ARTIFICIAL ATOMS

The charge and energy of a sufficiently small particle of metal or semiconductor are quantized just like those of an atom. The current through such a quantum dot or one-electron transistor reveals atom-like features in a spectacular way.

Marc A. Kastner

The wizardry of modern semiconductor technology makes it possible to fabricate particles of metal or "pools" of electrons in a semiconductor that are only a few hundred angstroms in size. Electrons in these structures can display astounding behavior. Such structures, coupled to electrical leads through tunnel junctions, have been given various names: single-electron transistors, quantum dots, zero-dimensional electron gases and Coulomb islands. In my own mind, however, I regard all of these as artificial atoms—atoms whose effective nuclear charge is controlled by metallic electrodes. Like natural atoms, these small electronic sytems contain a discrete number of electrons and have a discrete spectrum of energy levels. Artificial atoms, however, have a unique and spectacular property: The current through such an atom or the capacitance between its leads can vary by many orders of magnitude when its charge is changed by a single electron. Why this is so, and how we can use this property to measure the level spectrum of an artificial atom, is the subject of this article.

To understand artificial atoms it is helpful to know how to make them. One way to confine electrons in a small region is by employing material boundaries—by surrounding a metal particle with insulator, for example. Alternatively, one can use electric fields to confine electrons to a small region within a semiconductor. Either method requires fabricating very small structures. This is accomplished by the techniques of electron and x-ray lithography. Instead of explaining in detail how artificial atoms are actually fabricated, I will describe the various types of atoms schematically.

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Figures 1a and 1b show two kinds of what is sometimes called, for reasons that will soon become clear, a single-electron transistor. In the first type (figure 1a), which I call the all-metal artificial atom,[1] electrons are confined to a metal particle with typical dimensions of a few thousand angstroms or less. The particle is separated from the leads by thin insulators, through which electrons must tunnel to get from one side to the other. The leads are labeled "source" and "drain" because the electrons enter through the former and leave through the latter—the same way the leads are labeled for conventional field-effect transistors, such as those in the memory of your personal computer. The entire structure sits near a large, well-insulated metal electrode, called the gate.

Figure 1b shows a structure[2] that is conceptually similar to the all-metal atom but in which the confinement is accomplished with electric fields in gallium arsenide. Like the all-metal atom, it has a metal gate on the bottom with an insulator above it; in this type of atom the insulator is AlGaAs. When a positive voltage V_g is applied to the gate, electrons accumulate in the layer of GaAs above the AlGaAs. Because of the strong electric field at the AlGaAs–GaAs interface, the electrons' 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 feature that makes this an artificial atom is the pair of electrodes on the top surface of the GaAs. When a negative voltage is applied between these and the source or drain, the electrons are repelled and cannot accumulate underneath them. 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 a potential similar to the one seen by the electrons is shown in the inset in figure 1. For an electron to travel

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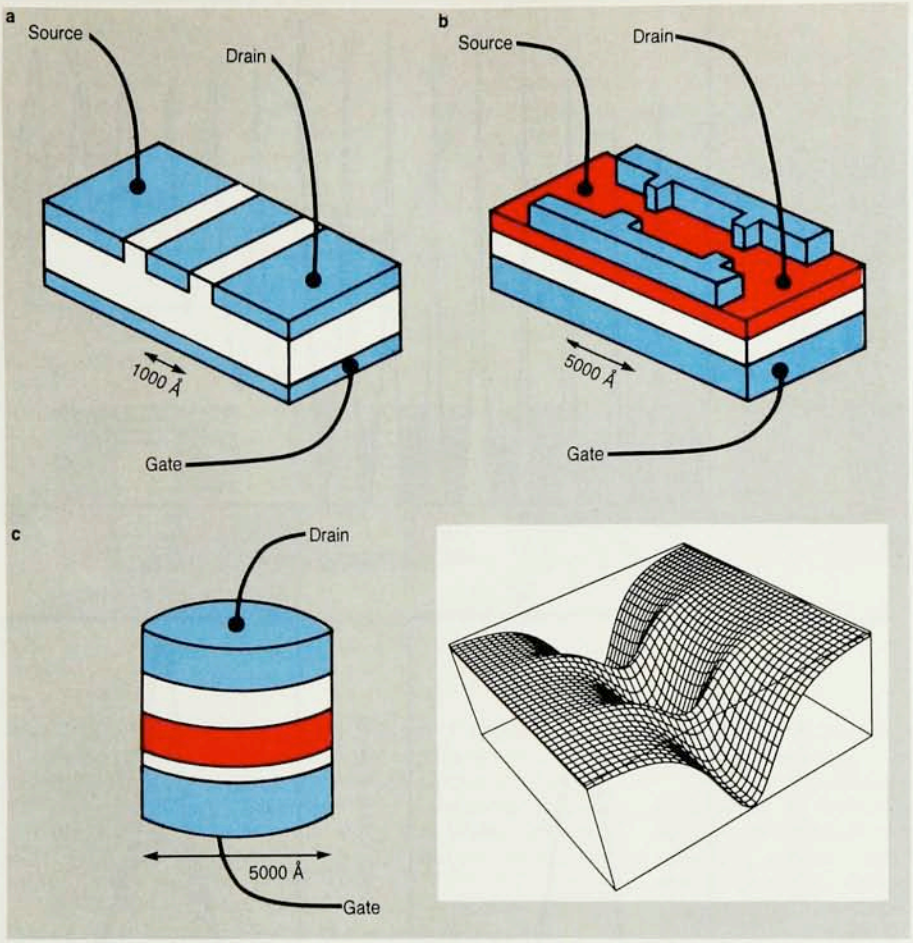


