Charge detector realization for AlGaAs/GaAs quantum-dot cellular automata

G. Bazán,[a)] A. O. Orlov, G. L. Snider, and G. H. Bernstein
Department of Electrical Engineering, University of Notre Dame, Notre Dame, Indiana 46556

(Received 28 May 1996; accepted 16 August 1996)

We perform measurements on an AlGaAs/GaAs double-quantum-dot structure, where dots are separated by an opaque barrier and each dot conductance is measured independently and simultaneously. We measure the Coulomb blockade oscillations (CBOs) for each dot when the structure is configured for one and two dots. When configured as a single-dot device, we sweep the backgate and observe different CBO periods for each dot measured independently, implying dots of different sizes. When the device is configured for two dots, we observe strongly modulated CBOs in the larger dot while CBOs in the smaller dot exhibit almost no influence due to the changing charge of the larger dot. From this experiment, we have realized a charge detection scheme where we observe strong coupling in the detector signal in addition to the detector exhibiting minimal effect on the dot being measured. For an implementation of quantum-dot cellular automata (QCA), (1) cells must couple capacitively and (2) one must be able to detect electron occupation of a quantum dot within a cell. With this investigation, we demonstrate these two key components required for QCA in AlGaAs/GaAs materials. © *1996 American Vacuum Society.*

I. INTRODUCTION

Lent *et al.*[1] proposed a novel computational paradigm where computation is performed by coupled cells containing an arrangement of coupled quantum dots. The cell is defined to have two polarization states analogous to a logic ''0'' and ''1.'' With a nonlinear two-state transfer characteristic defined for each cell, a full implementation of logic functions including wire crossovers can be realized. Among the requirements for operation, the output cell state must be detected in order to use information processed by the cellular automata array. In this article we report progress toward a sensitive charge detector that utilizes a quantum dot with the conditions that the detector dot be larger than the dot being detected and the coupling capacitance between the dots be a large fraction of the total capacitance of the detected dot and a small fraction of the detector dot. The latter condition is necessary to minimize the invasiveness of the probing dot. In our system, the detector dot is lithographically defined and the detected dot is the result of random potential fluctuations in the vicinity of the two-dimensional electron gas. We report our results for this coupled quantum-dot system.

One method of charge detection was proposed and realized in metal (Al) tunnel junctions by Lafarge *et al.*,[2] where a single electron transistor (SET) was used to detect charge in a single electron box. The advantage of this method lies in the sensitivity of the SET to the presence of charge near the SET island. Other charge detection methods have been proposed and investigated in AlGaAs/GaAs materials.[3,4] Field *et al.*[3] demonstrated a ''noninvasive'' detector for measuring the electrostatic potential change on a quantum dot. A narrow constriction adjacent to a quantum dot showed a change in resistance when the dot electron population changed. This method of charge detection is considered noninvasive, since the constriction (one-dimensional channel) has a negligible effect on the behavior of the quantum dot. However, this detection scheme suffers from a large background signal, resulting in a small change in detector resistance ($\Delta R/R < 1\%$) due to a change in dot electron population. Another implementation for an ultrasensitive charge detector has been used to study the scaling of Coulomb energy due to quantum fluctuations in the charge on a quantum dot.[4] In this experiment, the electron population on the detected dot is changed and the current in the detector dot is measured. From this measurement, they are able to extract the charging energy of the detected dot. Experiments on a semiconductor double-dot structure linked by an adjustable barrier were performed,[5] but the gate structure provided one conductance probe for the double dot device. In this experiment, current is measured for the detector dot and pronounced periodic shifts in the Coulomb blockade oscillations (CBOs) are observed as a consequence of the coupling to the nonconducting dot. Ultrasensitive charge detectors have also been proposed for single electron memory.[6] This scheme uses the electrostatic potential change in an island due to electron occupation to shift the threshold voltage of a field-emission transistor (FET). The threshold shift is determined by the FET $I_d - V_g$ characteristic. This scheme has been demonstrated,[6] but only for a granular disordered poly-Si implementation. Relying on the granular properties of poly-Si to produce both the island and the FET may be a problem for robustness, repeatability, and reliability.

