Chapter 5. Single-Electron Spectroscopy

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5.1 Project Description

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Two years ago, we developed single-electron capacitance spectroscopy (SECS). This is a means for measuring the quantum energy levels of nanoscale objects such as quantum dots, single impurity atoms, and localized electronic states in a semiconductor. The resolution of the method is limited only by the sample temperature, and objects containing as few as one electron may be probed. We intend to develop this type of single-electron spectroscopy into a general tool for studying nanostructured materials. Since my arrival at MIT in 1993, the focus of our work has been largely in the setup of our low temperature laboratory. Here I will discuss the SECS technique and our use of it to study a single quantum dot or artificial atom.

Our artificial atoms are semiconductor structures so small that they can contain as few as one electron. These can be considered as small boxes containing a number of electrons which can be varied. Like real atoms, electrons are attracted to a central location. In a real atom, this central location is a positively charged nucleus; in an artificial atom, electrons are typically trapped in a bowl-like parabolic potential well in which electrons tend to fall in toward the center of the bowl. One can consider the artificial atom as a tiny laboratory in which quantum mechanics and the effects of the electron-electron interaction can be studied. Because of its large size, the artificial atom is in a different physical regime from real atoms; as such we can expect a lot of new physics in the electronic energy level spectra of artificial atoms.

Atomic spectra of real atoms of a particular species are identical. This is not true of artificial atoms. It is not yet possible to manufacture many identical artificial atoms. For this reason, we have developed SECS, a method for observing spectra in a *single* artificial atom.

Figure 1a shows the new scheme. The artificial atom is placed between the plates of a tunnel capacitor. It is close enough to one of the plates so that single electrons can quantum mechanically tunnel between the artificial atom and the nearby plate. The artificial atom is far enough from the other capacitor plate to prohibit any tunneling to this plate occurring. Electric fields can be created by applying a voltage between the plates of the capacitor. If the top plate is made positive compared to the bottom one, electrons from the bottom plate will be attracted in the direction of the top plate, toward the artificial atom. Single electrons can thus be coaxed to tunnel into the artificial atom. Similarly, they can be expelled from the artificial atom using negative top plate voltages.

The motion of the single electrons can be detected using a simple physical principle. When a single electron tunnels into the artificial atom, it moves closer to the top plate of the capacitor. Electrons in the top plate tend to be pushed away from the plate; i.e., some charge is induced on the top plate. In our samples, the amount of charge induced is about half of an electron's charge.

The induced charge on the capacitor plates gives rise to a detectable voltage across the tunnel capacitor. The voltage measured by a detector will be the amount of the charge divided by the input capacitance of the detector. Given that our artificial atom samples are in a cryostat (typically at 0.3 K), wires leading to a room temperature detector will have on order 1000 pF of shunt capacitance. This large shunt capacitance would make measurement of the induced charge impossible.

In order to greatly reduce the shunt capacitance, we build an on-chip capacitance bridge with a high electron mobility transistor (HEMT) detector located about 1 mm away from the tunnel capacitor. In this arrangement, the tunneling of a single electron induces a voltage of about 10 nV at the input of the HEMT. The artificial atom is contained in a GaAs/AlGaAs quantum well produced by molecular

