

creased hardness; they also absorb particular frequencies of light. The yellow powder, for example, consists of cadmium selenide clusters roughly 15 angstroms in diameter—about 100 atoms. Red clusters measure 40 angstroms across (about 1,200 atoms). The frequency of light absorbed reflects the band-gap energy of the cluster. The smaller the cluster, the larger the band-gap energy, Steigerwald explains. So changing the size of clusters tunes the energy level of a material.

To make clusters, the chemists capture tiny groups of atoms in sheaths or in cages. A few years ago Steigerwald's colleague Louis E. Brus found he could suspend tiny clusters of cadmium selenide, ranging from 10 to 100 angstroms in diameter, in a solution.

Later Brus and Steigerwald, a synthetic chemist by training, began wrapping the clusters in soapy films of organic polymers that dried and molded around the atoms. Such sheaths keep the atoms from recombining when they are taken out of solution. Others, including Galen D. Stucky and his team at the University of California at Santa Barbara, are trying to stuff atomic clusters into porous glasses or zeolites, which act like cages. Still others, working with metals, use lasers to chip metallic clusters from larger materials [see "Microclusters," by Michael A. Duncan and Dennis H. Rouvray; SCIENTIFIC AMERICAN, December, 1989].

Yet although chemists can make far smaller clusters, or quantum dots, than can lithographers, there is a catch. In

any batch of clusters, sizes will vary, on average, by about 10 percent, Steigerwald says. That variation is far too great for electronic or optical devices, which demand arrays of identical clusters. "I don't know a good way to answer that problem," Steigerwald concedes. "There are lots of ways to dream about, but the world will need another inspiration."

A California team hopes to have an answer for him. Recently Kerry J. Vahala, a physicist at the California Institute of Technology, teamed up with a chemist and an engineer to build a system for separating clusters with a laser beam. Vahala's team will begin testing their idea early next year when their equipment is up and running. The plan: form a batch of semiconductor

ELECTRONS TRAVELING ONE BY ONE

Current in conventional electronic devices is considered a kind of flowing river of electrons, in which the electrons are as uncountable as molecules of water. Reduce the dimensions of the material, and the energy of those electrons becomes quantized, or divided into discrete increments. Still, the precise number of electrons defies calculation.

Now researchers at Delft University in the Netherlands, the Centre d'Études Nucleaires de Saclay in France, Chalmers University of Technology in Sweden and Moscow State University have shown they can count the individual electrons that make up a weak current. Instead of quantized electron energy, they and many others are studying quantized electron charges.

The implications of the efforts are twofold: devices that clock individual electrons may produce a new, highly precise measurement standard for current. Longer term, currents composed of single electrons could lead to alternative schemes for very small-scale electronic devices.

SYNCPATED ELECTRONS. The basic design for a single-electron device calls for a central aluminum electrode of about one micron long and coated with aluminum oxide. This bar overlaps with two symmetrically arranged metallic electrodes on either side. Although small, the device is not a dimensionally confined system, points out Theodore A. Fulton of AT&T Bell Laboratories, who has also been building single-electron devices.

Apply a voltage across this device, and it behaves like a conventional resistor. But at temperatures of about one kelvin and voltages of a few tenths of a millivolt, the resistance increases dramatically. No current will flow through the device because the electrons have insufficient energy to charge the central bar. Increasing the voltage to about one millivolt gives electrons just enough energy to tunnel from the voltage-carrying electrode into the central electrode.

Only one electron at a time successfully tunnels through to the

bar, however. This happens because an incoming electron charges the bar, thereby raising the energy barrier the next electron would have to overcome to reach the bar. When the first electron leaves the bar, the bar's charge falls. The flow of electrons consequently becomes highly syncopated: one electron must leave the central bar before another can enter.

ONE IN A THOUSAND. To employ this single-electron effect in a precise standard for current, researchers at Delft and Saclay synchronized a single-electron current with a radiofrequency signal. The workers first construct a series of small electrodes. By attaching additional voltage sources to the electrodes, the energy barriers of the device can be raised or lowered. The investigators then couple one secondary voltage source to a radiofrequency signal and let the signal meter the electrons through the device, one per cycle. "They've been successful as near as you can measure it," Fulton says.

So far the workers have recorded current of a few picoamps—plus or minus a few femtoamps—at frequencies of about five to 20 million electrons per second. Their measurements are therefore precise to one electron within 1,000. For them to top the existing standard for current, precision to better than one in 10 million would be necessary, Fulton notes.

The gates built at Delft and Saclay operate much like a simple shift register, an electronic device for storing binary numbers. Moreover, single-electron devices may prove easier to fabricate than quantum wires and dots; the metal gates do not rely on complex junctions of different compound materials.

But demonstrating physics principles is a far cry from building devices. So far all the research has taken place at temperatures near one kelvin. Whether the single-electron effects will hold up as workers try to raise the temperature remains to be seen. Adds Fulton: "I'm glad to say that I don't yet know the answer to that question."