In this article we study the Coulomb interaction between two semiconductor dots of unequal area, separated by an adjustable barrier with the conductance of each dot measured independently and simultaneously. Thus we are able to measure changes in CBOs of each dot due to coupling. From the analysis, we explore the applicability of charge detection with this double-dot configuration with an emphasis on the

[a)]Electronic mail: gbazan@vnet.ibm.com

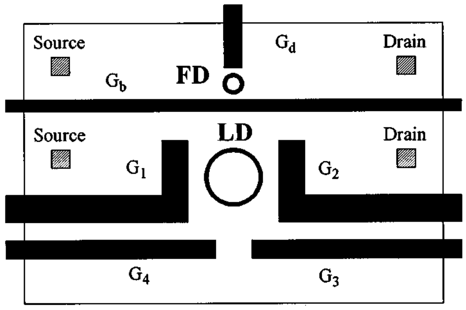

FIG. 1. Gate layout for device under investigation.

noninvasiveness of the detector dot. We have found, as discussed below, that this rule can be accommodated by requiring the coupling capacitance between the detector and the dot to be a significant fraction of the total dot capacitance and a minor fraction of the detector capacitance. Without this consideration, the electrostatic potential change in the detector can ''feed back'' into the dot shifting the electrostatic potential in the measured island.

II. EXPERIMENT

For our experiment we use an AlGaAs/GaAs heterostructure grown by Quantum Epitaxial Designs, Inc. The two-dimensional electron gas (2DEG) is confined at the AlGaAs/GaAs interface 65 nm from the surface and the material layer structure consists of a 15 nm undoped AlGaAs spacer layer, a 30 nm n^+-AlGaAs Si-doped donor layer, and a 20 nm n^+-GaAs cap layer. The ohmic contacts are formed by annealed AuGeNi and the gates are patterned by electron-beam lithography (EBL) and thermally evaporated AuPd. Before the EBL gates are patterned, the cap layer is progressively etched to minimize leakage current. The 2DEG carrier concentration and mobility at 4.2 K were 3×10^{15} m^{-2} and 45 m^2/V s, respectively. All experiments are performed in an Oxford Heliox ^{3}He system with base temperature of 300 mK. Sample conductance is measured using standard lock-in techniques with a 10 μV excitation voltage at 17 Hz in one dot and 24 Hz in the other dot.

The gate pattern shown Fig. 1 defines a narrow constriction adjacent to a lithographically defined dot (LD) when appropriate negative biases are applied. The lithographic dot has a total area of 490×360 nm^2 when negative gate voltages V_b, V_1, V_2, V_3, V_4, are applied to corresponding gates G_b, G_1, G_2, G_3, G_4, respectively. The constrictions between G_b,G_1 and G_b,G_2 form tunneling barriers through which the dot is weakly coupled to the source and drain. The population of the LD can be changed by varying any of the top and back gate potentials.

III. RESULTS AND DISCUSSION

At low temperatures (<0.6 K), Coulomb blockade oscillations [Fig. 2(a)] with a distinct frequency ω_{LD} [Fig. 3(a)] are observed as a function of gate voltage V_4. However, for some settings of V_d we also observe conductance oscillations