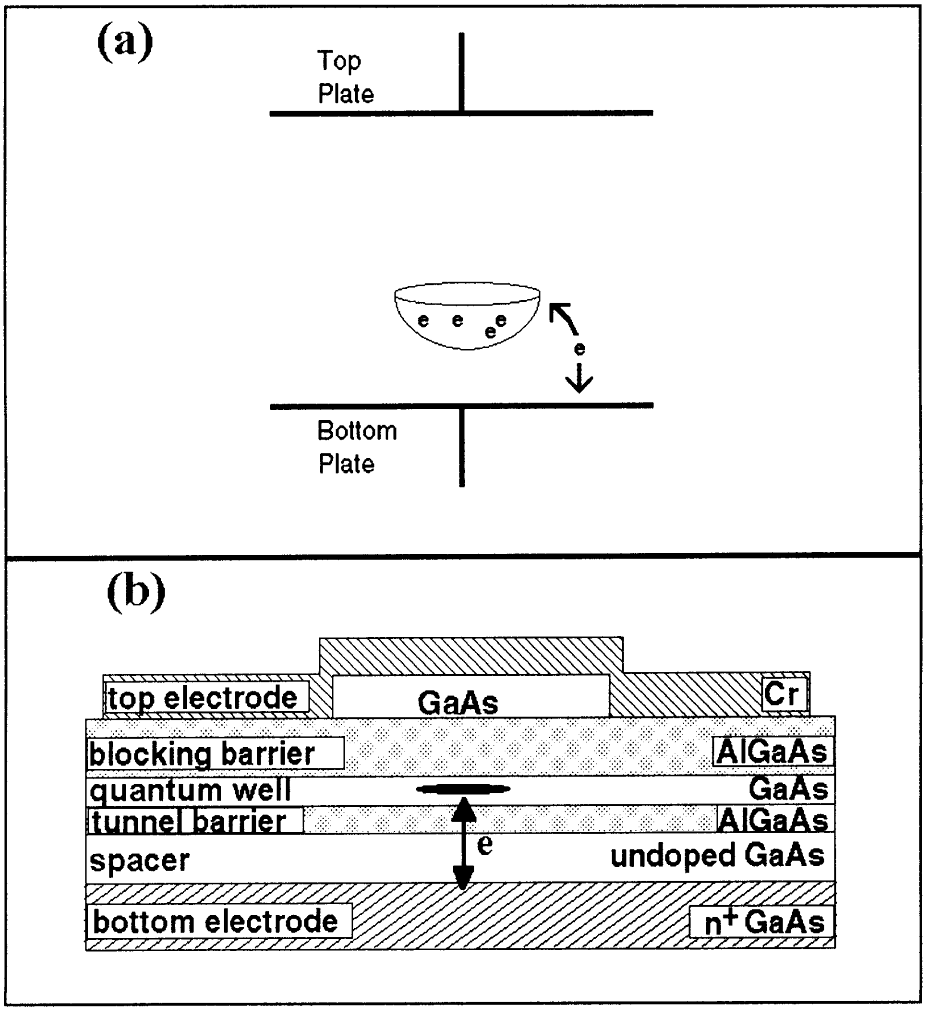

Figure 1. (a) A scheme for making precision measurements on an artificial atom. The artificial atom may be thought of as a small bowl in which electrons can be collected one at a time. It is positioned between two plates of a capacitor. Single electrons can be induced to tunnel into the artificial atom by application of a voltage on the top plate. Detectable charge is induced on the top plate as a result of this tunneling. (b) Schmatic cross section through the structure containing the artificial atom.

beam epitaxy. Figure 1b is a schematic diagram. The bottom n^+ GaAs layer serves as the bottom tunnel capacitor plate. A thin (150 Angstrom) $Al_{.3}Ga_{.7}As$ acts as the tunnel barrier. The thick $Al_{.3}Ga_{.7}As$ layer above the GaAs electrically insulates the electrons in the artificial atom from the top Cr electrode. Patterning, by electron beam lithography and reactive ion etching, of the top layer of the structure provides lateral confinement of electrons in the quantum well.

Figure 2 displays the output of the HEMT, corresponding to the capacitance of the small capacitor, as the voltage on the capacitor plates is swept. Notice the peaks. The first of these peaks, moving from left to right, is caused by the first electron to move into the previously empty artificial atom. Electrons can then be counted one by one as they move into the artificial atom. Shown in figure 2 are signals from the first 25 electrons to enter the artificial atom. An obvious question is: what is the meaning of the spacings between the peaks? It turns out that the horizontal scale in figure 2 can actually be read as an energy scale, with energy increasing to the right. It takes a certain amount of energy to add each subsequent electron to the arti-