The many forms of artificial atoms include the all-metal atom (**a**), the controlled-barrier atom (**b**) and the two-probe atom, or "quantum dot" (**c**). Areas shown in blue are metallic, white areas are insulating, and red areas are semiconducting. The dimensions indicated are approximate. The inset shows a potential similar to the one in the controlled-barrier atom, plotted as a function of position at the semiconductor–insulator interface. The electrons must tunnel through potential barriers caused by the two constrictions. For capacitance measurements with a two-probe atom, only the source barrier is made thin enough for tunneling, but for current measurements both source and drain barriers are thin. **Figure 1**

from the source to the drain, it must tunnel through the barriers. The "pool" of electrons that accumulates between the two constrictions plays the same role that the small particle plays in the all-metal atom, and the potential barriers from the constrictions play the role of the thin insulators. Because one can control the height of these barriers by varying the voltage on the electrodes, I call this type of artificial atom the controlled-barrier atom. Controlled-barrier atoms in which the heights of the two potential barriers can be varied independently have also been fabricated.[3] (The constrictions in these devices are similar to those used for measurements of quantized conductance in narrow channels as reported in PHYSICS TODAY, November 1988, page 21.) In addition, there are structures that behave like controlled-barrier atoms but in which the barriers are caused by charged impurities or grain boundaries.[2,4]

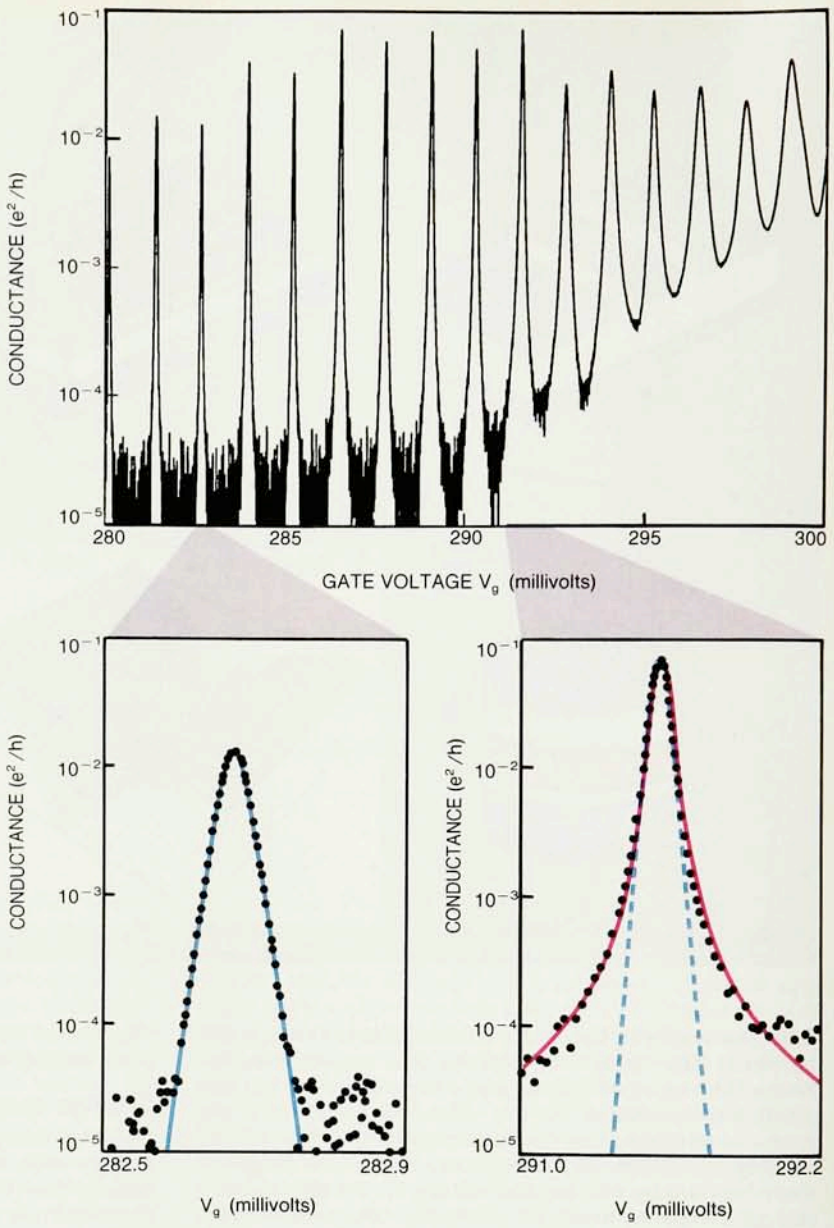
Figure 1c shows another, much simpler type of artificial atom. The electrons in a layer of GaAs are sandwiched between two layers of insulating AlGaAs. One or both of these insulators acts as a tunnel barrier. If both barriers are thin, electrons can tunnel through them, and the structure is analogous to the single-electron transistor without the gate. Such structures, usually called quantum dots, have been studied extensively.[5,6] To create the structure, one starts with two-dimensional layers like those in figure 1b. The cylinder can be made by etching away unwanted regions of the layer structure, or a metal electrode on the surface, like those in figure 1b, can be used to repel electrons everywhere except in a small circular section of GaAs. Although a gate electrode can be added to this kind of structure, most of the experiments have been done without one, so I call this the two-probe atom.

