Single-electron quantum dot in Si/SiGe with integrated charge sensing

C. B. Simmons, a Madhu Thalakulam, Nakul Shaji, Levente J. Klein, Hua Qin, R. H. Blick, D. E. Savage, M. G. Lagally, S. N. Coppersmith, and M. A. Eriksson b

University of Wisconsin-Madison, Madison, Wisconsin 53706, USA
(Received 18 October 2007; accepted 1 November 2007; published online 20 November 2007)

Single-electron occupation is an essential component to the measurement and manipulation of spin in quantum dots, capabilities that are important for quantum information processing. Si/SiGe is of interest for semiconductor spin qubits, but single-electron quantum dots have not yet been achieved in this system. We report the fabrication and measurement of a top-gated quantum dot occupied by a single electron in a Si/SiGe heterostructure. Transport through the quantum dot is directly correlated with charge sensing from an integrated quantum point contact, and this charge sensing is used to confirm single-electron occupancy in the quantum dot. © 2007 American Institute of Physics. [DOI: 10.1063/1.2816331]

Semiconductor quantum dots provide highly tunable structures for trapping and manipulating individual electrons, with significant potential for integration and scaling, and therefore are promising candidates as qubits for quantum computation. Because silicon has small spin-orbit coupling and an abundant isotope with zero nuclear magnetic moment, it is attractive for spin-based quantum computing and for spintronics applications. These features have motivated efforts to develop quantum dots in silicon using a wide variety of confinement techniques.

Here, we report the achievement of a single-electron quantum dot in a Si/SiGe modulation-doped heterostructure, in which an integrated charge-sensing quantum point contact is used to monitor electron transitions in and out of the dot and to verify the electron number. Analogous single-electron quantum dots in GaAs/AlGaAs heterostructures have been used to form spin qubits—quantum dots with spin states that can be manipulated and measured.

To achieve single-electron quantum dots in Si/SiGe heterostructures, one must overcome complications that do not arise in GaAs/AlGaAs heterostructures, including (1) smaller Schottky barriers, leading to difficulty in the fabrication of low-leakage gates, (2) the need to implement strain management in Si/SiGe heterostructures, leading to disorder in the form of dislocations, mosaic tilt, and surface roughness, and (3) the larger effective mass of carriers in Si compared to GaAs, which decreases the tunneling rate through otherwise equivalent barriers to the leads. Further more, mobility in Si/SiGe is typically smaller than in III-V systems. Our work builds on much recent progress in overcoming many of these issues in Si/SiGe, including the fabrication of gated quantum dots, the observation of the Kondo and Fano effects in such a dot, and the demonstration of transport through spin channels in Si/SiGe double dots.

The quantum dot used in this work was formed in a two-dimensional electron gas (2DEG) located 60 nm below the surface in a Si/SiGe heterostructure containing a Si quantum well. Details of the sample can be found in reference 28. The sample was illuminated for 20 s while at a temperature of 4.2 K at the beginning of the experiment before cooling the dilution refrigerator to base temperature, in order to decrease the resistance of the Ohmic contacts. The results we report below depend critically on the ability to apply large gate voltages without causing leakage currents. The quantum dot was formed on a mesa 10 µm wide by 20 µm long. The Schottky gates were formed by Pd deposition immediately following the removal of the native oxide by brief immersion in hydrofluoric acid. The resulting Schottky gates supported applied voltages as large as −3.25 V relative to the electron gas.

A scanning electron micrograph of the top-gate design is shown in Fig. 1(a). Negative voltages applied to the top gates deplete the underlying electron gas, forming both a single quantum dot defined by gates top (T), left (L), right (R), and the plunger gate (G), and an integrated charge-sensing quantum point contact (QPC) formed by the charge sensor gate (CS) and gate R. Ohmic contacts to the 2DEG (shown schematically on the micrograph by superimposed white squares) were fabricated by the evaporation of an Au:Sb (1%) alloy with subsequent annealing at 550 °C. A dc bias voltage across the top pair or the right pair of these Ohmic contacts causes current to flow through the quantum dot ($I_{sd}$) or

![Figure 1.](image-url)
of Coulomb peaks. For this reason, we focus in this paper on charge sensing to confirm single-electron occupation.

