Controlled single electron transfer between Si:P dots

T. M. Buehler, V. Chan, A. J. Ferguson, A. S. Dzurak, F. E. Hudson, D. J. Reilly*, A. R. Hamilton and R. G. Clark  
Centre for Quantum Computer Technology Schools of Physics and Electrical Engineering, University of New South Wales, NSW 2052, Australia

D. N. Jamieson, C. Yang, C. I. Pakes and S. Prawer  
Centre for Quantum Computer Technology School of Physics, University of Melbourne, VIC 3010, Australia

We demonstrate electrical control of Si:P double dots in which the potential is defined by nanoscale phosphorus doped regions. Each dot contains approximately 600 phosphorus atoms and has a diameter close to 30 nm. On application of a differential bias across the dots, electron transfer is observed, using single electron transistors in both dc- and rf-mode as charge detectors. With the possibility to scale the dots down to few and even single atoms these results open the way to a new class of precision-doped quantum dots in silicon.

Considerable progress has recently been made towards spin-based quantum computing in semiconductors, most notably with experiments that probe and control electron spin coherence in GaAs quantum dots [1, 2, 3]. An outstanding challenge for semiconductors remains coherent control of single electron spins bound to individual 31P donors in isotropically pure silicon 28Si which promises to allow extremely long coherence times. In Kane’s original scheme [4] the qubits were defined by nuclear spin states of 31P dopants in Si. Since then, other Si:P schemes have been proposed based on both spin [5, 6, 7, 8] and their diffusion to ~1nm based on bulk rates [13]. The control gates are deposited using EBL, followed by the two Al/Al2O3 SETs, fabricated using a bilayer resist and double-angle metallization process.

To control the transfer of electrons in the double dot structures, the symmetry of the double well potential is adjusted by applying a differential voltage to gates SL and SR. The resulting charge distribution in the double dot is then determined by monitoring the source-drain current (or reflected rf amplitude in the case of rf operation) ISD of either of the two SET charge detectors on the device.

Fig. 1b plots the SET current as VSL is swept over a 100mV range for a device with a dot separation d=100nm. Throughout these measurements, compensation voltages on additional gates keep the SETs at operating points of maximum sensitivity. We show four periods of a sawtooth waveform, characteristic of single electron transfer between the two dots (inset Fig. 1a). The sawtooth can be understood as a steady polarization of the system until it becomes energetically favourable for an electron to be transferred. The transfer events occur with an average period of VSL=24mV over a wide range of gate voltages. We note that these events are not perfectly periodic and additional charge noise is also present, discussed below.

In Fig. 1c, we plot (dISD/dVSL) as a function of the two gate voltages VSL and VSR. The locus of the charge transfer events is highlighted by the dark lines, indicating high transconductance. These follow linear trajectories and show a period of 24mV in VSL and 224mV in VSR, indicating a stronger capacitive coupling of the double dot to the left symmetry gate SL than to SR. This can be explained by lithographic alignment errors between the surface gates and the buried double dot. We have measured five double dot devices, with dot separations of d=80nm, 100nm and 150nm. All show the characteristic quasi-periodic sawtooth seen in Fig. 1b, but in each case the relative coupling capacitance and period varies

*Now at Dept. Physics, Harvard University, Cambridge MA 02138, USA
due to differing misalignment. We have calculated the capacitance matrix for our devices for varying displacement between the surface gates and buried double dots, finding values consistent with our data [14]. Displacements of order 50nm can modify the capacitance or transfer period of induced charge $\Delta q$ due to a single electron transfer event. For the inter-dot transfer event we deduce $\Delta q = 0.035e$. T = 50 mK, B = 1T.

**FIG. 1:** a) SEM image of a Si:P double-dot device with three control gates and two SETs. White circles indicate implant regions. b) SET current $I_{SD}$ as a function of $V_{SL}$ with $V_{SR}$ = -30mV (horizontal line in a) for a double dot device with $d = 100nm$. c) SET transconductance $dI_{SD}/dV_{SL}$ (intensity plot) as a function of $V_{SL}$ and $V_{SR}$ for the same sample. B = 1T was applied to suppress superconductivity at T = 50 mK.