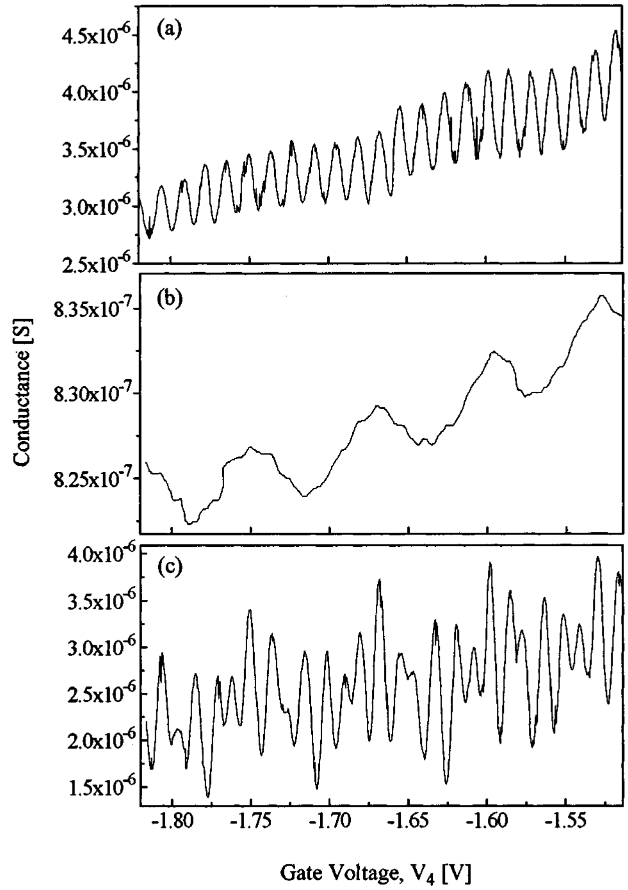

FIG. 2. Conductance vs gate voltage V_4 for (a) lithographic dot (LD), (b) fluctuation dot (FD) when LD is present, and (c) LD when FD is present.

as a function of V_4 in the constriction adjacent to LD [Fig. 2(b)]. These oscillations are characterized by frequency ω_{FD} [Fig. 3(b)]. We believe these oscillations are due to the addition or removal of charge trapped by a random fluctuation potential in the narrow constriction. Such ''fluctuation dots'' (FDs) have been studied previously in different systems,[7–10] and observed oscillations were interpreted in terms of Coulomb blockade transport through a dot formed by fluctuation potentials. A postmeasurement examination by a field emission scanning electron microscope revealed small (~20 nm) islands of n^+-GaAs on the device surface, and we believe the poor surface morphology contributes to the fluctuation potential seen by electrons at the AlGaAs/GaAs interface. With proper bias settings on G_d, LD CBOs change dramatically when FD is formed and oscillations are measured [Fig. 2(c)]. The FD influence is reflected in the fast Fourier transform (FFT) of data for this case [Fig. 3(c)] where $\omega_{\mathrm{LD}}+\omega_{\mathrm{FD}}$ and $\omega_{\mathrm{LD}}-\omega_{\mathrm{FD}}$ components are clearly seen. We also note that almost no trace of LD oscillations is seen in the FFT of FD oscillations [Fig. 3(b)]. The resistance of the barrier between LD and the constriction (FD) was determined to be greater than 100 GΩ, guaranteeing that FD and LD are not coupled resistively. To confirm the coupling of FDs and LDs, we also scanned the back gate, and as shown in Fig. 4, further evidence of coupling is observed. Based on these data