Charge quantization

One way to learn about natural atoms is to measure the energy required to add or remove electrons. This is usually done by photoelectron spectroscopy. For example, the minimum photon energy needed to remove an electron is the ionization potential, and the maximum energy of photons emitted when an atom captures an electron is the electron affinity. To learn about artificial atoms we also measure the energy needed to add or subtract electrons. However, we do it by measuring the current through the artificial atom.

Figure 2 shows the current through a controlled-barrier atom[7] as a function of the voltage V_g between the gate and the atom. One obtains this plot by applying a very small voltage between the source and drain, just large enough to measure the tunneling conductance between them. The results are astounding. The conductance displays sharp resonances that are almost periodic in V_g. By calculating the capacitance between the artificial atom and the gate we can show[2,8] that the period is the voltage necessary to add *one electron* to the confined pool of electrons. That is why we sometimes call the controlled-barrier atom a single-electron transistor: Whereas the transistors in your personal computer turn on only once when many electrons are added to them, the artificial atom turns on and off again every time a single electron is added to it.

A simple theory, the Coulomb blockade model, ex-



Conductance of a controlled-barrier atom as a function of the voltage V_g on the gate at a temperature of 60 mK. At low V_g (solid blue curve) the shape of the resonance is given by the thermal distribution of electrons in the source that are tunneling onto the atom, but at high V_g a thermally broadened Lorentzian (red curve) is a better description than the thermal distribution alone (dashed blue curve). (Adapted from ref. 7.) **Figure 2**

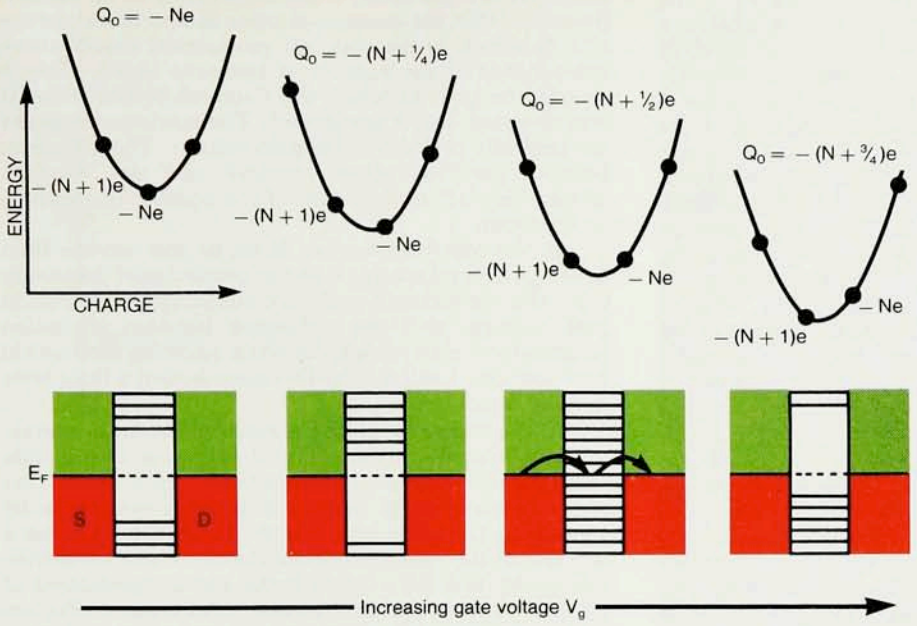
plains the periodic conductance resonances.[9] (See PHYSICS TODAY, May 1988, page 19.) This model is quantitatively correct for the all-metal atom and qualitatively correct for the controlled-barrier atom.[10] To understand the model, think about how an electron in the all-metal atom tunnels from one lead onto the metal particle and then onto the other lead. Suppose the particle is neutral to begin with. To add a charge Q to the particle requires energy $Q^2/2C$, where C is the total capacitance between the particle and the rest of the system; since you cannot add less than one electron the flow of current requires a Coulomb energy $e^2/2C$. This energy barrier is called the Coulomb blockade. A fancier way to say this is that charge quantization leads to an energy gap in the spectrum of states for tunneling: For an electron to tunnel onto the particle, 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.

