

Chapter 2. Single Electron Transistors

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2.1 Project Description

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Several years ago we discovered² that while conventional field-effect transistors turn from the off-state to the on-state only once as electrons are added to them, a very small transistor turns on and then off every time one electron is added. The near-term goal of our research is to understand why the single electron transistor works the way it does. Our long-term goal is to make the device characteristics useful for applications.

A sketch of our first single electron transistor³ is shown in figure 1a. We begin with a crystal of GaAs which has such a high density of impurities that it is metallic. This plays the role of the gate. On top of this we grow a layer of AlGaAs, which is an insulator, and a layer of pure GaAs, where the electrons reside. If a positive voltage is applied between the gate and the source or drain, electrons accumulate at the AlGaAs/GaAs interface. Because of the strong electric field at this interface,

each electron's energy for motion perpendicular to the interface is quantized, and at low temperatures the electrons move only in the two dimensions parallel to the interface. The special trick that makes this a single electron transistor is the creation by electron beam lithography of a pair of electrodes on the top surface of the GaAs. When negative voltage is applied between these and the source or drain, the electrons are repelled and cannot accumulate underneath the electrodes. Consequently, the electrons are confined in a narrow channel between the two electrodes. Constrictions sticking out into the channel repel the electrons and create potential barriers at either end of the channel. A plot of the potential is shown in figure 1b. For an electron to travel from the source to the drain, it must tunnel through these barriers. A "pool" of electrons accumulates between the two constrictions, separated from the leads by the tunnel barriers.

Figure 2 shows the current through the device⁴ as a function of the voltage V_g between the gate and the source. A very small amount of voltage is applied between the two leads, which is just large enough to measure the tunneling conductance between source and drain. The results are astounding. The conductance displays sharp resonances that are almost periodic in V_g . By calculating the capacitance between the pool of electrons and the gate,

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² J.H.F. Scott-Thomas, S.B. Field, M.A. Kastner, H.I. Smith, and D.A. Antoniadis, "Conductance Oscillations Periodic in the Density of a One-Dimensional Electron Gas," *Phys. Rev. Lett.* 62: 583 (1989); M.A. Kastner, "The Single-Electron Transistor," *Rev. Mod. Phys.* 64: 849 (1992).

³ U. Meirav and S.J. Wind, "Single Electron Charging and Periodic Conductance Resonances in GaAs Nanostructures," *Phys. Rev. Lett.* 65: 771 (1990).

⁴ 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, "The Effects of Quantum Levels on Transport Through a Coulomb Island," unpublished; M.A. Kastner, "Artificial Atoms," *Phys. Today*, 46(1): 24-31 (1993).

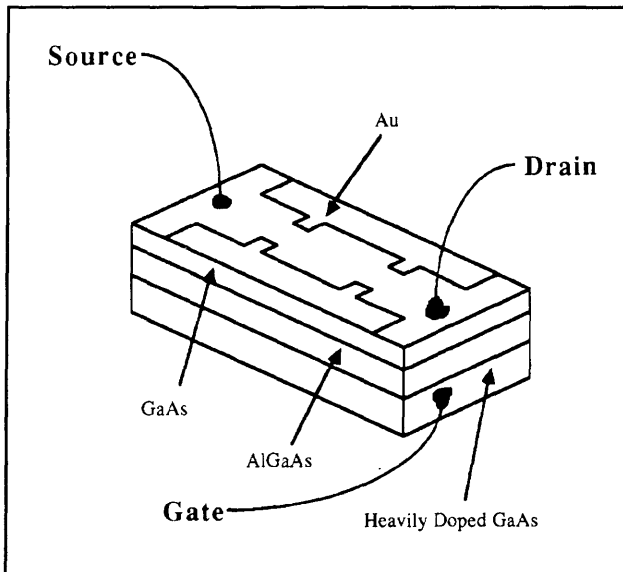


Figure 1a. (a) Schematic drawing of the single electron transistor.

we can show⁵ that the period is the voltage necessary to add *one electron* to the pool.

There is a simple way to explain the periodic conductance resonances;⁶ the theory is called the Coulomb blockade model. When an electron tunnels from one lead onto the pool of electrons and then onto the other lead, adding a charge Q to the pool requires energy $Q^2/2C$, where C is the total capacitance between the pool and the rest of the system; since you can add no less than one electron, the flow of current requires a Coulomb energy $e^2/2C$. A fancier way to explain this is that because of charge quantization there is an energy gap in the spectrum of states for tunneling: For an electron to tunnel onto the pool its energy must exceed the Fermi energy of the contact by $e^2/2C$, and for a hole to tunnel its energy must be below the Fermi energy by the same amount. Consequently, the energy gap has width e^2/C . If the temperature is low enough that $kT < e^2/2C$, neither electrons nor holes can flow from one lead to the other.

