude I_0) for an uncharged (dashed line) and a charged (solid line) helium pool at 150 mK. The charge induced in the SET island $Q=(\phi/2\pi)e$, where ϕ is the phase of the oscillations. The arrows show phase and charge steps for the charged pool, giving an offset in the phase compared to the uncharged state. (b) Charge steps in $\Delta Q/e=(Q+C_{g1}V_g)/e$ from (a), as individual electrons enter the trap as V_g is swept. The dashed lines are spaced at intervals of 0.092e. (c) Model potential energy of a five-electron trap for $V_g=+40$, 0, and -40 mV, showing inversion of the potential well for negative gate voltages.

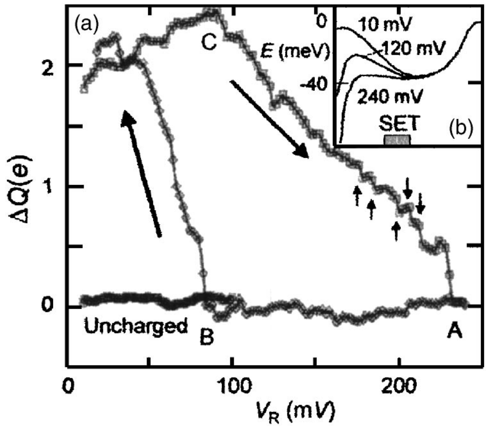

FIG. 3. Filling the electron trap. (a) Induced charge $\Delta Q/e$ while sweeping the reservoir voltage V_R for charged and uncharged helium. Arrows show steps in induced charge as the trap empties. (b) Model potential energy of the electron trap for $V_R=10$, 120, and 240 mV, showing the reduction in the barrier height as V_R increases.

positively biased at V_R. This electrode also extends into the circular helium pool whose surface forms an electron trap. This injector electrode enables electrons to be transferred between the reservoir and the electron trap, controlled by dc voltages on the SET, gate, and reservoir electrodes. The number of electrons N in a 2D trap is estimated from $N\approx CV(R)/e$, where $C=8\varepsilon_0 R$ is the capacitance of an unscreened charged pool of radius R, and $V(R)$ is the potential in the pool, with R and $V(R)$ measured from the potential minimum. A 10 mV trap, of radius 1 µm, will hold $N\approx 4$ electrons.

A single-electron transistor is placed beneath the helium surface in the electron trap. Periodic Coulomb blockade oscillations are observed in the dc current through the SET, as shown in Fig. 2(a), as the gate voltage V_g is swept. Each oscillation corresponds to an electronic charge $Q=-e$ induced in the SET island by capacitive coupling $Q=-C_{g1}V_g$ from the gate electrode (a positive gate voltage induces negative charge in the SET). The oscillation period $\Delta V_{g1}=7.3$ mV, corresponds to $C_{g1}=e/\Delta V_{g1}=21.92$ aF. For an uncharged helium pool the relative long-term charge stability of this SET is about 0.01e, comparable with the best Si-based SETs.[14] The short-term $1/f$ noise is less important than this long-term drift in these experiments. The linear variation of Q with V_g provides a reference for the extra induced charge $\Delta Q=Q+C_{g1}V_g$ from surface-state electrons on the helium. Each surface-state electron in the trap induces a *positive* fractional charge in the SET island

$$\frac{\Delta Q_1}{e}=\frac{c_1}{c_1+c_2}>0, \tag{1}$$

where c_1 and c_2 are the capacitive electrostatic couplings from the free charge to the island and the rest of the world. The phase of the oscillations $\phi=2\pi(Q/e)$ is measured, using the SET as a sensitive electrometer.

The Coulomb blockade oscillations for a charged pool are shown in Fig. 2(a). As V_g is swept, jumps in the phase ϕ of the oscillations are observed, relative to the oscillations for an uncharged pool. These correspond to positive steps in $\Delta Q/e$ above the uncharged baseline, as electrons enter or leave the electron trap. Here some five electrons leave the trap. Free electrons are attracted into the electron trap by a positive gate potential, inducing an extra positive charge on the SET island. This only occurs after charging the helium surface. Random phase shifts and two-level fluctuators[15] are sometimes observed from the movement of substrate charges, but with different characteristics from charging the electron trap. Sweeping the electrodes negative removes all the surface-state electrons and recovers the uncharged results.

The steps in Fig. 2 reflect the discrete nature of electronic charge. The voltage, or Coulomb gap, required to increase the charge on a capacitor C by one electron is $\Delta V=e/[C+V(dC/dV)]=e/C'$, allowing for variations in C with voltage V (i.e., from changes in the electron trap size). The gate electrode is coupled to the trapped electrons through a capacitance C_{g2}. A gate voltage increment $\Delta V_{g2}=e/C'_{g2}$ is required to attract each extra electron into the trap. The average spacing between the arrows in Fig. 2(a) implies that $C'_{g2}\approx 13$ aF. The size of the charge steps $\Delta Q_1/e$ is typically 0.092e. An electrostatic model reproduces these values and demonstrates the effects of the gate and reservoir potentials. Figure 2(c) shows model potential energy plots for a five-electron trap, controlled by the gate.