The gap in the tunneling spectrum is the difference between the "ionization potential" and the "electron affinity" of the artificial atom. For a hydrogen atom the ionization potential is 13.6 eV, but the electron affinity, the binding energy of H^-, is only 0.75 eV. This large difference arises from the strong repulsive interaction between the two electrons bound to the same proton. Just as for natural atoms like hydrogen, the difference between the ionization potential and electron affinity for artificial atoms arises from the electron–electron interactions; the difference, however, is much smaller for artificial atoms because they are much bigger than natural ones.

By changing the gate voltage V_g one can alter the energy required to add charge to the particle. V_g is applied between the gate and the source, but if the drain–source voltage is very small, the source, drain and particle will all be at almost the same potential. With V_g applied, the electrostatic energy of a charge Q on the particle is

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

For negative charge Q, the first term is the attractive



Total energy (top) and tunneling energies (bottom) for an artificial atom. As the gate voltage is increased the charge Q_0 for which the energy is minimized changes from $-Ne$ to $-(N + 3/4)e$. Only the points corresponding to discrete numbers of electrons on the atom are allowed (dots on upper curves). Lines in the lower diagram indicate energies needed for electrons or holes to tunnel onto the atom. When $Q_0 = -(N + 1/2)e$ the gap in tunneling energies vanishes and current can flow. **Figure 3**

interaction between Q and the positively charged gate electrode, 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 its minimum at $Q_0 = -CV_g$. For simplicity I have assumed that the gate is the only electrode that contributes to C; in reality, there are other contributions.[7]

By varying V_g we can choose any value of Q_0, the charge that would minimize the energy in equation 1 if charge were not quantized. However, because the real charge *is* quantized, only discrete values of the energy E are possible. (See figure 3.) When $Q_0 = -Ne$, an integral number N of electrons minimizes E, and the Coulomb interaction results in the same energy difference $e^2/2C$ for increasing or decreasing N by 1. For all other values of Q_0 except $Q_0 = -(N + 1/2)e$ there is a smaller, but nonzero, energy for either adding or subtracting an electron. Under such 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, and 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 $CV_g = Q_0 = -(N + 1/2)e$, spaced in gate voltage by e/C.

As shown in figure 3, there is a gap in the tunneling spectrum for all values of V_g except the charge-degeneracy points. The more closely spaced discrete levels shown outside this gap are due to excited states of the electrons present on the artificial atom and will be discussed more in the next section. As V_g is increased continuously, the gap is pulled down relative to the Fermi energy until a charge-degeneracy point is reached. On moving through this point there is a discontinuous change in the tunneling spectrum: The gap collapses and then reappears shifted up by e^2/C. Simultaneously the charge on the artificial atom increases by 1 and the process starts over again. A charge-degeneracy point and a conductance peak are reached every time the voltage is increased by e/C, the amount necessary to add one electron to the artificial atom. Increasing the gate voltage of an artificial atom is therefore analogous to moving through the periodic table for natural atoms by increasing the nuclear charge.

The quantization of charge on a natural atom is something we take for granted. However, if atoms were larger, the energy needed to add or remove electrons would be smaller, and the number of electrons on them would fluctuate except at very low temperature. The quantization of charge is just one of the properties that artificial atoms have in common with natural ones.

Energy quantization

The Coulomb blockade model accounts for charge quantization but ignores the quantization of energy resulting from the small size of the artificial atom. This confinement of the electrons makes the energy spacing of levels in the atom relatively large at low energies. If one thinks of the atom as a box, at the lowest energies the level spacings are of the order $\hbar^2/ma^2$, where a is the size of the box. At higher energies the level spacings decrease for a three-dimensional atom because of the large number of standing electron waves possible for a given energy. If there are many electrons in the atom, they fill up many levels, and the level spacing at the Fermi energy becomes small. The all-metal atom has so many electrons (about 10^7) that the level spectrum is effectively continuous. Because of this, many experts do not regard such devices as "atoms," but I think it is helpful to think of them as being atoms in the limit in which the number of electrons is large. In the controlled-barrier atom, however, there are only about 30–60 electrons, similar to the number in natural atoms like krypton through xenon. Two-probe atoms sometimes have only one or two electrons. (There are actually many more electrons that are tightly bound to the ion cores of the semiconductor, but those are unimportant because they cannot move.) For most cases, therefore, the spectrum of energies for adding an extra electron to the atom is discrete, just as it is for natural atoms. That is why a discrete set of levels is shown in figure 3.

One can measure the energy level spectrum directly by observing the tunneling current at fixed V_g as a function of the voltage V_{ds} between drain and source. Suppose we adjust V_g so that, for example,