With the gate voltage V_g we can alter the energy required to add charge to the pool. V_g is applied between the gate and source, but if the drain-source voltage is very small, the source, drain and pool are all at almost the same potential. With V_g

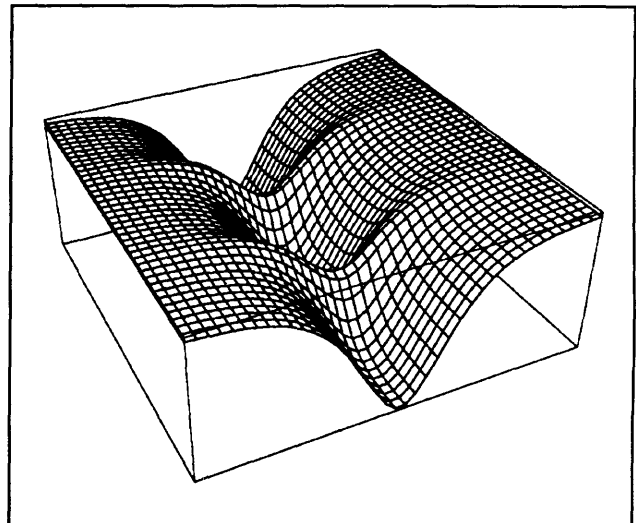


Figure 1b. (b) Potential similar to the one in the single electron transistor plotted as a function of position at the GaAs/AlGaAs interface.

applied the electrostatic energy of charge Q on the pool is

$$E = QV_g + Q^2/2C. \quad (1)$$

The first term is the attractive interaction between the positively charged gate electrode and the negative charge Q , and the second term is the repulsive interaction among the bits of charge in the pool. Equation 1 shows that the energy as a function of Q is a parabola with minimum at $Q_0 = -CV_g$.

By varying V_g , we can choose any value of Q_0 , the charge that would minimize the energy in equation 1 if the charge were not quantized. However, because the real charge *is* quantized, only discrete values of the energy E are possible. For all values of Q_0 except $Q_0 = -(N + 1/2)e$, there is a non-zero energy for adding or subtracting an electron. Under these circumstances, no current can flow at low temperature. However, if $Q_0 = -(N + 1/2)e$, the state with $Q = -Ne$ and that with $Q = -(N + 1)e$ are degenerate; the charge fluctuates between the two values even at zero temperature. Consequently, the energy gap in the tunneling spectrum disappears, and current can flow. The peaks in conductance are, therefore, periodic, occurring whenever

⁵ U. Meirav and S.J. Wind, "Single Electron Charging and Periodic Conductance Resonances in GaAs Nanostructures," *Phys. Rev. Lett.* 65: 771 (1990); A. Kumar, "Self-consistent Calculations on Confined Electrons in Three-dimensional Geometries," *Surf. Sci.* 263: 335-340 (1992).

⁶ G. Grabert and M.H. Devoret, eds. *Single Charge Tunneling—Coulomb Blockade Phenomena in Nanostructures*, (New York: Plenum Press, 1992).

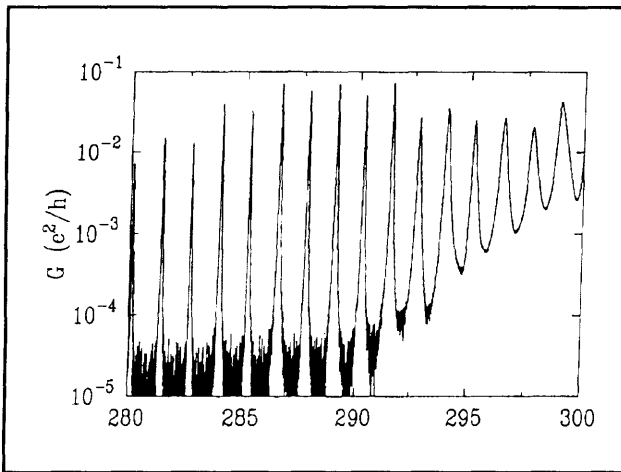


Figure 2. Conductance in units of the quantum of conductance e^2/h versus voltage on the n -GaAs substrate. On the logarithmic plot, it is clear that the transistor has an on-to-off conductance ratio that exceeds 10^3 for the lowest gate voltages.

the average charge on the artificial atom is $Q_0 = -(N + 1/2)e$, spaced in gate voltage by e/C .

The Coulomb blockade model accounts for charge quantization but ignores the quantization of energy resulting from the small size of the region in which the electrons are confined. If one thinks of the region between the potential barriers as a box, the lowest energy spacings are of the order $\hbar^2/2ma^2$ where a is the size of the box. Because the energy as well as the charge is quantized, we find it useful to think of the single electron transistor as an artificial atom.

