

Chapter 2. Single-Electron Transistors

Academic and Research Staff

Professor Marc A. Kastner, Dr. Olivier Klein¹

Visiting Scientists and Research Affiliates

Shalom Wind²

Graduate Students

Paul A. Belk, David M. Abusch

2.1 Project Description

Sponsors

Joint Services Electronics Program
 Contract DAAL03-92-C-0001
 National Science Foundation
 Grant ECS-88-13250
 Grant ECS-92-03427

Our JSEP-supported research on the behavior of electrons in nanometer-sized semiconductor structures has led to an unexpected and remarkable discovery. We found that, when a field effect transistor (FET) is made very small and separated from its source and drain by tunnel junctions, it behaves in a way completely different from a conventional FET. A conventional device turns on only once when electrons are added. For example, to turn on a Si transistor that is $0.5 \mu\text{m}$ square, a few thousand electrons must be added. However, if a device of similar size is separated from its leads by tunnel junctions, it turns on and off again each time an electron is added.

In collaboration with IBM, we fabricated a device structure using MBE GaAs as shown in figure 1 (inset). This device is similar to a conventional FET because heavily doped GaAs serves as the substrate and functions as the gate. To accomplish this, first a layer of AlGaAs is grown to serve as the insulator. On top of this is a layer of GaAs in which the electrons accumulate when a positive voltage is applied to the gate. To confine the electrons to a small region and isolate them from source and

drain, gold electrodes are patterned on top of the GaAs layer. The protrusions of these electrodes create potential barriers through which electrons must tunnel when passing through the device. The constrictions also create a pool of electrons between the barriers.

Figure 1 also shows the behavior of the device as the gate voltage is increased. The conductance from source to drain shows sharp peaks turning on and off with ratios as high as 10^4 . A calculation shows that the capacitance of the device is only 10^{-16} F, so that the voltage between peaks or valleys in figure 1 is exactly that necessary to add a single electron to the transistor. Thus, the device is called a single-electron transistor.

For our purposes, it is more accurate to think about this and other structures in which electrons are confined in all three dimensions as artificial atoms.³ When electrons are confined to a small region of space their charge and energy become quantized. The quantization of energy is something we are familiar with: for instance, solving the Schrodinger equation in a small volume gives discrete energy levels. As the typical dimension r of the region is decreased, the spacing of the levels increases, typically as r^{-2} .

However, quantization of the charge is less familiar to us. Although the charge of an electron in free space is quantized, the charge in any small region of a conductor is not, because the wavefunction of the electrons extends over the entire volume of conductor. Charge quantization is induced by iso-

¹ Postdoctoral associate, Department of Physics.

² IBM Thomas J. Watson Research Laboratories, Yorktown Heights, New York.

³ M.A. Kastner, "Artificial Atoms," *Phys. Today* 46(1): 24-31 (1993); U. Meirav, M.A. Kastner, and S.J. Wind, "Single-Electron Charging and Periodic Conductance Resonances in GaAs Nanostructures," *Phys. Rev. Lett.* 65: 771 (1990); M.A. Kastner, "The Single-Electron Transistor," *Rev. Mod. Phys.* 64: 849 (1992).