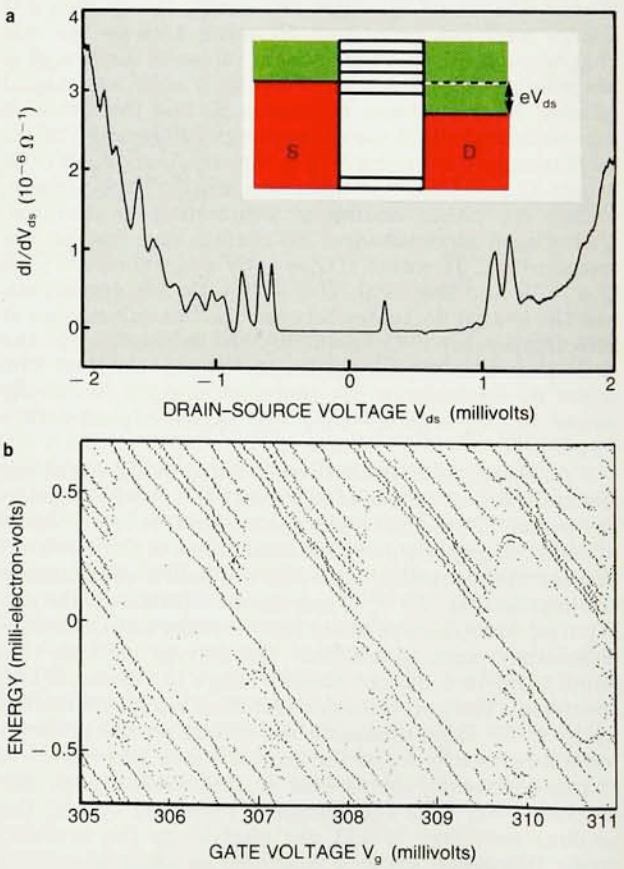
$Q_0 = -(N + \frac{1}{4})e$ and then begin to increase V_{ds}. The Fermi level in the source rises in proportion to V_{ds} relative to the drain, so it also rises relative to the energy levels of the artificial atom. (See the inset to figure 4a.) Current begins to flow when the Fermi energy of the source 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 it, and more current flows because there are additional channels for electrons to use for tunneling onto the artificial atom. We measure an energy level 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 need to correct for the increase in the energy of the atom with V_{ds}, but this is a small effect.) Many beautiful tunneling spectra of this kind have been measured[5] for two-terminal atoms. Figure 4a shows one for a controlled-barrier atom.[7]

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, as sketched in figure 3. One can observe this effect by plotting the values of V_{ds} at which peaks appear in dI/dV_{ds}. (See figure 4b.) As V_g increases you can see the gap in the tunneling spectrum shift lower and then disappear at the charge-degeneracy point, just as the Coulomb blockade model predicts. You can also see the discrete energy levels of the artificial atom. For the range of V_{ds} shown in figure 4 the voltage is only large enough to add or remove one electron from the atom; the discrete levels above the gap are the excited states of the atom with one extra electron, and those below the gap are the excited states of the atom with one electron missing (one hole). At still higher voltages (not shown in figure 4) one observes levels for two extra electrons or holes and so forth. 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.

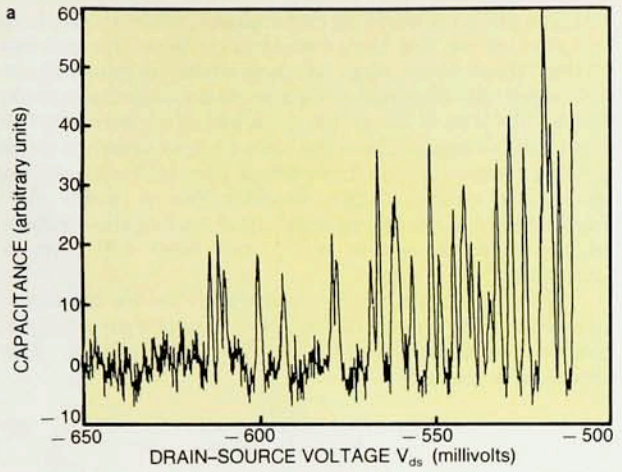
In a natural atom one has little control over the spectrum of energies for adding or removing electrons. There the electrons interact with the fixed potential of the nucleus and with each other, and these two kinds of interaction determine the spectrum. In an artificial atom, however, one can change this spectrum completely by altering the atom's geometry and composition. For the all-metal atom, which has a high density of electrons, the energy spacing between the discrete levels is so small that it can be ignored. The high density of electrons also results in a short screening length for external electric fields, so electrons added to the atom reside on its surface. Because of this, the electron–electron interaction is always e^2/C (where C is the classical geometrical capacitance), independent of the number of electrons added. This is exactly the case for which the Coulomb blockade model was invented, and it works well: The conductance peaks are perfectly periodic in the gate voltage. The difference between the "ionization potential" and the "electron affinity" is e^2/C, independent of the number of electrons on the atom.

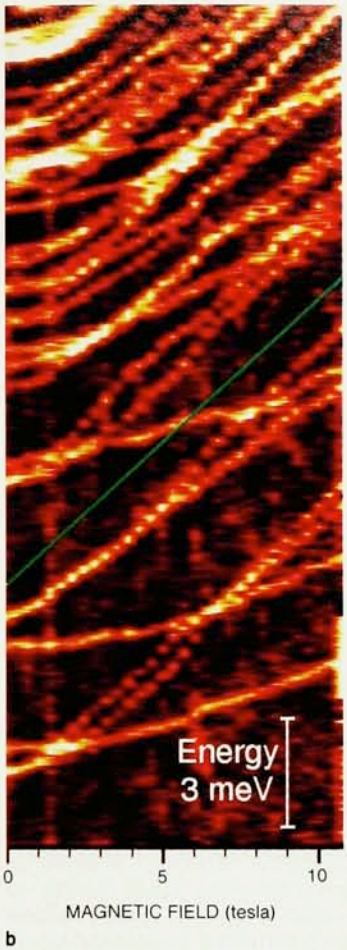
In the controlled-barrier atom, as you can see from figure 4, the level spacing is one or two tenths of the energy gap. The conductance peaks are not perfectly periodic in gate voltage, and the difference between ionization potential and electron affinity has a quantum mechanical contribution. I will discuss this contribution a little later in more detail.