The energy level spectrum of the atom can be measured directly by observing the tunneling current at fixed V_g as a function of the voltage (V_{ds}) between drain and source. The Fermi level in the source rises in proportion to V_{ds} relative to the drain, so it also rises relative to the energy levels of the artificial atom (see the inset to figure 3). Current begins to flow when the Fermi energy of the source is raised just above the first quantized energy level of the atom. As the Fermi energy is

raised further, higher energy levels in the atom fall below the Fermi energy, and more current flows because there are additional channels for the electron to use for tunneling onto the artificial atom. We measure the energies by measuring the voltage at which the current increases, or, equivalently, the voltage at which there is a peak in the derivative of the current dI/dV_{ds} . We show results of such a measurement⁷ in the upper part of figure 3.

Increasing the gate voltage lowers all the energy levels in the atom by $-eV_g$, so that the entire tunneling spectrum shifts with V_g . This effect can be observed by plotting the values of V_{ds} at which peaks appear in dI/dV_{ds} , as is done in the lower part of figure 3. You can see the gap in the tunneling spectrum shift lower with increasing V_g and then disappear at the charge-degeneracy point, just as predicted by the Coulomb blockade model. You can also see the discrete energy levels of the artificial atom. The charge-degeneracy points are the values of V_g , for which one of the energy levels of the artificial atom is degenerate with the Fermi energy in the leads when $V_{ds} = 0$, because only then can the charge of the atom fluctuate.

During the past year, we have developed a thorough understanding of the energy spectrum of single electron transistors. In addition, we now know what limits their operating temperature. As shown in figure 3, the devices we have made so far have a Coulomb-blockade gap that is about 1 meV wide and energy level spacings that are about one-fifth to one-tenth of that. As the temperature is raised, the conductance resonances acquire a width of $\sim 4 kT$. Since $kT = 1$ meV is equivalent to $T = 12$ K, the peak-to-valley ratio becomes small above a few degrees K. Making the single electron transistor useful will require making its operating temperature much higher. This requires decreasing the size because both the Coulomb energy, which varies inversely with the capacitance, and the energy level spacings will get larger for smaller structures. This is the direction of our next research effort.

⁷ 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, "The Effects of Quantum Levels on Transport Through a Coulomb Island," unpublished; M.A. Kastner, "Artificial Atoms," *Phys. Today*, 46(1): 24-31.

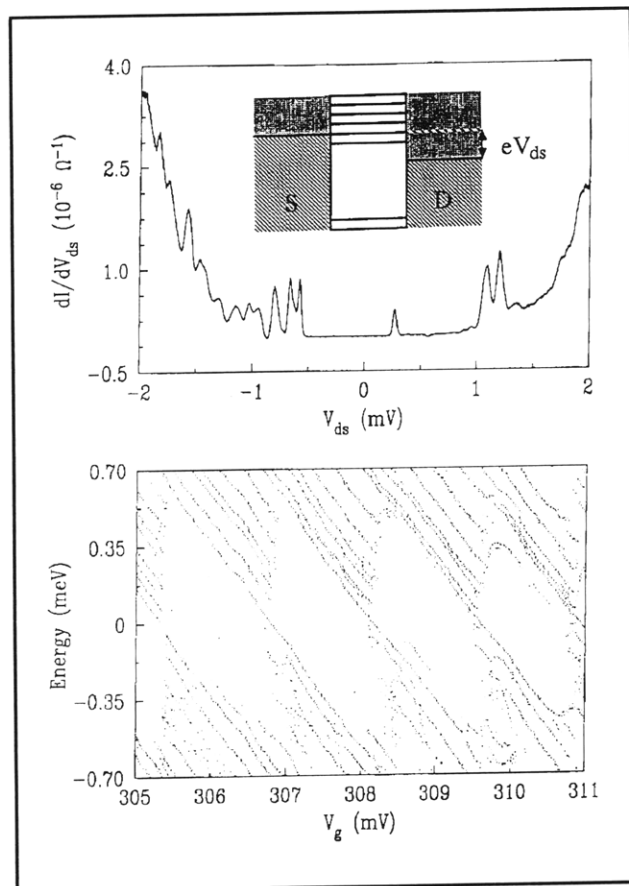


Figure 3. Discrete energy levels of a single electron transistor can be detected by varying the drain-source voltage. When a large enough V_{ds} is applied, electrons overcome the energy gap and tunnel from the source to the pool of electrons (see inset of upper panel). Upper panel: Every time a new discrete state is accessible, the tunneling current increases, giving a peak in dI/dV_{ds} . The Coulomb blockade gap is the region between about -0.5mV and $+0.3\text{mV}$ where there are no peaks. Lower panel: Plotting the positions of these peaks at various gate voltages gives the level spectrum. Note how the levels and the gap move downward as V_g increases.

2.2 Publications

Bagwell, P.F., S.L. Park, A. Yen, D.A. Antoniadis, H.I. Smith, T.P. Orlando, and M.A. Kastner. "Magnetotransport in Multiple Narrow Silicon Inversion Channels Opened Electrostatically into a Two-dimensional Electron Gas." *Phys. Rev. B* 45(16): 9214-9221 (1992).

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