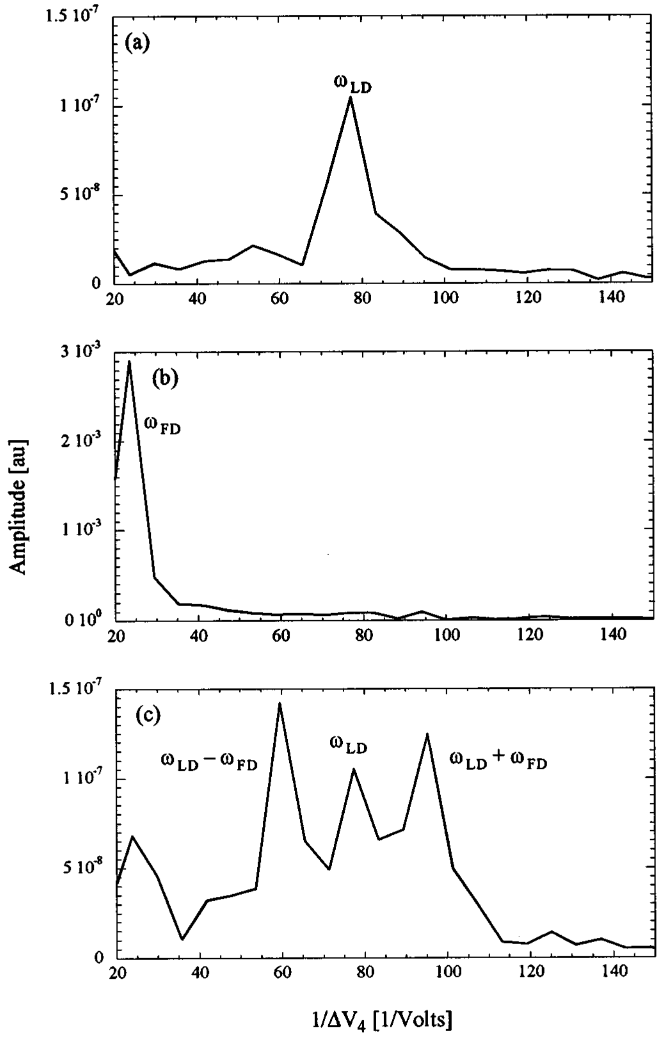

FIG. 3. Calculated FFT results for data in Fig. 2: (a) FFT spectrum for LD; (b) FFT spectrum for FD in the presence of LD; and (c) FFT spectrum for LD in the presence of FD.

and the fact that the 2DEGs of each dot form a similar parallel-plate capacitor to the back contact, it can be seen that the capacitance of LD is about three times that of FD, and their sizes can be inferred to be in the same proportions. The data of Fig. 2 can be used to calculate a gate/LD capacitance of about 12 aF, which is consistent with the lithographically defined size of LD.[3]

We analyze our results using the circuit schematic diagram for the experiment shown in Fig. 5, where C_c is the coupling capacitor between FD and LD, C_g^{LD} represents the capacitance between G_4 and LD, and C_g^{FD} is the capacitance between FD and G_4. C_o^{LD} and C_o^{FD} are the tunnel junction capacitances for each dot respectively. Using simple electrostatics, we find

$$Q_o^{\mathrm{LD}}=\frac{C_o^{\mathrm{LD}}}{C_g^{\mathrm{LD}}+C_o^{\mathrm{LD}}}\,(en_{\mathrm{LD}}-C_g^{\mathrm{LD}}V_4+Q_c), \tag{1}$$

$$Q_o^{\mathrm{FD}}=\frac{C_o^{\mathrm{FD}}}{C_g^{\mathrm{FD}}+C_o^{\mathrm{FD}}}\,(en_{\mathrm{FD}}-C_g^{\mathrm{FD}}V_4-Q_c), \tag{2}$$