In the two-probe atom the electron–electron interaction can be made very small, so that one can in principle reach the limit opposite to that of the all-metal atom. One can find the energy levels of a two-probe atom by measuring the capacitance between its two leads as a function of the voltage between them.[6] When no tunneling occurs, this capacitance is the series combination of the source–atom and atom–drain capacitances. For capacitance measurements, two-probe atoms are made with the insulating layer between the *drain* and atom so thick that current cannot flow under any circumstances. Whenever the Fermi level in the *source* lines up with one of the energy levels of the atom, however, electrons can tunnel freely back and forth between the atom and the source. This causes the total capacitance to increase, because the source–atom capacitor is effectively shorted by the tunneling current. The amazing thing about this experiment is that a peak occurs in the capacitance every



Discrete energy levels of an artificial atom 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 artificial atom. (See inset of **a**.) **a:** 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 -0.5 mV and $+0.3$ mV where there are no peaks. **b:** 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, just as sketched in the lower part of figure 3. (Adapted from ref. 7.) **Figure 4**





Capacitance of a two-probe atom that has only one barrier thin enough to allow tunneling. **a:** The capacitance has a peak every time a single electron is added to the atom. The positions of the peaks give the energy spectrum of the atom. **b:** Peaks in capacitance plotted versus applied magnetic field. The green line indicates the rate of change of the energy expected when the magnetic field dominates. (Adapted from ref. 6.) **Figure 5**

time a *single electron* is added to the atom. (See figure 5a.) The voltages at which the peaks occur give the energies for adding electrons to the atom, just as the voltages for peaks in dI/dV_{ds} do for the controlled-barrier atom or for a two-probe atom in which both the source–atom barrier and the atom–drain barrier are thin enough for tunneling. The first peak in figure 5a corresponds to the one-electron artificial atom.

Figure 5b shows how the energies for adding electrons to a two-probe atom vary with a magnetic field perpendicular to the GaAs layer. In an all-metal atom the levels would be equally spaced, by e^2/C, and would be independent of magnetic field because the electron–electron interaction completely determines the energy. By contrast, the levels of the two-probe atom are irregularly spaced and depend on the magnetic field in a systematic way. For the two-probe atom the fixed potential determines the energies at zero field. The level spacings are irregular because the potential is not highly symmetric and varies at random inside the atom because of charged impurities in the GaAs and AlGaAs. It is clear that the electron–electron interactions that are the source of the Coulomb blockade are not always so important in the two-probe atom as in the all-metal and controlled-barrier atoms. Their relative importance depends in detail on the geometry.[5]

Artificial atoms in a magnetic field

Level spectra for natural atoms can be calculated theoretically with great accuracy, and it would be nice to be able to do the same for artificial atoms. No one has yet calculated an entire spectrum, like that in figure 4a. However, for a simple geometry we can now predict the charge-degeneracy points, the values of V_g corresponding to conductance peaks like those in figure 2. From the earlier discussion it should be clear that in such a calculation one must take into account the electron's interactions with both the fixed potential and the other electrons.

The simplest way to do this is with an extension of the Coulomb blockade model.[11–13] It is assumed, as before, that the contribution to the gap in the tunneling spectrum from the Coulomb interaction is e^2/C no matter how many electrons are added to the atom. To account for the discrete levels one pretends that once on the atom, each electron interacts independently with the fixed potential. All one has to do is solve for the energy levels of a single electron in the fixed potential that creates the artificial atom and then fill those levels in accordance with the Pauli exclusion principle. Because the electron–electron interaction is assumed always to be e^2/C, this is called the constant-interaction model.

Now think about what happens when one adds electrons to a controlled-barrier atom by increasing the gate voltage while keeping V_{ds} just large enough so one can measure the conductance. When there are $N-1$ electrons on the atom the $N-1$ lowest energy levels are filled. The next conductance peak occurs when the gate voltage pulls the energy of the atom down enough that the Fermi level in the source and drain becomes degenerate with the Nth level. Only when an energy level is degenerate with the Fermi energy can current flow; this is the condition for a conductance peak. When V_g is increased further and the next conductance peak is reached, there are N electrons on the atom, and the Fermi level is degenerate with the $(N+1)$-th level. Therefore to get from one peak to the next the Fermi energy must be raised by $e^2/C + (E_{N+1} - E_N)$, where E_N is the energy of the Nth level of the atom. If the energy levels are closely spaced the Coulomb blockade result is recovered, but in general the level spacing contributes to the energy between successive conductance peaks.