Applying a negative voltage to gate CS, in combination with the effect of gate R, forms a QPC in close proximity to the quantum dot. By precisely tuning the gate voltage $V_{CS}$, the conductance of the QPC can be fixed on a steep transition in the pinch-off curve. In this configuration, the QPC functions as a sensitive electrometer for the neighboring quantum dot, because changes in the electron occupation of the dot result in measurable shifts in the QPC pinch-off curve. Numerically differentiating $I_{QPC}$ with respect to $V_G$ turns these discrete shifts into peaks, and such a differentiated curve is plotted in Fig. 2(top). The horizontal axes for the two plots are identical, and the data for each plot were acquired sequentially. There is a clear correspondence between the peaks in the two curves, demonstrating that the QPC functions as a reliable detector of charge transitions in the quantum dot. Importantly, this sensitivity is preserved even when transport through the dot is not measurable, as shown in Fig. 2.

The QPC is most sensitive to charge transitions in the quantum dot when its conductance varies rapidly as a function of gate voltage, and hence also as a function of the charge on the dot. However, changing $V_G$ to remove electrons from the dot also changes the potential of the coupled QPC. The result is that, for a particular value of $V_{CS}$, there is a finite range over which $V_G$ can vary for which the QPC is sensitive to charge transitions on the dot. Outside this range, the slope of the QPC conductance, which determines the sensitivity to charge transitions in the quantum dot, is too small to allow charge sensing of single electrons. In our system, transitions cannot be detected when $dI_{QPC}/dV_G$ is below 1 $\mathrm{fA/V}$. This provides an effective operational range of approximately 300 mV in $V_G$. When the dot contains the order of 30 electrons, this range is large enough to observe many charge transitions in the dot, because the spacing between the transitions is relatively small ($\sim 22$ mV). In the few electron regime, however, the spacing between transitions is larger and this range is not sufficient to observe more than three transitions with confidence. Nonetheless, a large dynamic range can still be obtained by compensating the effect of $V_G$ on the QPC by changing $V_{CS}$ in the opposite sense, keeping the QPC in the most sensitive operating point.

An example of this type of compensation is shown in Fig. 3(a). The voltage on gate G is swept through a range much larger than that corresponding to the sensitive region of the QPC. By changing $V_{CS}$, high sensitivity is maintained across the entire range of $V_G$, so that many charge transitions can be monitored on a single image plot. These charge transitions appear as the dark vertical lines in Fig. 3(a). The spacing in gate voltage between the peaks is not uniform, as is expected for a dot with very few electrons. The dot is empty of electrons for the most negative values of $V_G$, as indicated by the absence of dark lines on the left half of the figure. A rigid shift was applied to each horizontal line scan in Fig. 3(a) to remove two effects. First, before the shift is applied, the cross capacitance between gate CS and the quantum dot causes the vertical lines in Fig. 3(a) to slope to more negative $V_G$ for less negative $V_{CS}$ with a lever arm of 26%. In addition, random charge fluctuations cause shifts from line scan to line scan with a rms magnitude of 3.9 mV, which can be compared to the average spacing of 62.1 mV between the peaks.

![FIG. 2. (Color online) (top) The derivative of the quantum point contact current with respect to the gate voltage $dI_{QPC}/dV_G$ as a function of the gate voltage $V_G$. The peaks correspond to changes in the number of electrons in the dot. (bottom) The current through the quantum dot as a function of the gate voltage $V_G$. The peaks in the two curves are well aligned, indicating that the charge-sensing quantum point contact and the Coulomb blockade peaks in transport through the dot correspond to the same quantum dot charging phenomena.](image-url)
Figure 3(b) shows an average of seven diagonal linecuts taken parallel to the sensitive slice in Fig. 3(a). The charge transitions appear as five sharp peaks, corresponding to the removal of the last five electrons from the dot. The sequence of peaks terminates at $V_G = -1.68$ V, indicating that the quantum dot is empty of electrons in this regime. It is possible to then reduce the magnitude of $V_G$, refilling the dot with a known number of electrons starting from zero, something we have done many times over the course of the measurements reported in the dot.

The authors thank Lisa McGuire, Mark Friesen, and Robert Joynt for helpful discussions. This work was supported by NSA and ARO under Contract No. W911NF-04-1-0389, by NSF under Grant Nos. DMR-0325634 and DMR-0520527, and by DOE under Grant No. DE-FG02-03ER46028.