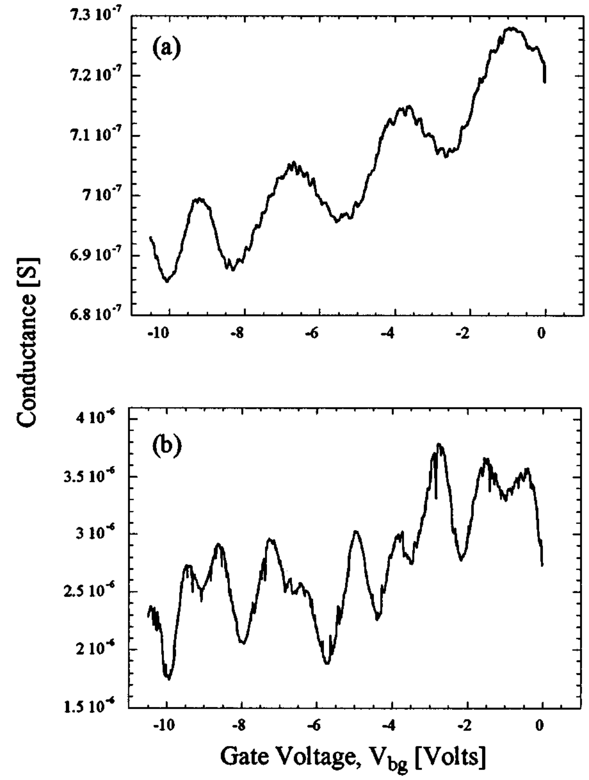

FIG. 4. Conductance vs backgate voltage V_{bg} for (a) FD when LD is present, and (b) LD when FD is present.

$$Q_c=\frac{C_c}{C_o^{\mathrm{FD}}}\,Q_o^{\mathrm{FD}}-\frac{C_c}{C_o^{\mathrm{LD}}}\,Q_o^{\mathrm{LD}}, \tag{3}$$

where Q_o^{LD} and Q_o^{FD} represent the junction charge on each dot and Q_c represents the charge on the coupling capacitor. For LD not to affect FD, Q_o^{FD} must not depend on Q_o^{LD}. This condition is satisfied when C_c is much less than C_o^{LD}. Also, to maximize the sensitivity of LD, the ratio of C_c to C_o^{FD} should be as large as possible. We believe that FD is smaller than LD due both to the physical area that LD and FD occupy, and to their relative oscillation periods when the back gate is scanned. Because FD is smaller than LD they have

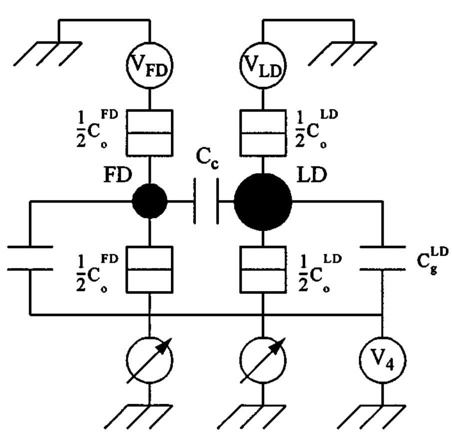

FIG. 5. Circuit diagram for measured device.

different self-capacitances and thus charging energies. This leads to a different influence of one extra electron added to each of these dots; addition or removal of one electron to LD changes the charge on the coupling capacitor C_c, while the appearance of one extra electron on the FD leads to a stronger change of the charge on C_c since C_c, in this case, is a larger part of the total capacitance of FD. In terms of charge detection, it means that the dot with greater charging energy is less affected by a change of the charge on the dot with a smaller charging energy, and hence the dot with a smaller charging energy will serve as a ''noninvasive'' probe to the smaller dot even if the coupling is strong. The fact that the coupling capacitor represents a major part of the total capacitance of FD results in a strong response in the current through LD. Therefore, we believe we have satisfied the conditions for a dot to detect another dot noninvasively.

Using the noninvasive probing feature of LD, we can extract the change in FD charge. This procedure requires that the change in LD be known when FD is not present. It can be shown that the current through LD exhibits periodic current oscillations as a function of external charge $Q_{\mathrm{ext}} \equiv \Sigma\, C_{g^i} V_{g^i}$ where C_{g^i} are all capacitors which connect external sources V_{g^i} to a dot. When FD is not present, C_{g^i} is C_g^{LD}, and V_{g^i} is V_4. When FD is formed, the current through LD is influenced by the charge changing on FD. We can write the LD current as a function of external charge,

$$I^{\mathrm{LD}} = \int \frac{dI^{\mathrm{LD}}}{dQ_{\mathrm{ext}}}\, dQ_{\mathrm{ext}}. \tag{4}$$