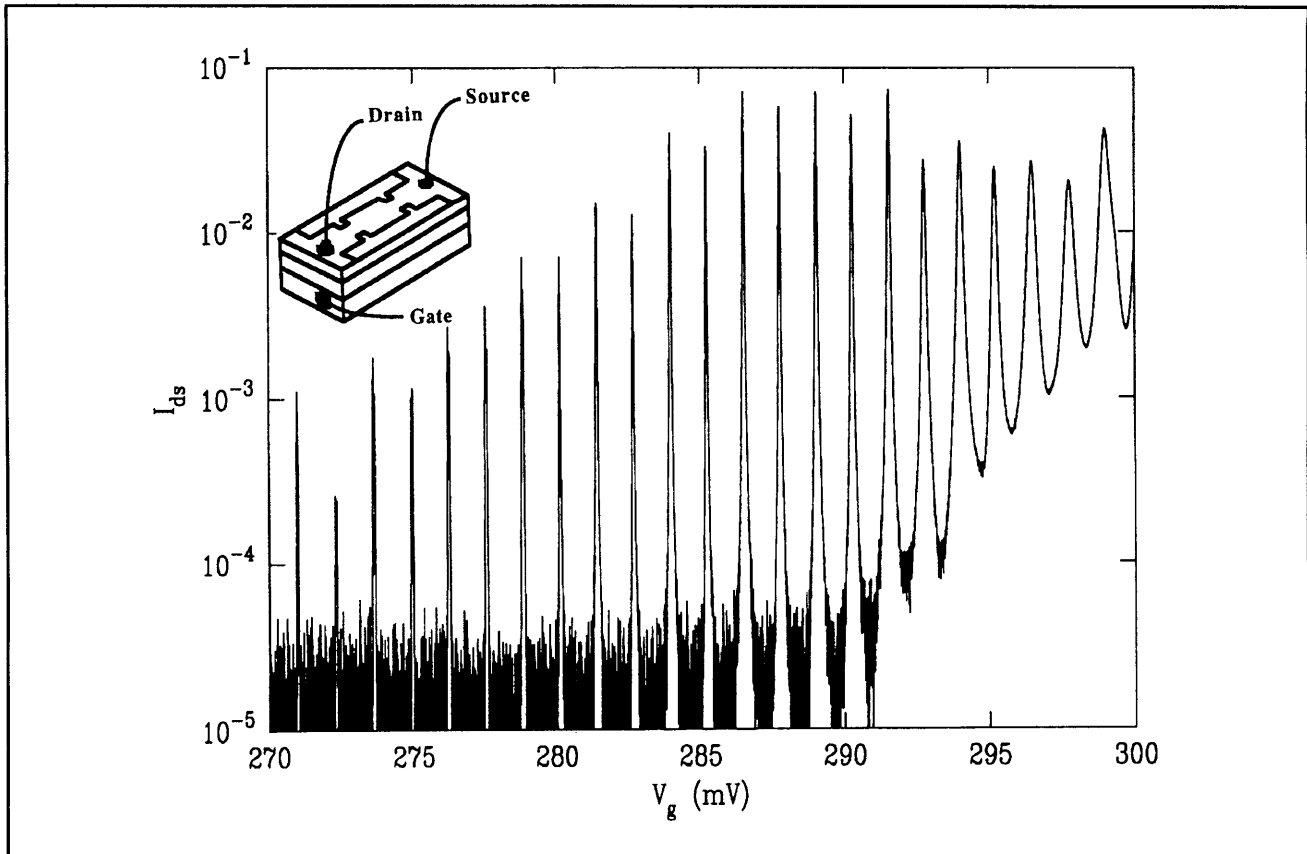


Figure 1. Current through the controlled-barrier atom as a function of the voltage on the gate at a temperature of 60 mK. The inset shows a schematic of the device structure.

lating a small part of the conductor. From the scaling theory of conductance developed in the 1980s, we know that this isolation occurs when the conductance of the insulator is less than e^2/h . Thus, when the tunnel barriers conduct less than e^2/h , both the charge and energy of the isolated region are quantized.

A simple way to explain the periodic conductance resonances shown in figure 1 follows. An electron tunnels from one lead onto the pool of electrons between the barriers and then onto the other lead. First we assume that the pool is neutral, compensated by charge on the gate. To add a charge Q to the pool requires energy $Q^2/2C$, where C is the total capacitance between the particle and the rest of the system. Since one can add no less than one electron, the flow of current requires a Coulomb energy $e^2/2C$. Therefore, because of charge quantization there is an energy gap in the spectrum of states for tunneling. For an electron to tunnel onto the artificial atom, 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 the width e^2/C . If the temperature is low enough so 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 particle. V_g is applied between the gate and source, but if the drain-source voltage is very small, the source, drain and particle are at almost the same potential. With V_g applied, the electrostatic energy of charge Q on the particle 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 on the particle. Equation 1 shows that the energy as a function of Q is a parabola with minimum at $Q_0 = -CV_g$. For simplicity, it is assumed that the gate is the only electrode that contributes to C ; in

reality, there are additional factors.⁴ By varying V_g , we can choose any value of Q_0 , which is 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. When $Q_0 = -Ne$, for which an integer number N of electrons minimizes E , the Coulomb interaction results in the same energy difference $e^2/2C$ for increasing or decreasing N by one. For all values of Q_0 except $Q_0 = -(N+1/2)e$, there is a smaller, but 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. Therefore, the peaks in conductance are periodic, occurring whenever $CV_g = Q_0 = -(N+1/2)e$, spaced in gate voltage by e/C . This explanation is called the Coulomb blockade model.⁵

