APPLIED PHYSICS LETTERS VOLUME 77, NUMBER 17 23 OCTOBER 2000

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

W. Lu and A. J. Rimberg[a)]
Department of Physics, Rice University, Houston, Texas 77005

K. D. Maranowski and A. C. Gossard
Department of Materials, University of California, Santa Barbara, California 93106

(Received 21 June 2000; accepted for publication 30 August 2000)

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 $1.2\times10^{-4}\,e/\sqrt{\text{Hz}}$, 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. © *2000 American Institute of Physics.* [S0003-6951(00)04243-1]

The advent of the high sensitivity, high bandwidth (>100 MHz) radio-frequency single-electron transistor (rf–SET)[1] has made detecting rapid charge motion in real time a practical possibility.[2] 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 (δq_d) referred to the dot charge is needed. Several groups have successfully coupled a SET to a quantum dot in a lateral configuration.[3,4] 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 δq_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.[5] In their work, however, steady-state transport through the dot could not be probed. Furthermore, no value for δq_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) ≈ 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.[6] 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.[7]

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_s

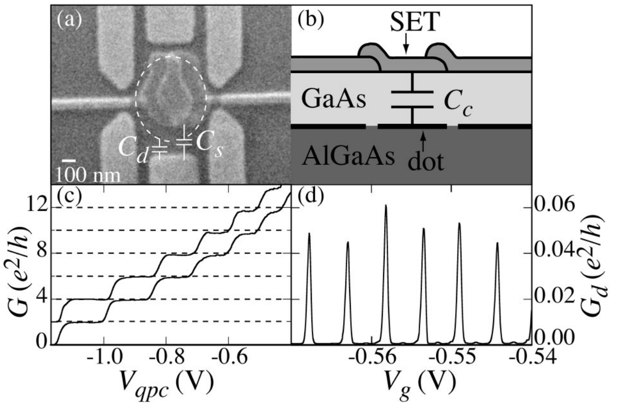

FIG. 1. (a) Scanning electron micrograph of a typical sample. The approximate location of the dot is illustrated by the dashed line. The capacitances C_s and C_d described are also indicated. (b) Schematic cross-sectional view showing the SET, the dot, and the coupling capacitance C_c. (c) Conductance through the two point contacts, showing well-formed plateaus. (d) Zero-bias conductance through the dot.

[a)] Electronic mail: rimberg@rice.edu

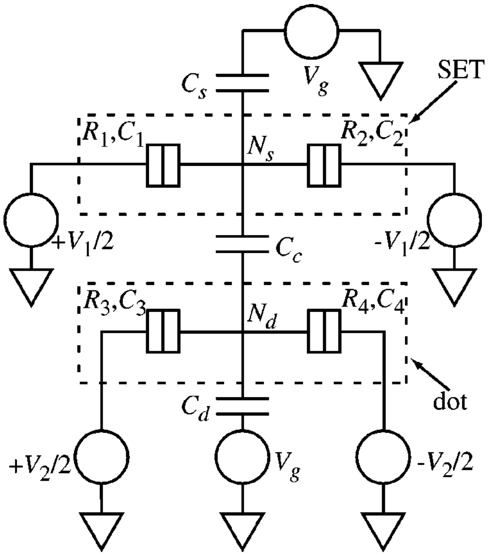

FIG. 2. A SET coupled to a quantum dot through a capacitance C_c. The dot and SET are biased independently by voltages V_1 and V_2. The gate capacitances C_s and C_d can have significantly different values.

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

$$Q_{0s} = C_s V_g + (C_d V_g - N_d e)\frac{C_c}{C_d + C_3 + C_4 + C_c}, \tag{1}$$

$$Q_{0d} = C_d V_g + (C_s V_g - N_s e)\frac{C_c}{C_s + C_1 + C_2 + C_c}, \tag{2}$$

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_d, 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_c 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, $Q_{0d} \approx C_d V_g$,[8] 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_c 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.