We can substitute $V_4 C_g^{\mathrm{LD}}$ for Q_{ext} in the derivative in the absence of FD. When FD is formed, however, Q_{ext} becomes a function of both the charge change on the gate and the charge change on the coupling capacitor. As mentioned above, the charge on the coupling capacitor is primarily a function of the charge on FD and not LD due to the noninvasive nature of the coupling. Therefore, we can write Q_{ext} as

$$Q_{\mathrm{ext}} = V_4 C_g^{\mathrm{LD}} + Q_c, \tag{5}$$

where Q_c is the charge on the coupling capacitor due to a change in charge on FD. Combining Eqs. (3), (4), and (5), we get

$$I^{\mathrm{LD}} = \int \frac{1}{C_g^{\mathrm{LD}}} \frac{dI_o^{\mathrm{LD}}}{dV_4} \left(C_g^{\mathrm{LD}}\, dV_4 + \frac{C_c}{C_o^{\mathrm{FD}}} \frac{dQ^{\mathrm{FD}}}{dV_4}\, dV_4 \right), \tag{6}$$

where I_o^{LD} represents the current through LD when FD is not present. As calculated in Ref. 2, the charge on a dot as function of external charge (gate voltage) is a sawtooth function at zero temperature. As the temperature increases, the charge on the dot and current through the dot can be adequately described as a sinusoidal function of external charge. With this in mind, we describe the current through LD and the charge on FD as a function of V_4 by $\alpha \cos(\omega_{\mathrm{LD}} V_4)$ and $\beta \cos(\omega_{\mathrm{FD}} V_4)$, respectively. By substituting into Eq. (6), we get

$$I^{\mathrm{LD}} = \alpha \cos(\omega_{\mathrm{LD}} V_4) + \frac{\alpha\beta\omega_{\mathrm{LD}}\omega_{\mathrm{FD}} C_c}{2 C_g^{\mathrm{LD}} C_o^{\mathrm{FD}}} \times \left(\frac{\sin[V_4(\omega_{\mathrm{LD}} - \omega_{\mathrm{FD}})]}{\omega_{\mathrm{LD}} - \omega_{\mathrm{FD}}} - \frac{\sin[V_4(\omega_{\mathrm{LD}} + \omega_{\mathrm{FD}})]}{\omega_{\mathrm{LD}} + \omega_{\mathrm{FD}}} \right). \tag{7}$$

The frequencies shown in Fig. 3 can be clearly recognized. We can also use Eq. (6) to determine the FD charge. Taking the derivative of Eq. (6) with respect to V_4 and solving for dQ^{FD}/dV_4, we get

$$\frac{Q^{\mathrm{FD}}}{dV_4} = \frac{[(dI^{\mathrm{LD}}/dV_4) - (dI_o^{\mathrm{LD}}/dV_4)]}{(C_c / C_o^{\mathrm{FD}} C_g^{\mathrm{LD}})(dI_o^{\mathrm{LD}}/dV_4)}. \tag{8}$$

Performing the appropriate derivatives on the data shown in Figs. 2(a) and 2(c) and inserting into Eq. (8), we obtain the data shown in Fig. 6. dQ^{FD}/dV_4 is in phase with FD conductance because the conductance is a maximum at precisely the same gate voltage for which the charge changes.