The correlation signal exhibits a sharp peak whenever a charge transfer event occurs, whilst uncorrelated events correspond to single electron transfer events. d) Determination of induced charge $\Delta q$ due to a single electron transfer event. For the inter-dot transfer event we deduce $\Delta q = 0.035e$. T = 50 mK, B = 1T.

**FIG. 2:** Electron transfer events observed in $dI_{SD}/dV_{SL}$ of a) left SET, and b) right SET, as a function of $V_{SL}$ and $V_{SR}$ for a double dot sample with $d=100nm$. c) Correlated SET output plotted against $V_{SL}$ (horizontal line in a,b). Sharp peaks correspond to single electron transfer events. d) Determination of induced charge $\Delta q$ due to a single electron transfer event. For the inter-dot transfer event we deduce $\Delta q = 0.035e$. T = 50 mK, B = 1T.

Readout of qubits requires detectors that operate on time scales faster than the qubit relaxation (or excitation) time. Towards this goal, the radio-frequency SET (rf-SET) offers near quantum-limited sensitivity [16, 17] with switchable back-action [18]. Large (100 MHz) measurement bandwidths can be achieved by embedding the SET detector in a LC matching network, mapping dc conductance to reflected rf power. In rf measurements with $B = 0T$, the SET source-drain bias data (Fig. 3a) exhibit a typical Josephson quasiparticle spectrum. To maximize the detection signal we bias the SET to a region of small differential resistance ($V_{SD} \approx 4\Delta$), where the sensitivity exceeds $10^{-5}e/\sqrt{\text{Hz}}$. Fig. 3b shows the time-domain response of an rf-SET to a voltage step applied to a SET bias gate which induces a charge of $\Delta q = 0.1e$ on the SET island. Fig. 3c shows the output signal from one rf-SET on a double dot device with $d = 150nm$ as a function of time while a differential bias is applied between the control gates $V_B$ and $V_{SR}$. Here again, the rf signal shows a characteristic sawtooth response, indicating periodic transfer of single electrons between the buried phosphorus dots. The signal to noise ratio of the rf response is greater than the dc data in Fig. 1a since there is reduced 1/f charge noise due to the shorter timescale.

A number of control experiments were also carried out on the double dots and related devices. The integrity of the ion-stopping mask was confirmed by fabricating nanocircuitry as in Fig. 1a but omitting the apertures for substrate doping. These devices showed no evidence of periodic charge motion in the substrate. The metallic density of states in the dots was confirmed by the observation of 75 electron transfers in the voltage range $V_{SL} = [-900mV, 900mV]$, all with a period close to 24 mV and all with the same slope in gate bias (Fig. 1a, 2a,b). Small variations in periodicity, seen in all data, are believed to be related to internal physical and electronic structure of the dots. Control devices with no implants, or with silicon implants, but with the same SET and gate structures were measured under identical conditions. No pe-
FIG. 3: Measurements using rf-SET detection. a) Bias spectroscopy of a rf-SET in the superconducting state (B = 0T) where $\Delta$ is the superconducting gap for Al. b) Single-shot response of the rf-SET to a small step in gate voltage creating an induced charge of 0.1e at the SET island. c) Sawtooth signal from periodic electron transfer in a double dot with d = 150nm, observed in the rf-SET signal (left axis scale) as a function of time while a differential bias voltage (right axis scale) is applied to control gates B and S$^R$. Data is an average of 16 traces, each with acquisition time 1.7 ms.

Periodic transfer was seen in these although random charge transfer features, most likely due to electron traps in the substrate, were observed [19].

The results here demonstrate a gate-controlled Si:P double dot system with the facility for fast measurement of inter-dot electron transport. To our knowledge these Si:P double dots are the only type defined by localized doping of silicon. They can also be reduced to single atom dots using single-ion implantation [11].

