Single-electron transistor strongly coupled to an electrostatically defined quantum dot

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A system is described in which an Al-based superconducting single-electron transistor (S–SET) is fabricated directly above an electrostatically defined quantum dot formed in a two-dimensional electron gas. This arrangement allows the coupling capacitance between the S–SET central island and the dot to be comparable to the tunneling capacitances of the dot. As a result, the measured sensitivity of the S–SET referred to charge on the dot is $1.2 \times 10^{-4} e/\sqrt{\text{Hz}}$, about an order of magnitude better than previously reported results. The increased sensitivity makes this system ideally suited for broadband measurements such as study of individual tunneling events.

The advent of the high sensitivity, high bandwidth (>100 MHz) radio-frequency single-electron transistor (rf–SET) has made detecting rapid charge motion in real time a practical possibility. One possible application would be to study individual tunneling events in semiconductor devices such as quantum dots. However, in order to fully exploit the merits of the rf–SET technique, a high sensitivity ($\delta q_d$) referred to the dot charge is needed. Several groups have successfully coupled a SET to a quantum dot in a lateral configuration. The resulting coupling between the SET and dot is relatively weak, i.e., the capacitance between them is much smaller than the tunneling capacitances of the dot. As a result, only a moderate sensitivity ($\delta q_d > 10^{-3} e/\sqrt{\text{Hz}}$) was achieved, so that operation with even a 1 MHz bandwidth will result in a charge noise larger than $e$. A vertical configuration will provide stronger SET-dot coupling and in principle smaller $\delta q_d$ can be achieved. Recently, Koltonyuk et al. have studied a configuration in which a SET was fabricated directly on top of an etched dot. In their work, however, steady-state transport through the dot could not be probed. Furthermore, no value for $\delta q_d$ was reported. Here we describe a system in which a SET is fabricated on top of an electrostatically defined quantum dot. A very high charge sensitivity referred to the dot has been achieved, making this system well suited for study of single charge tunneling events using the rf–SET technique.

Figure 1(a) shows a scanning electron micrograph of the sample, illustrating the SET and six gates surrounding it which are used to form the quantum dot. The sample is fabricated in a two-step process on a GaAs/AlGaAs heterostructure containing a layer of high mobility two-dimensional electron gas (2DEG) $\approx 50$ nm below the surface. The gates are patterned first using electron beam lithography and Cr–Au metallization. The Al-based SET is then fabricated in a second lithographic step, using a standard shadow evaporation technique to produce the tunnel junctions. The quantum dot, which is formed in the 2DEG via application of negative voltages to the gates, is located immediately beneath the SET, as illustrated in Figs. 1(a) and 1(b). Figures 1(c) and 1(d) show the zero-bias conductances of the two quantum point contacts (QPCs) and the dot, indicating that the presence of the SET leads does not prevent formation of a good dot.

Both the SET and dot are Coulomb blockade devices. In general, varying the voltage on a nearby gate causes a change in the electrostatic potential on the device island, which in turn determines whether or not an extra electron can tunnel onto the island. As a result, Coulomb blockade oscillations will be observed in the current through such a device, with each oscillation corresponding to the addition of a single electron to the island.

Our configuration is unique in that the SET is located immediately above the quantum dot, providing very strong coupling between the two devices. We use a simple model shown in Fig. 2 to study this strongly coupled SET-dot system. Normally, one of the central gates with capacitance $C_g$...
to the SET and \( C_d \) to the dot is used to adjust the offset charges on both. The tunneling capacitances of the SET and the dot are represented by \( C_1-C_4 \).

Changing the gate voltage \( V_g \) will affect both the offset charge on the SET (\( Q_{0s} \)) and that on the dot (\( Q_{0d} \)). A calculation of \( Q_{0s} \) and \( Q_{0d} \) gives

\[
Q_{0s} = C_s V_g + \frac{(C_d V_g - N_s e)}{C_{c} + C_3 + C_4 + C_c}, \tag{1}
\]

\[
Q_{0d} = C_d V_g + \frac{(C_s V_g - N_d e)}{C_{c} + C_1 + C_3 + C_c}. \tag{2}
\]

where \( N_s \) and \( N_d \) are the number of electrons on the SET and the dot, respectively.

From Eq. (1), we see that besides the induced offset charge \( C_s V_g \) due to direct coupling to the gate, \( Q_{0s} \) is also affected by \( N_s \), which itself varies with \( V_g \) as described by Eq. (2). Changes in \( N_d \) cannot be neglected in the strongly coupled case, i.e., when \( C_s \) is comparable to the tunneling capacitances. If \( C_s \approx C_d \), both \( N_s \) and \( N_d \) will change at roughly the same rate, making identification of the origin of individual oscillations difficult.

However, our sample design is intentionally asymmetric, so that for the bottom central gate \( C_s \ll C_d \) [see Fig. 1(a)]. In this limit \( N_s \) changes much more slowly than \( N_d \) due to its weaker coupling to the gate. In Eq. (2), except for occasional changes in \( N_s \), \( Q_{0d} \approx C_d V_g \), and \( N_d \) which equals the integer closest to \( Q_{0d}/e \) changes periodically with \( V_g \). The SET as an electrometer thus has only weak feedback to the dot, whose properties remain mostly undisturbed.