Artificial atoms can be made in various ways. One way uses only metals.⁶ For this "all-metal atom", the energy separation of the quantized levels is too small to measure, but the effects of charge quantization are clear. For this case, the Coulomb blockade works very well. Many researchers⁷ have made "quantum dots", which are analogous to the single-electron transistor with no gate. By varying the voltage between source and drain, one can measure the spectrum of energy levels for adding an extra electron to the atom.⁴ Figure 2 shows the differential conductance of our device as a function of source-drain voltage. Near zero bias there is a gap, in which the conductance is zero, caused by the Coulomb blockade. It takes an energy $e^2/2C$, where C is the device capacitance, to add an extra electron to the artificial atom. Thus, no current

flows until the source-drain voltage shifts the energy by this amount. Once the Coulomb blockade gap is overcome, a spectrum of peaks are seen in the differential conductance. These correspond to excited states of an artificial atom with an extra electron or hole. If the gate voltage is increased, energy levels shift to lower energy because the electrons are attracted by the positively charged gate.

In figure 2, we show the positions of peaks similar to those in the top panel plotted as a function of the gate voltage. The Coulomb blockade gap is clearly seen opening and then closing for each electron added to the atom. In addition, the quantized excited states are evident, separated by a smaller energy ΔE . The level at the top of the gap corresponds to the minimum energy required to add an extra electron to the atom. The next level is the amount of energy required to add one electron in the first excited state, and so on. At higher voltage (not shown) are levels required for adding two and more electrons.

From figure 1, one sees that the voltage necessary to add one electron is about 1 mV. That means that the Coulomb energy gap for our device is about 1 meV. As expected, when kT is comparable to this, the single-electron behavior is washed out by thermal fluctuations. In fact, because other electrodes contribute to the capacitance of our small transistor, the energy scale is about 0.5 meV. Furthermore, our analysis shows that the conductance peaks disappear when kT is about one-quarter of the gap, that is, at temperatures above a few K. Since any practical application will require operating temperatures that are much higher, a primary goal of our research is the exploration of what needs to be done to increase the energy scale. Reaching this goal will have a major impact on basic physics studies as well. The resolution of single-electron spectroscopies is kT . Therefore,

4 E.B. Foxman, P.L. McEuen, U. Meirav, N.S. Wingreen, Y. Meir, P.A. Belk, N.A. Belk, M.A. Kastner, and S.J. Wind, "Effects of Quantum Levels on Transport Through a Coulomb Island," *Phys. Rev. B* 47: 10020 (1993).

5 D.V. Averin and K.K. Likharev, "Single-Electronics: A Correlated Transfer of Single Electrons and Cooper Pairs in Systems of Small Tunnel Junctions," in *Mesoscopic Phenomena in Solids*, eds. B.L. Altshuler, P.A. Lee, and R.A. Webb (Amsterdam: Elsevier, 1991), p. 173; H. van Houton and C.W.J. Beenakker, "Comment on Conductance Oscillation Periodic in the Density of a One-Dimensional Electron Gas," *Phys. Rev. Lett.* 63: 1893 (1989); D.V. Averin and A.N. Korotkov, "Influence of Discrete Energy Spectrum on Correlated Single-Electron Tunneling via a Mesoscopically Small Metal Granule," *Zh. Eksp. Teor. Fiz.* 97: 1661 (1990) [*Sov. Phys. JETP* 70: 937 (1990)].

6 T.A. Fulton and G.J. Dolan, "Observation of Single-Electron Charging in Small Tunnel Junctions," *Phys. Rev. Lett.* 59: 109 (1987).

7 B. Su, V.J. Goldman, and J.E. Cunningham, "Observation of Single-Electron Charging in Double Barrier Heterostructures," *Sci.* 255: 313 (1992). M.A. Reed, J.N. Randall, R.J. Aggarwal, R.J. Matyi, T.M. Moore, and A.E. Wetsel, "Observation of Discrete Electronic States in a Zero-Dimensional Semiconductor Nanostructure," *Phys. Rev. Lett.* 60: 535 (1988); M. Tewordt, L. Martin-Moreno, J.T. Nicholls, M. Petter, M.J. Kelley, V.J. Law, D.A. Ritchie, J.E.F. Frost, and G.A.C. Jones, "Single-Electron Tunneling and Coulomb Charging Effects in Asymmetric Double-Barrier Resonant-Tunneling Diodes," *Phys. Rev. B* 45: 14407 (1992); R.C. Ashoori, H.L. Stormer, J.S. Weiner, L.N. Pfeiffer, S.J. Pearton, K. Baldwin, and K.W. West, "Single-Electron Capacitance Spectroscopy of Discrete Quantum Levels," *Phys. Rev. Lett.* 68: 3088 (1992).