The Si:P double dot devices demonstrated here represent a critical step towards silicon-based quantum computing, being configured with control and readout circuitry at the scale required for a two-atom Si:P charge qubit. The fast detection of single electron transfer over a distance of order 100nm provides good prospects for qubit readout, while correlated twin-SET detection offers additional immunity from materials-related charge noise. Future experiments will involve microwave spectroscopy on both DQD and two-P-atom devices to map out the energy levels and determine $T_1$ and $T_2$.

This work was supported in part by the Australian Research Council, the Australian Government, the U.S. National Security Agency, the Advanced Research and Development Agency and the U.S. Army Research Office under contract no. DAAD19-01-1-0653. We acknowledge E. Gauja, R. Starrett and A. Greentree for useful discussions.

[1] J.M. Elzerman, R. Hanson, L.H. Williams van Beveren, B. Witkamp, L.M.K. Vandersypen and L.P. Kouwenhoven Nature 430, 431 (2004).
[2] J. R. Petta, A. C. Johnson, J. M. Taylor, E. A. Laird, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson and A. C. Gossard, Science 309, 2180 (2005).
[3] F. H. L. Koppens, J. A. Folk, J. M. Elzerman, R. Hanson, L. H. Willems van Beveren, I. T. Vink, H. P. Tranitz, W. Wegscheider, L. P. Kouwenhoven, and L. M. K. Vandersypen, Science 309, 1346 (2005).
[4] B. E. Kane, Nature 393, 133 (1998).
[5] R. Vrijen, E. Yablonovitch, K. Wang, H.W. Jiang, A. Balandin, V. Roychowdhury, T. Mor and D. DiVincenzo, Phys. Rev. A 62, 012306 (2000).
[6] M. Friesen, P. Rugheimer, D. E. Savage, M. G. Lagally, D. W. van der Weide, R. Joynt, and M. A. Eriksson, Phys. Rev. B 67, 121301(R) (2003).
[7] R. de Sousa, J. D. Delgado, and S. Das Sarma, Phys. Rev. A 70, 052304 (2004).
[8] C. D. Hill, L. C. L. Hollenberg, A. G. Fowler, C. J. Wellard, A. D. Greentree, and H.-S. Goan, Phys. Rev. B 72, 045350 (2005).
[9] L. C. L Hollenberg, A. S. Dzurak, C. Wellard, A. R. Hamilton, D. J. Reilly, G. J. Milburn and R. G. Clark, Phys. Rev. B 69, 113301 (2004).
[10] F. E. Hudson, A. J. Ferguson, C. Yang, D. N. Jamieson, A. S. Dzurak and R. G. Clark, cond-mat/0510488
[11] D.N. Jamieson, C. Yang, T. Hopf, S.M. Hearne, C.I. Pakes, S. Prawer, M. Mitic, E. Gauja, S.E. Andresen, F.E. Hudson, A.S. Dzurak, R.G. Clark, Appl. Phys. Lett., 86 202101 (2005).
[12] D.R. McCamey, M. Francis, J.C. McCallum, A.R. Hamilton, A.D. Greentree and R.G. Clark, Semicond. Sci. Technol. 20 363 (2005).
[13] P. M. Fahey, P. B. Griffin and J. D. Plummer, Rev. Mod. Phys. 61, 289 (1989).
[14] K. H. Lee, A. D. Greentree, J. P. Dinale, C. C. Escott, A. S. Dzurak and R. G. Clark, Nanotechnology 16 74 (2005).
[15] T. M. Buehler, D. J. Reilly, R. Brenner, A. R. Hamilton, A. S. Dzurak and R. G. Clark, Appl. Phys. Lett. 82, 577 (2003).
[16] R. J. Schoelkopf, P. Wahlgren, A. A. Kozhevnikov, P. Delsing and D. E. Prober, Science 280, 1238 (1998).
[17] A. N. Korotkov, Phys. Rev. B 49, 10381 (1994).
[18] G. Johansson, A. Käck and G. Wendin, Phys. Rev. Lett. 88, 046802 (2002).
[19] M. Furlan and S. V. Lotkhov, Phys. Rev. B 67, 205313 (2003).