Figure 3(a) shows charging the trap by sweeping the reservoir voltage V_R. At point A (large positive V_R) there is no potential barrier between the reservoir and the electron trap [see Fig. 3(b)] and the trap is empty. As V_R is reduced, a potential barrier forms, but the trap remains empty (i.e., $\Delta Q/e\approx 0$). The potential energy of the surface-state electrons in the reservoir will be $E\approx -eV_R+ne^2d/\varepsilon\varepsilon_0=-eV_{el}$ where n m^{-2} is the number density of the electrons on the reservoir and d is the depth of the helium. As V_R is reduced, this increases faster than the barrier potential. At point B the electrons spill over from the reservoir to fill the trap and the extra induced charge ($\Delta Q/e>0$) on the SET island increases

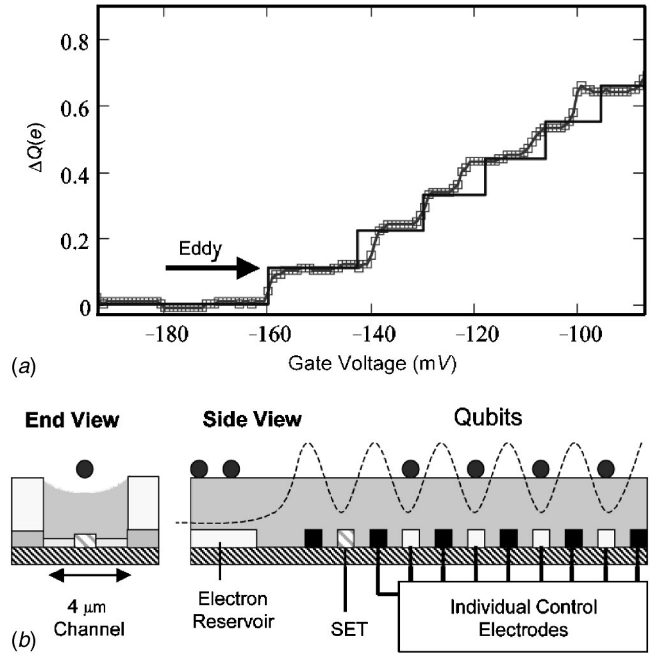

FIG. 4. Trapping single electrons. (a) The trapping of a single localized electron (called Eddy) is shown. The solid line shows the fitted theoretical voltage steps for the discrete charging of a parabolic potential well (Ref. 16). (b) Schematic cross sections of a linear quantum information processor in a helium microchannel showing the electron reservoir, electronic qubits, control electrodes, and SET detector readout. The qubits are held in periodic potential wells.

rapidly. This continues until $V_{\mathrm{el}}=0$ when electrons will no longer be confined by the grounded guard electrode (note that $V_R>0$ at this point). Electrons remain in the trap as V_R is swept positive again. At C the potential energy of the electrons in the reservoir falls below the top of the barrier and the trapped electrons become isolated. As V_R increases further the barrier height decreases and electrons escape from the trap. For $V_R>170$ mV, a series of small steps in $\Delta Q/e \approx 0.1$ can be identified as electrons leave one–by–one. The hysteresis is a key feature of the filling and emptying of the electron trap.

At low temperatures Coulomb interactions between the electrons in the trap leads to localized electrons in specific structural arrangements[16–18] related to the 2D Wigner crystal or a Coulomb glass, depending on any disorder potential. The simple Coulomb gap capacitance model will then only be an approximation. Experimentally, the electron addition spectrum can show double electron addition (as seen in semiconductors[19]) and hysteresis, consistent with these ideas.

Figure 4(a) shows a single isolated electron in a quantum well trap, as the first in a charging sequence. This enables a design for a linear chain quantum information processor, Fig. 4(b). An electron channel reservoir feeds electrons across an SET detector into a series of single-electron traps as qubits, controlled by electrodes and microwave pulses. Such a tuneable interacting linear chain would have many advantages for quantum information processing.[20] The crucial read-out stage, following a processing sequence, starts by ionizing those electrons in the upper $|1\rangle$ state. The remaining $|0\rangle$ electrons are then conveyed along the linear trap array and detected with the SET in classical time, hence reading the output register. Such a scheme could also be incorporated in a recent proposal for spin-based qubits using electrons on helium.[21]

To conclude, we have shown that we can trap electrons, including single electrons, in a microfabricated potential well and detect and count them with a single-electron transistor. The detection of individual localized electrons is of great interest in itself and is an essential precursor to the detection of the quantum state of individual electrons and their potential application as qubits.