Since \( C_d V_g \) changes continuously while \( N_d \) must be an integer, their difference shows a saw-tooth behavior and causes an oscillation in \( Q_{0s} \) in Eq. (1). If \( C_s \) is comparable to \( C_d + C_3 + C_4 \), this oscillatory term can have an amplitude of a significant fraction of \( e \), with a frequency the same as the change in \( N_d \). On the other hand, the first term in Eq. (1) causes a slow but linear change in \( Q_{0s} \). Since \( C_d \gg C_s \), the rapidly oscillating term associated with \( N_d \) will complete many periods before \( N_s \) changes by 1.

We have performed measurements on three samples in a dilution refrigerator at a mixing chamber temperature of 20 mK, with the SET in the superconducting state to obtain better charge sensitivity. In these measurements, we linearly increase the voltage on the bottom central gate, while monitoring the current \( I_s \) through the SET and the dot conductance \( G_d \). \( I_s \) was measured in a voltage biased four-probe configuration at a bias voltage slightly above \( 4\Delta \), where \( \Delta \) is the superconducting gap, while \( G_d \) is measured with a lock-in technique at zero direct current bias. All three samples show very similar results, and here we present data from one of them.

Figure 3 shows \( I_s \) and \( G_d \) versus gate voltage \( V_g \). Singly periodic Coulomb blockade oscillations are observed in \( G_d \), while two periods of oscillation are observed in \( I_s \). From the inset of Fig. 3, we can see that the faster oscillations in \( I_s \) have the same period as the oscillations in \( G_d \), indicating that they are indeed caused by changes in \( N_d \). To verify the origin of the slower oscillation, we measure \( I_s \) vs \( V_g \) when the dot charge is not quantized, as shown in Fig. 3(c). Singly periodic Coulomb blockade oscillations caused by direct coupling to the gate are observed in \( I_s \) in this case, with the same period as the slower oscillation in Fig. 3(a), indicating that the slower oscillation in \( I_s \) is indeed caused by direct coupling to the gate.

The sample parameters can be deduced from the periods of the oscillations and measurements of the \( I(V_{bias}) \) surfaces. For this sample, we find \( C_1 = 194 \text{ aF}, C_2 = 138 \text{ aF}, \) and \( C_3 \approx C_4 \approx 200 \text{ aF}, \) while \( C_s = 325 \text{ aF} \) is larger than the dot
tunneling capacitances. In addition, \( C_d = 32 \text{ aF} \gg C_i \approx 1.5 \text{ aF} \), as expected. From Eq. (1), we see that addition of an electron to the dot will cause a peak-to-peak oscillation of about \( 0.4 \text{ e} \) in \( Q_{0d} \), and that \( N_d \) will change by roughly 20 before \( N_s \) changes by 1. Both predictions are verified by the data. The sensitivity \( \delta q_d \) of the SET referred to the dot charge, which is calculated by comparing the measured current noise to the change in \( I_s \), caused by a change in \( N_d \) of 1, turns out to be \( \delta q_d = 1.2 \times 10^{-4} \text{ e}/\sqrt{\text{Hz}} \), an order of magnitude better than obtained previously.\(^3\,^4\) This achievement is primarily due to the improved SET-dot coupling in our vertical configuration. As a result, a rf–SET measurement based on this sample with a 1 MHz bandwidth would give a charge noise of 0.12 \text{ e} referred to the dot charge \( Q_{0d} \). For a fully optimized sample,\(^1\,^9\) we would expect a sensitivity of \( 4 \times 10^{-6} \text{ e}/\sqrt{\text{Hz}} \) referred to the dot charge, giving a charge noise of 0.05 \text{ e} in a 100 MHz bandwidth.\(^10\)

As \( V_g \) increases, the effective voltage \( V_{QPC} \) on the side gates used to form the QPCs also changes due to electrostatic coupling. The measured coupling between the gates gives \( \Delta V_{QPC} = 0.05 \Delta V_g \). As a result, over a large voltage range, the QPCs will be more pinched off as \( V_g \) becomes more negative, resulting in the decrease in \( G_d \), shown in Fig. 3(b). In the end, the QPCs are completely pinched off \( (G_{QPC} \approx e^2/h) \), and \( G_d \) becomes too small to be measured. However, the change in \( N_d \) still affects \( Q_{0d} \) as before, and causes oscillations in \( I_s \) with the same amplitude, as shown in Fig. 3(a). This is a clear indication that a SET is more sensitive to \( N_d \) than direct transport measurements on the dot, as demonstrated earlier.\(^3\) The persistence of the oscillations in \( I_s \) for very small \( G_d \) circumvents another obstacle for detection of individual tunneling events: to observe such events, the lifetime \( \tau \) associated with the energy levels of the dot must be greater than the inverse detector bandwidth. For a 100 MHz rf–SET a lifetime \( \tau > 10^{-8} \text{ s} \) is required, implying a level width \( \Gamma = h/\tau < 0.4 \mu eV \). Such small level widths can be achieved only for very small \( G_d \),\(^11\) for which direct transport measurement on the dot becomes very difficult, if not impossible.

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\(^7\)Single Charge Tunneling, edited by H. Grabert and M. H. Devoret (Plenum, New York, 1992), and references therein.
\(^8\)Occasional changes in \( N_s \) will cause phase shifts in \( Q_{0d} \), as can be seen in Fig. 3(b).
\(^10\)We obtain this estimate by assuming an optimized charge sensitivity referred to the SET of \( 2 \times 10^{-6} \text{ e}/\sqrt{\text{Hz}} \) and the measured values of \( C_r, C_3, C_4, \) and \( C_d \).