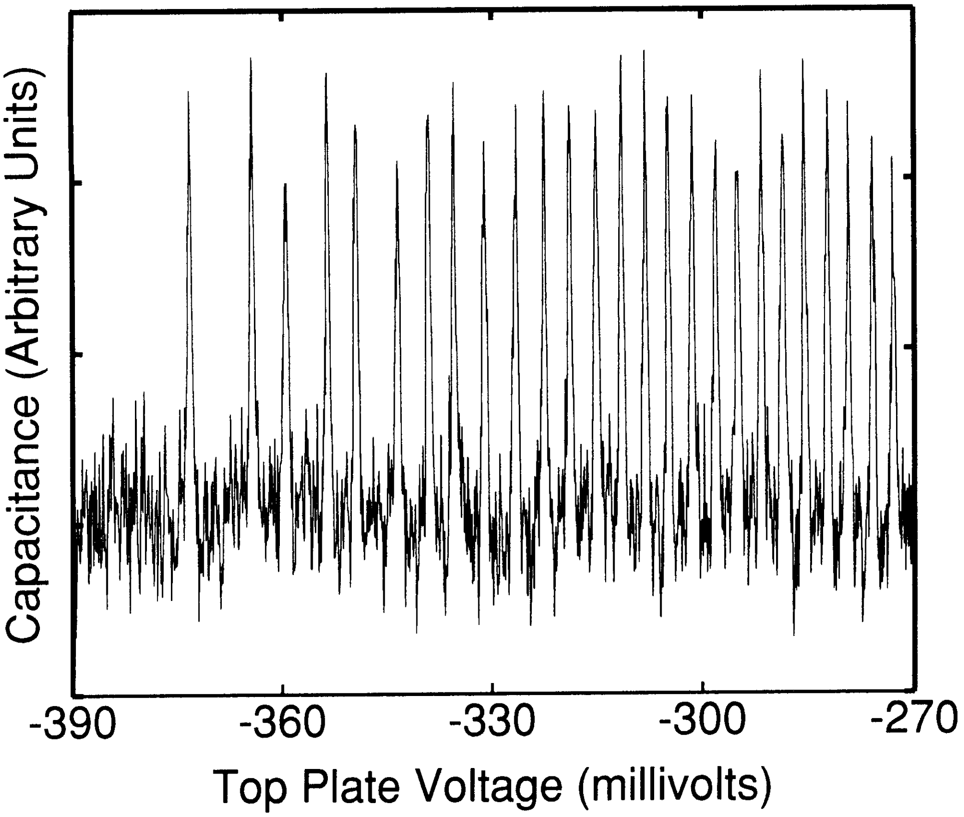

Figure 2. The results of an ultrasensitive capacitance vs. top plate voltage measurement on the sample pictured in figure 1. Moving from left to right, the first peak corresponds to the first electron entering the previously empty artificial atom. Each successive peak indicates a subsequent electron admission. The spacings between the peaks indicate the energy required to add a successive electron to the artificial atom, and the widths of the peaks are determined by the sample temperature (0.35 Kelvins).

ficial atom, and this amount is directly reflected in the spacings between the peaks of figure 2.

Why does it take more energy to add each subsequent electron to the atom? There are two reasons. One is that the electrons already in the atom repel subsequent electrons from being admitted; it takes a certain amount of energy to overcome this repulsion. Additionally, newly admitted electrons cannot enter quantum states that are already occupied (Pauli Principle); they must enter higher quantum energy levels.

If a magnetic field is turned on, the energies of the quantum energy levels change. In the simplest sense, this happens because the magnetic field places a force on moving electrons. The orbits of electrons in the artificial atom are thus changed by the magnetic field, causing the peaks seen in figure 2 to move. This ability to follow quantum energy levels in magnetic field is a powerful probe of the way electrons behave within the atom. To observe it better, plots such as the one in figure 3 are created. It is a compendium of many data sets such as the one shown in figure 2, now taken at varying values of the magnetic field strength. In figure 3, the horizontal axis represents magnetic field strength and the vertical axis represents voltage across the capacitor (or energy). The capacitance is plotted on a gray-scale, with white representing a capacitance peak.

Let us first examine the bottom trace of figure 3. It plots the energy of the first electron as a function of magnetic field. Notice that this energy increases as the magnetic field strength is increased. This behavior of the one electron energy turns out to be easily predictable. A magnetic field will tend to make a moving electron move in circles instead of in a straight line. The sizes of these circles become smaller as the magnetic field strength is increased. Effectively, the magnetic field confines the electrons. According to quantum theory, the more tightly