The authors thank A. J. Dahm, M. I. Dykman, J. Goodkind, S. A. Lyon, P. J. Meeson, P. M. Platzman, and J. Saunders for discussions and F. Greenough, A. K. Betts, and others for technical support. The work was supported by the EPSRC, by the EU Human Potential Programme under Contract No. HPRN-CT-2000-00157 *Surface Electrons*, and by Royal Holloway, University of London.

[1]M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information*, CUP, Cambridge, 2000; see also the Quantum Information Science and Technology Roadmap on http://www.qist.lanl.gov
[2]Hans Dehmelt, Science **247**, 539 (1990); M. F. Bartusiak, B. Burke, A. Chaikin, A. Greenwood, T. A. Heppenheimer, M. Hoffman, D. Holzman, E. J. Maggio, and A. S. Moffat, *A Positron named Priscilla* (National Academies Press, Washington, 1994).
[3]P. D. Dresselhaus, L. Ji, S. Han, J. E. Lukens and K. K. Likharev, Phys. Rev. Lett. **72**, 3226 (1994).
[4]P. M. Petroff, A. Lorke, and A. Imamoglu, Phys. Today **54**, 46 (May 2001).
[5]L. P. Kouwenhoven, D. G. Austing, and S. Tarucha, Rep. Prog. Phys. **64**, 701 (2001).
[6]M. Ciorga, A. S. Sachrajda, P. Hawrylak, C. Gould, P. Zawadzki, S. Jullian, Y. Feng, and Z. Wasilewski, Phys. Rev. B **61**, R16315 (2000); D. Sprinzak, Yang Ji, M. Heiblum, D. Mahalu, and Hadas Shtrikman, Phys. Rev. Lett. **88**, 176805 (2002).
[7]R. Hanson, B. Witkamp, L. M. K. Vandersypen, L. H. Willems van Beveren, J. M. Elzerman, and L. P. Kouenhoven, Phys. Rev. Lett. **91**, 196802 (2003).
[8]J. M. Elzerman, R. Hanson, J. S. Greidanus, L. H. Willems van Beveren, S. De Franceschi, L. M. K. Vandersypen, S. Tarucha, and L. P. Kouenhoven, Phys. Rev. B **67**, 161308(R) (2003).
[9]M. I. Dykman, P. M. Platzman, and P. Seddighrad, Phys. Rev. B **67**, 155402 (2003).
[10]*Two Dimensional Electron systems on Helium and Other Cryogenic Substrates*, edited by E. Y. Andrei (Kluwer, New York, 1997); Y. Monarkha and K. Kono, *Two-dimensional Coulomb Liquids and Solids* (Springer-Verlag, Berlin, 2004).
[11]E. Collin, W. Bailey, P. Fozooni, P. G. Frayne, P. Glasson, K. Harrabi, M. J. Lea, and G. Papageorgiou, Phys. Rev. Lett. **89**, 245301 (2002).
[12]G. Papageorgiou, PhD thesis, Royal Holloway, University of London, 2004.
[13]P. Glasson, V. Dotsenko, P. Fozooni, M. J. Lea, G. Papageorgiou, S. E. Andresen, and A. Kristensen, Phys. Rev. Lett. **87**, 176802 (2001).
[14]N. M. Zimmerman, W. H. Huber, A. Fujiwara, and Y. Takahashi, Appl. Phys. Lett. **79**, 3188 (2001).
[15]M. Furlan and S. V. Lotkhov, Phys. Rev. B **67**, 205313 (2003).
[16]V. M. Bedanov and F. M. Peeters, Phys. Rev. B **49**, 2667 (1994).
[17]M. E. Raikh, L. I. Glazman, and L. E. Zhukov, Phys. Rev. Lett. **77**, 1354 (1996); A. A. Koulakov, and B. I. Shklovskii, Philos. Mag. B **77**, 1235 (1998).
[18]A. A. Koulakov, F. G. Pikus, and B. I. Shklovskii, Phys. Rev. B **55**, 9223 (1997).
[19]R. C. Ashoori, H. L. Stormer, J. S. Weiner, L. N. Pfeiffer, S. J. Pearton, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **68**, 3088 (1992).
[20]L. F. Santos, M. I. Dykman, M. Shapiro, and F. M. Izrailev, Phys. Rev. A **71**, 012317 (2005); S. C. Benjamin and S. Bose, Phys. Rev. Lett. **90**, 247901 (2003); S. C. Benjamin, J. Phys. **6**, art 61 (2004).
[21]S. A. Lyon, cond-mat/0301581 (2003).