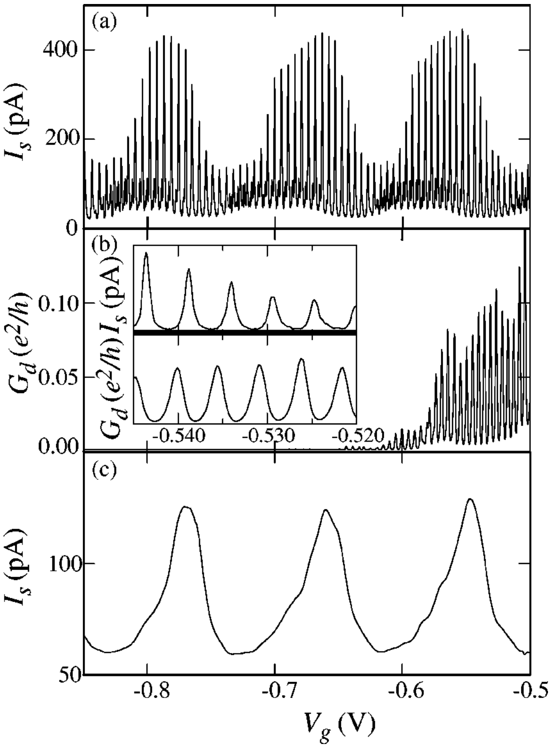

FIG. 3. (a) Current through the SET at $V_{\mathrm{bias}} = 810\ \mu$V, illustrating two periods of oscillations. (b) Zero-bias conductance through the dot, showing simple Coulomb oscillations. A phase shift is visible at $V_g \approx -0.58$ V, when N_s changes by 1. The inset shows an expanded view of I_s and G_d around -0.53 V. (c) Current through the SET at the same bias voltage when the dot is not formed. The different scales in (a) and (c) are caused by a change in the charging energy of the SET with and without the dot.

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 4Δ, where Δ 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 $I(Q_0, V_{\mathrm{bias}})$ surfaces. For this sample, we find $C_1 = 194$ aF, $C_2 = 138$ aF, and $C_3 \approx C_4 \approx 200$ aF, while $C_c = 325$ aF is larger than the dot tunneling capacitances. In addition, $C_d = 32\,\mathrm{aF} \gg C_s = 1.5\,\mathrm{aF}$, as expected. From Eq. (1), we see that addition of an electron to the dot will cause a peak-to-peak oscillation of about $0.4\,e$ in Q_{0s}, and that N_d will change by roughly 20 before N_s changes by 1. Both predictions are verified by the data. The sensitivity δq_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 $\delta q_d \cong 1.2 \times 10^{-4}\, e/\sqrt{\mathrm{Hz}}$, about 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 $0.12\,e$ referred to the dot charge Q_{0d}. For a fully optimized sample,[1,9] we would expect a sensitivity of $4 \times 10^{-6}\, e/\sqrt{\mathrm{Hz}}$ referred to the dot charge, giving a charge noise of $0.05\,e$ 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 $\Delta V_{\mathrm{QPC}} \approx 0.05 \Delta V_g$. 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 ($G_{\mathrm{QPC}} \ll e^2/h$), and G_d becomes too small to be measured. However, the change in N_d still affects Q_{0s} 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 τ associated with the energy levels of the dot must be greater than the inverse detector bandwidth. For a 100 MHz rf–SET a lifetime $\tau > 10^{-8}$ s is required, implying a level width $\Gamma = h/\tau < 0.4\,\mu\mathrm{eV}$. 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.

This work was supported at Rice by the NSF under Grant No. DMR-9974365 and by the Robert A. Welch Foundation, and at UCSB by the QUEST NSF Science and Technology Center. One of the authors (A. J. R.) acknowledges support from the Alfred P. Sloan Foundation.

[1] R. J. Schoelkopf, P. Wahlgren, A. A. Kozhevnikov, P. Delsing, and D. E. Prober, Science **280**, 1238 (1998).
[2] T. Fujisawa and Y. Hirayama, Appl. Phys. Lett. **77**, 543 (2000).
[3] D. S. Duncan, C. Livermore, R. M. Westervelt, K. D. Maranowski, and A. C. Gossard, Appl. Phys. Lett. **74**, 1045 (1999).
[4] D. Berman, N. B. Zhitenev, R. C. Ashoori, and M. Shayegan, Phys. Rev. Lett. **82**, 161 (1999).
[5] M. Koltonyuk, D. Berman, N. B. Zhitenev, R. C. Ashoori, L. N. Pfeiffer, and K. W. West, Appl. Phys. Lett. **74**, 555 (1999).
[6] T. A. Fulton and G. J. Dolan, Phys. Rev. Lett. **59**, 109 (1987).
[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).
[9] A. N. Korotkov and M. A. Paalanen, Appl. Phys. Lett. **74**, 4052 (1999).
[10] We obtain this estimate by assuming an optimized charge sensitivity referred to the SET of $2 \times 10^{-6}\, e/\sqrt{\mathrm{Hz}}$ and the measured values of C_c, C_3, C_4, and C_d.
[11] E. B. Foxman, P. L. McEuen, U. Meirav, N. S. Wingreen, Y. Meir, P. A. Belk, N. R. Belk, M. A. Kastner, and S. J. Wind, Phys. Rev. B **47**, 10020 (1993).