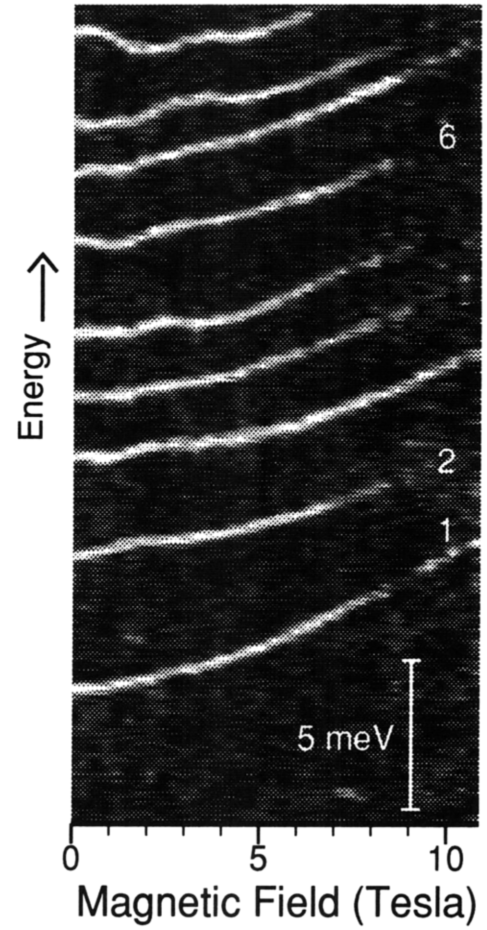

Figure 3. A gray scale capacitance plot for the first nine electrons to enter the artificial atom. The white traces represent capacitance peaks such as those seen in figure 2. The lowest white trace corresponds to the first electron. The vertical axis represents the energy required to add single electrons to the artificial atom (derived from top plate voltage), and the horizontal axis represents the magnetic field. The behavior of the white traces is discussed in the text.

one confines an electron, the higher its energy. A fit to this trace determines that the diameter of the first electron's wavefunction is about 400 Angstroms.

The next trace seen in figure 3 is for two electrons in the artificial atom. Notice that this trace appears qualitatively different from that of the first electron. Rather than smoothly moving up in energy, the two-electron energy shows a very clear kink at a magnetic field strength of 1.5 Tesla.

Why does the energy to add the second electron energy differ so much from the one electron energy? The reason is that the two electrons in the artificial atom interact with one another. Indeed this interaction produces the kink at 1.5 Tesla. Aside from carrying electric charge, electrons also carry magnetism. If electrons are thought of as small bar magnets, then the spin of an electron points between the poles of the magnet. At zero magnetic field, the two electrons in their lowest energy configuration have their spins pointing in opposite directions. At 1.5 Tesla, the spin of one of the electrons flips, so that the magnet moments of both electrons line up with the external magnetic field. This spin-flipping has never been observed before. In a Helium atom, a real atom containing two electrons, this spin-flipping is predicted to take place at the astronomic magnetic field of 400,000 Tesla! It turns out that the large size of the artificial atom brings the magnetic field required for the spin-flipping into the observable range.

At higher electron numbers, the physics of the artificial atom becomes difficult to solve and sophisticated computer modeling is required to understand the energy levels. For low magnetic fields, an model of electronic "shell" structure analgous to the **s, p, d,** and **f** shells in real atoms is appropriate. However, for more than about 10 electrons in the artificial atom and at magnetic fields above a few Tesla, features appear in the data that are understandable in terms of a magnetic shell structure in which confinement by the applied magnetic field dominates the confinement of the artificial atom's parabolic potential.

With the creation of the few electron artificial atom, the ultimate limit of small sized electronics is being achieved. There remains much physics to explore, with a vast amount of information in the details of the spectra. Basic ideas about the effects of interactions between electrons can be tested in an unprecedented way.

Several projects are presently underway to enhance both the utility and sensitivity of SECS. We have commissioned a top loading dilution refrigerator which will allow samples to be cooled from room temperature to 20 mK in about three hours. This will allow us to measure a large quantity and variety of samples. Also, a scanning electron microscope has been converted for use in electron beam lithography. Initial experiments will focus on spectra of artificial atoms and spectra of individual silicon impurity atoms in GaAs. Finally, we expect that the use of single-electron transistors (see chapter 2 of this section) as charge sensors may significantly enhance the sensitivity of our SECS measurement. We are commencing work on integrating metallic single-electron transistors onto our artificial atom samples.

5.2 Publications

Ashoori, R.C., H.L. Stormer, J.S., Weiner, L.N. Pfeiffer, S.J. Pearton, K.W. Baldwin, and K.W. West. "Single-Electron Capacitance Spectroscopy of Discrete Quantum Levels." *Phys. Rev. Lett.* 68(20): 3088-3091 (1992).

Ashoori, R.C., H.L. Stormer, J.S. Weiner, L.N., Pfeiffer, K.W. Baldwin, and K.W. West. "N-Electron Ground State Energies of a Quantum Dot in Magnetic Field." *Phys. Rev. Lett.* 71(4): 613-616 (1993).