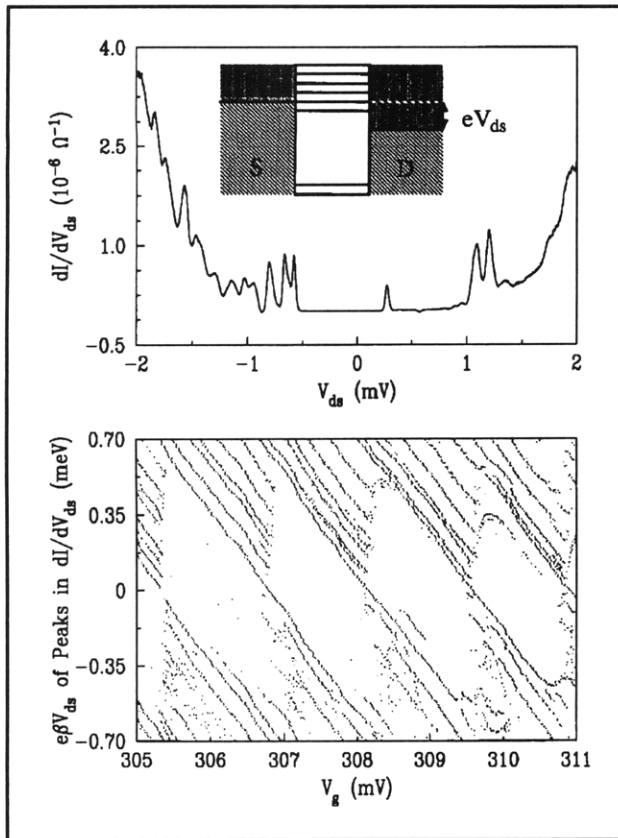


Figure 2. When a large enough V_{ds} is applied, electrons overcome the energy gap and tunnel onto the artificial atom. The inset shows the case for $Q_0 = -(N+1/4)e$. Each time a new discrete state is accessible, the tunneling current increases, giving a peak in dI/dV_{ds} (upper panel). Plotting the positions of these peaks gives the level spectrum in the lower panel. Note how the levels and the gap move downward as V_g increases.

increasing the underlying energy scale increases the relative resolution of the spectroscopies. This will surely reveal new phenomena that are important to our research.

One way to make the energy scale larger is to make the capacitance smaller. In our current devices, the gate capacitance scales with the area

of the device. However, as the size of the device is reduced, the capacitance will eventually be dominated by the edges and will scale only with the linear dimension of the isolated region. Fortunately, the quantum mechanical energy spacing ΔE continues to scale with the area. Therefore, we believe that, with careful design of the MBE layer structure and the gate configuration, we should be able to increase the energy scale by a factor ~ 100 so that liquid nitrogen temperature operation is probable and room temperature operation might be possible. This will require close collaboration with researchers growing MBE crystals. We have established this kind of collaboration with Michael R. Melloch of Purdue University.

Another way to reduce capacitance is using Si instead of GaAs. In Si MOSFETs, the lower dielectric constants of both the semiconductor and the insulator (SiO_2) are an advantage for single-electron devices. Although the charges at the Si-SiO₂ interface cause unwanted potential fluctuations interfering with the device operation, their density is low and may not cause serious problems in a very small device. In our early experiments, we found that the energy scale introduced by these surface charges was about 1 meV. Therefore, if we increase the energy scale, the surface charges will become less important.

Making devices in Si offers an additional advantage because they can be easily integrated with conventional circuits. This advantage will be crucial for useful applications to become a reality.

2.2 Publications

Foxman, E.B., P.L. McEuen, U. Meirav, N.S. Wingreen, Y. Meir, P.A. Belk, N.A. Belk, M.A. Kastner, and S.J. Wind. "Effects of Quantum Levels on Transport Through a Coulomb Island." *Phys. Rev. B* 47: 10020 (1993).

Kastner, M. "Artificial Atoms." *Phys. Today* 46(1): 24-31 (1993).