It turns out that we can test the results of this kind of calculation best if a magnetic field is applied perpendicular to the GaAs layer. For free electrons in two dimensions, applying the magnetic field results in the spectrum of Landau levels with energies $(n + \frac{1}{2})\hbar\omega_c$, where the cyclotron frequency is $\omega_c = eB/m^*c$, and m^* is the effective mass of the electrons. In the controlled-barrier atom and the two-probe atom, we expect levels that behave like Landau levels at high fields, with energies that increase linearly in B. This behavior occurs because when the field is large enough the cyclotron

radius is much smaller than the size of the electrostatic potential well that confines the electrons, and the electrons act as if they were free. Levels shifting proportionally to B, as expected, are seen experimentally. (See figure 5b.)

To calculate the level spectrum we need to model the fixed potential, the analog of the potential from the nucleus of a natural atom. The simplest choice is a harmonic oscillator potential, and this turns out to be a good approximation for the controlled-barrier atom. Figure 6a shows the calculated level spectrum as a function of magnetic field for noninteracting electrons in a two-dimensional harmonic oscillator potential. At low fields the energy levels dance around wildly with magnetic field. This occurs because some states have large angular momentum and the resulting magnetic moment causes their energies to shift up or down strongly with magnetic field. As the field is increased, however, things settle down. For most of the field range shown there are four families of levels, two moving up, the other two down. At the highest fields there are only two families, corresponding to the two possible spin states of the electron.

Suppose we measure, in an experiment like the one whose results are shown in figure 2, the gate voltage at which a specific peak occurs as a function of magnetic field. This value of V_g is the voltage at which the Nth energy level is degenerate with the Fermi energy in the source and drain. A shift in the energy of the level will cause a shift in the peak position. The blue line in figure 6a is the calculated energy of the 39th level (chosen fairly arbitrarily for illustration purposes), so it gives the prediction of the constant-interaction model for the position of the 39th conductance peak. As the magnetic field increases, levels moving up in energy cross those moving down, but the number of electrons is fixed, so electrons jump from upward-moving filled levels to downward-moving empty ones. The peak always follows the 39th level, so it moves up and down in gate voltage.

Figure 6b shows a measurement[14] of V_g for one conductance maximum, like one of those in figure 2, as a function of B. The behavior is qualitatively similar to that predicted by the constant-interaction model: The peak moves up and down with increasing B, and the frequency of level crossings changes at the field where only the last two families of levels remain. However, at high B the frequency is predicted to be much lower than what is observed experimentally. While the constant-interaction model is in qualitative agreement with experiment, it is not quantitatively correct.

To anyone who has studied atomic physics, the constant-interaction model seems quite crude. Even the simplest models used to calculate energies of many-electron atoms determine the charge density and potential self-consistently. One begins by calculating the charge density that would result from noninteracting electrons in the fixed potential, and then one calculates the effective potential an electron sees because of the fixed potential and the potential resulting from this charge density. Then one calculates the charge density again. One does this repeatedly until the charge density and potential are self-consistent. The constant-interaction model fails because it is not self-consistent. Figure 6c shows the results of a self-consistent calculation for the controlled-barrier atom.[14] It is in good agreement with experiment—much better agreement than the constant-interaction model gives.

Conductance line shapes

In atomic physics, the next step after predicting energy levels is to explore how an atom interacts with the electromagnetic field, because the absorption and emission of photons teaches us the most about atoms. For artificial atoms, absorption and emission of electrons plays this role, so we had better understand how this process works. Think about what happens when the gate voltage in the controlled-barrier atom is set at a conductance peak, and an electron is tunneling back and forth between the atom and the leads. Since the electron spends only a finite time τ on the atom, the uncertainty principle tells us that the energy level of the electron has a width $\hbar/\tau$. Furthermore, since the probability of finding the electron on the atom decays as $e^{-t/\tau}$, the level will have a Lorentzian line shape.

This line shape can be measured from the transmission probability spectrum $T(E)$ of electrons with energy E incident on the artificial atom from the source. The spectrum is given by

$$T(E) = \frac{\Gamma^2}{\Gamma^2 + (E - E_N)^2} \tag{2}$$

where Γ is approximately $\hbar/\tau$ and E_N is the energy of the Nth level. The probability that electrons are transmitted from the source to the drain is approximately proportional[15] to the conductance G. In fact, $G \simeq (e^2/h)T$, where e^2/h is the quantum of conductance. It is easy to show that one must have $G < e^2/h$ for each of the barriers separately to observe conductance resonances. (An equivalent argument is used to show that electrons in a disordered conductor are localized for $G < e^2/h$. See, for example, the article by Boris L. Al'tshuler and Patrick A. Lee in PHYSICS TODAY, December 1988, page 36.) This condition is equivalent to requiring that the separation of the levels is greater than their width Γ.