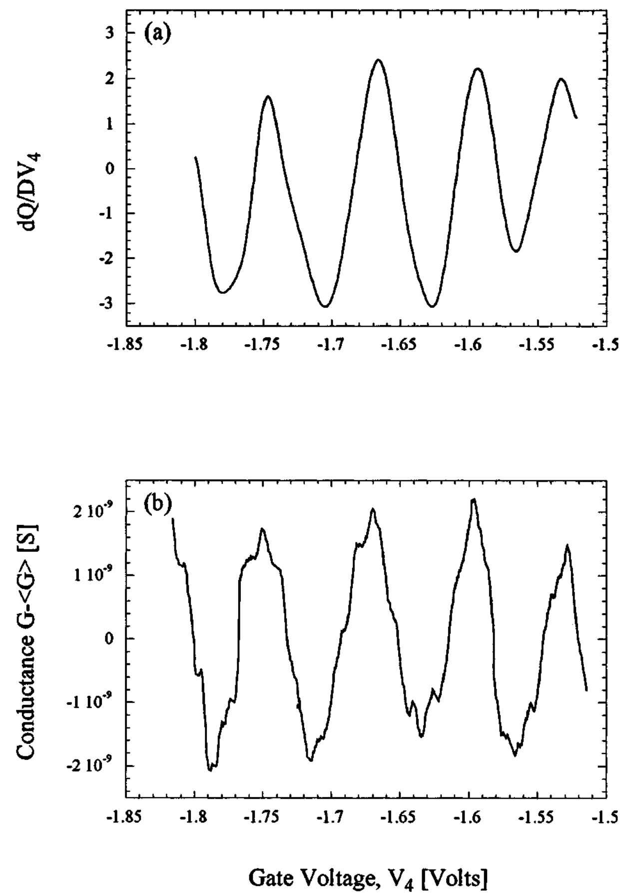

FIG. 6. (a) Reconstructed FD charge oscillations using Eq. 8. (b) Data from FD. The background conductance has been subtracted.

IV. SUMMARY AND CONCLUSIONS

In summary, we observe Coulomb coupling between semiconductor GaAs/AlGaAs dots of different area coupled by an opaque barrier and measured ''in parallel.'' We show that strong modulation of Coulomb blockade oscillations in the lithographic dot is explained in terms of Coulomb coupling between the dots of different areas. We also show charge detection by a single electron transistor in an AlGaAs/GaAs 2DEG. Compared to Ref. 3 this charge detection scheme is more sensitive ($\Delta G/G \sim 100\%$), which makes it possible to design a circuit where the detector state will change from zero current (blockade) to its maximum value (blockade lifted). As proposed in Ref. 1, for an implementation of quantum-dot cellular automata (QCA),

(1) cells must couple capacitively and
(2) one must be able to detect electron occupation of a quantum dot within a cell.

With this investigation, we demonstrate these two key components required for QCA operation.

ACKNOWLEDGMENTS

The authors thank W. Porod, P. D. Tougaw, and C. Lent for useful discussions. This work was supported in part by ARPA and NSF.

[1] C. S. Lent, P. D. Tougaw, W. Porod, and G. H. Bernstein, Nanotechnology **4**, 49 (1993).
[2] P. Lafarge, H. Pothier, E. R. Williams, D. Esteve, C. Urbina, and M. H. Devoret, Z. Phys. B **85**, 327 (1991).
[3] M. Field, C. G. Smith, M. Pepper, D. A. Ritchie, J. E. F. Frost, G. A. C. Jones, and D. G. Hasko, Phys. Rev. Lett. **70**, 1311 (1993).
[4] L. W. Molenkamp, K. Flensberg, and M. Kemerink, Phys. Rev. Lett. **75**, 4282 (1995).
[5] F. Hofmann, T. Heinzel, D. A. Wharam, J. P. Kotthaus, G. Böhm, W. Klein, G. Tränkle, and G. Weimann Phys. Rev. B **51**, 13 872 (1995).
[6] K. Yano, T. Ishii, T. Hashimoto, T. Kobayashi, F. Murai, and K. Seki, IEEE Trans. Electron Devices **ED-41**, 1628 (1994).
[7] J. H. F. Scott-Thomas, S. B. Field, M. A. Kastner, H. I. Smith, and D. A. Antoniadis, Phys. Rev. Lett. **62**, 583 (1990).
[8] A. A. M. Staring, H. van Houten, and C. W. J. Beenakker, Phys. Rev. B **45**, 9222 (1992).
[9] J. Weis, R. J. Haug, K. von Klitzing, and K. Ploog, Phys. Rev. B **46**, 12 837 (1992).
[10] V. Chandrasekhar, Z. Ovadyahu, and R. A. Webb, Phys. Rev. Lett. **67**, 2862 (1991).