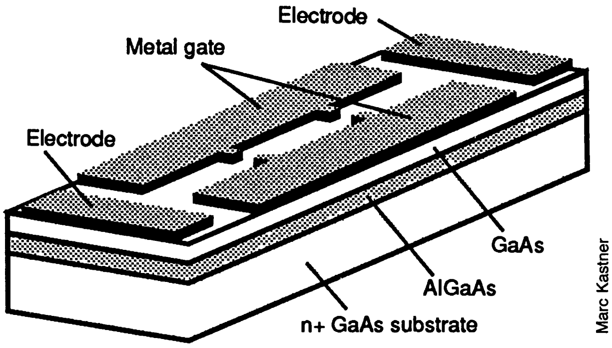
A Transistor That Works Electron by Electron

Quantum effects produce a transistor that cycles on and off as electrons are added or subtracted one at a time

HALF AN ELECTRON IS ALL IT TAKES to turn on or off a super-sensitive transistor built by researchers at the Massachusetts Institute of Technology and IBM. In the device developed by Udi Meirav and Marc Kastner at MIT and Shalom Wind at IBM, the current flow switches on and off, on and off, as electrons are added one at a time.

So far, the transistor operates only at temperatures below 1 K, which makes it impractical for commercial applications. The device does, however, open a window onto some intriguing new physics, since the researchers are not exactly sure how it works. And, Wind says, if they can figure out how to produce the behavior at higher temperatures, this could lead to "really spectacular electronic devices" that work in a totally different way from today's transistors.

The MIT/IBM device, which is described in the 6 August *Physical Review Letters*, is similar to a standard field-effect transistor. It consists of a thin layer of gallium arsenide grown on top of a thin layer of aluminum gallium arsenide, which in turn sits on a base of gallium arsenide doped so that it conducts electricity (see diagram). Two metal electrodes are mounted on each end of the GaAs layer. When a voltage is applied between the base and the top GaAs layer, it attracts electrons from the metal electrodes to the interface between the AlGaAs and the GaAs, and these free electrons allow the GaAs—which is normally an insulator—to carry an electrical current. The larger this applied voltage, the more free electrons, and the larger the current that can be carried between the electrodes. Nothing unusual so far: In normal transistors, an applied voltage is used in just this way to control the current between two electrodes.



Electron box. *The gate forms a channel with two bottlenecks.*

But the three researchers added two extra features that turned this normal transistor into a distinctly unusual device. The first is a pair of metal strips atop the GaAs that serve as a "gate" between the two electrodes. When a voltage is applied to these strips, it produces an electrical potential that extends into the GaAs. This herds the free electrons into the narrow strip of GaAs that lies beneath the gap between the metal strips. The result is that when the electrons in the GaAs layer move from one electrode to the other, they must stay in a narrow channel. In effect, the electrons are moving in only one dimension, held close to the GaAs/AlGaAs interface and squeezed between the two sides of the gate.

"Lots of fascinating effects have popped up in such one-dimensional structures," Wind says. One of the most intriguing was discovered accidentally a year and a half ago by Kastner and co-workers at MIT. They found that as they increased the applied voltage in a silicon field-effect transistor, the current between the electrodes did not go up in a smooth manner but instead went up and down periodically. "When we first saw these oscillations, we didn't know what they were," Kastner recalls. Indeed, one of his colleagues, when shown the data, told him, "This is physically impossible."

But the effect was real, and Kastner's group suggested a possible explanation. If a pair of impurities along the one-dimensional channel obstructs the flow of electrons through it, this could partially isolate the segment between the impurities from the rest of the channel. In this one-dimensional box, quantum effects could come into play, so that the current passing through it varied according to exactly how many electrons were inside it.

To test this hypothesis, Kastner worked with Meirav and Wind to create the same effect in a reproducible way, instead of depending on the chance occurrence of impurities in the channel. This was the second added feature: They mimicked the impurity-caused obstructions by adding two constrictions onto the gate (see figure). These constrictions, they reasoned, would squeeze the channel at two points, creating an isolated segment of fixed length.

Knowing the length of this segment was the key to proving exactly what was going on, Kastner says, since it allowed the group to calculate the number of electrons added to the box, for a given change in the applied voltage. (When the channel was constricted by impurities, there was no way to figure out the distance between them.) Kastner estimates that at the applied voltages they are using, their devices have less than 100 electrons inside the box.

The group's calculations prove that each time the number of electrons in the restricted segment of the channel increases by exactly one, the current through the channel goes down and back up in a complete cycle—that is, the transistor turns off and back on. Similarly, by changing the applied voltage so that the number of electrons in the box changes by one-half, the current goes from on to off, or off to on. ("Half an electron" is merely an average: To say that the segment holds 20½ electrons, for instance, means it has 20 electrons half the time and 21 electrons the other half.)

Although theory still has not caught up with experimentation in this case, the group's members believe they know qualitatively what is going on. By adjusting the applied voltage, they control precisely how many electrons are in the segment. If it contains a whole number of electrons, they act together to repel any other electrons from entering the segment. Thus the current is small or zero. But when the segment has a half-integer number of electrons, electrons are constantly moving in and out, allowing a current to pass through. Kastner says that a change as small as one-tenth of an electron can alter the current passing through the transistor by a factor of 100.

If the same effect can be achieved at higher, more practical temperatures, Kastner notes, it may be possible to create a multi-state transistor that would turn on and off many times with increasing voltage instead of just once, as in the standard transistor. This could open a whole range of applications. But that's in the distant future. First, the researchers want to understand exactly what is going on here. The theoretical explanations offered to account for the variation in current with the number of electrons do not explain other features of the device, such as puzzling variations in the amplitude of the current, and they still don't know how the electrons inside the box are interacting with one another.

■ ROBERT POOL