Like any spectroscopy, our electron spectroscopy of artificial atoms has a finite resolution. The resolution is determined by the energy spread of the electrons in the source, which are trying to tunnel into the artificial atom. These electrons are distributed according to the Fermi–Dirac function,

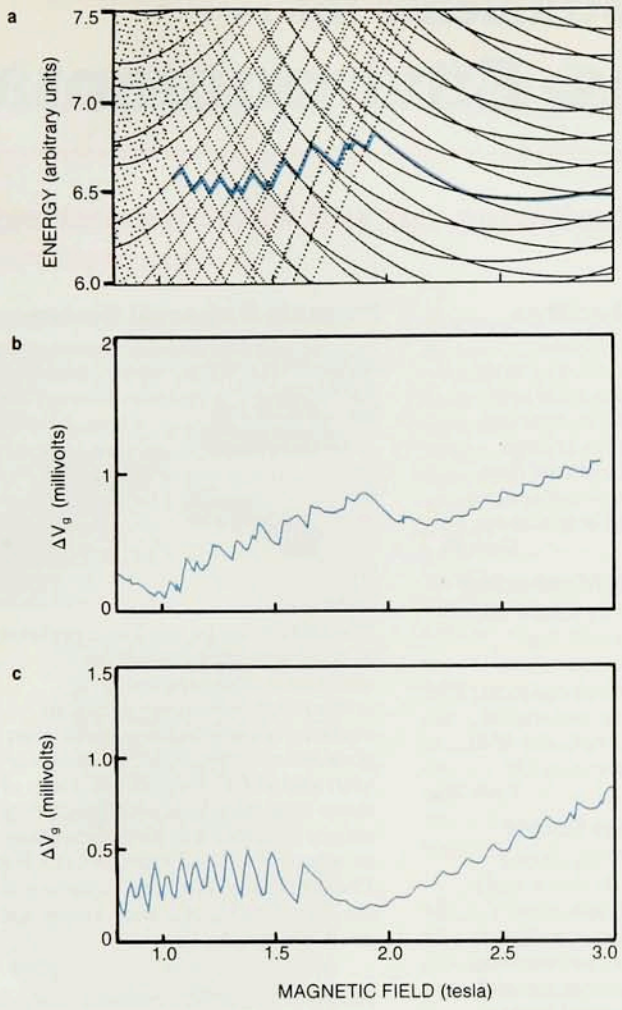
$$f(E) = \frac{1}{\exp\left(\frac{E - E_F}{kT}\right) + 1} \tag{3}$$

where E_F is the Fermi energy. The tunneling current is given by

$$I = \int \frac{e}{h} T(E)\,[f(E) - f(E - eV_{ds})]\,dE \tag{4}$$

Equation 4 says that the net current is proportional to the probability $f(E)T(E)$ that there is an electron in the source with energy E and that the electron can tunnel between the source and drain minus the equivalent probability for electrons going from drain to source. The best resolution is achieved by making $V_{ds} \ll kT$. Then $[f(E) - f(E - eV_{ds})] \simeq eV_{ds}(df/dE)$, and I is proportional to V_{ds}, so the conductance is I/V_{ds}.

Figure 2 shows that equations 2–4 describe the experiments well: At low V_g, where Γ is much less than kT, the shape of the conductance resonance is given by the resolution function df/dE. But at higher V_g one sees the Lorentzian tails of the natural line shape quite clearly. The width Γ depends exponentially on the height and width of the potential barrier, as is usual for tunneling. The height of the tunnel barrier decreases with V_g, which is why the peaks become broader with increasing V_g. Just as we have control over the level spacing in artificial atoms, we also can control the coupling to the leads and therefore the level widths. It is clear why the present generation of artificial atoms show unusual behavior only at low temperatures: When kT becomes comparable to



Effect of magnetic field on energy level spectrum and conductance peaks. **a:** Calculated level spectrum for noninteracting electrons in a harmonic oscillator electrostatic potential as a function of magnetic field. The blue line is the prediction that the constant-interaction model gives for the gate voltage for the 39th conductance peak. **b:** Measured position of a conductance peak in a controlled-barrier atom as a function of field. **c:** Position of the 39th conductance peak versus field, calculated self-consistently. The scale in **c** does not match that in **b** because parameters in the calculation were not precisely matched to the experimental conditions. (Adapted from ref. 14.) **Figure 6**

the energy separation between resonances, the peaks overlap and the features disappear.

Applications

The behavior of artificial atoms is so unusual that it is natural to ask whether they will be useful for applications to electronics. Some clever things can be done: Because of the electron–electron interaction, only one electron at a time can pass through the atom. With devices like the "turnstile" device[16,17] shown on the cover of this issue the two tunnel barriers can be raised and lowered independently. Suppose the two barriers are raised and lowered sequentially at a radio or microwave frequency ν. Then, with a small source–drain voltage applied, an electron will tunnel onto the atom when the source–atom barrier is low and off it when the atom–drain barrier is low. One electron will pass in each time interval ν^{-1}, producing a current $e\nu$. Other applications, such as sensitive electrometers, can be imagined.[9,18] However, the most interesting applications may involve devices in which several artificial atoms are coupled together to form artificial molecules[16,17,19] or in which many are coupled to form artificial solids. Because the coupling between the artificial atoms can be controlled, new physics as well as new applications may emerge. The age of artificial atoms has only just begun.

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