There Is Plenty of Room Between Two Atom Contacts

C. J. Muller and M. A. Reed

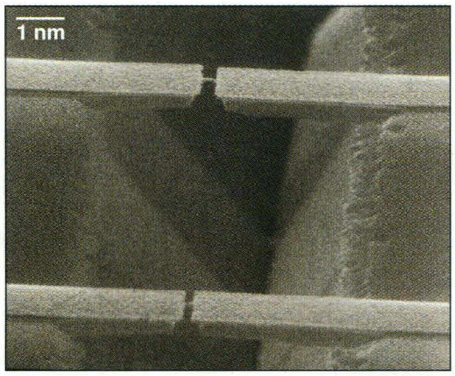
More than 35 years ago, Richard Feynman presented a talk "There's plenty of room at the bottom" (*1*), discussing the fascinating possibilities that would arise when we achieved the ability to manipulate matter at the atomic scale. Today this ability is, on the laboratory scale, a reality. New technologies and techniques have enabled a new view of this strange and interesting world, which undoubtedly will become the focus of science in the next generations. Recently, experiments with atomic scale contacts have begun to reveal the possibilities. (For example, see the report by Yazdani *et al.* on page 1921 of this issue.)

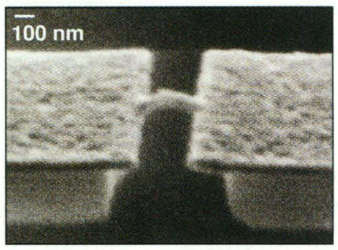
The origins of the capabilities that have led to the understanding of new quantum effects are in the field of semiconductor physics. These new quantum effects came within our reach when it was possible to confine the conduction electrons in semiconductors to low dimensions. This was enabled by semiconductor growth techniques developed in the 1970s that allowed the fabrication of atomically sharp interfaces between different semiconductors.

When one introduces dopants in one of the semiconductors, a two-dimensional (2D) electron gas forms at the interface, similar to how oil in water forms a thin layer at the surface. At the other, different semiconductor interface ("heterojunction"), the electrons are confined on the atomic scale, and thus, they are "two dimensional." When electrons are confined in additional dimension, a discrete set of energy levels is formed: the 3D example is the energy levels of an atom.

In semiconductors, every discrete energy level can carry an equal amount of current; and because the conductance is proportional to the current, every energy level contributes an equal amount of electrical conductance. Therefore, the conductance of electrons between adjacent 2D electron-gas reservoirs connected through a narrow channel called a quantum point contact (defined by applying an electrical potential to gate structures on top of the 2D electron gas, confining conduction electrons to only the connecting narrow channel) is quantized. The fundamental conductance unit observed in these systems equals $2e^2/h$, where e is an electron charge and h is Planck's constant (*2*). Typical dimensions between the two gates are on the order of a few tens of nanometers, accessible with nanolithographic techniques.

Why was this effect first seen in semiconductors? Electrons exhibit a wavelength related to their energy. Conduction electrons in semiconductors have a typical energy of a few thousandths of a electron volt, resulting in a wavelength of 30 to 100 nm. This relatively large wavelength makes confinement of the electrons possible by nanolithographic techniques. In metals, the conduction electrons have energies of a few electron volts, yielding a wavelength of only a few angstroms. Therefore, in order to confine and observe these effects in metals, the fabrication and confinement dimensions have to be at the atomic level. Recently, Crommie *et al.* (*3*) fabricated a "quantum corral" by positioning 48 iron atoms in a circle on an atomically flat copper substrate. Using a scanning tunneling microscope (STM), they picked up and placed the atoms in the desired configuration. Subsequently, they measured the quantum confinement of the surface electrons (using the same STM to map the electronic density of states) within this confining structure.





Scanning electron micrograph images of two devices suspended above a triangular pit in the Si substrate before the connecting wire is broken in the break junction setup. Each device consists of two SiO_2 cantilevers coated with gold and bridged by a small gold wire. (Right) Magnified view of the connecting wire prior to breaking.

Both structures described above are 2D planar structures. It is now possible to make 3D structures to confine electrons. Although these systems have different structures and are made from different materials, they have one thing in common: electron confinement in one or more dimensions. This confinement leads to a standing wave pattern of the electron wave function, or equivalently to a discrete set of electron levels. This restriction is in turn reflected in the conductance, density of states, and optical properties of these quantum systems with striking similarities in the physics that describes these different systems.

The first 3D structures in metals were fabricated using a STM-like configuration. A STM works by holding a metal electrode tip over a surface; when the tip-surface distance is small enough, conduction by means of quantum mechanical tunneling occurs. Gimzewski and Müller (*4*) were among the pioneers who studied the transition from the tunnel regime to a mechanical contact. They recorded the conductance while continuously decreasing the tunnel distance. A discontinuous increase in the conductance was observed, indicating a jump to contact. The metallic contact consists of a single atom bridging the contact, thus creating a "metallic" quantum point contact for the electrons. When this jump occurred, the conductance settled close to $2e^2/h$; that is, the atomic size constriction carried a conductance of one quantum unit. Subsequent measurements using similar systems confirmed this finding (*5*).

Similarly, a broken wire (that is, two opposing electrodes) exhibits the same phenomena, but the tunneling is dominantly between the two closest atoms (because the electrodes are rough on an atomic scale, there is always a pair of atoms that are closest, and the tunneling has an exponential dependence on distance). A device called the "mechanically controllable break (MCB) junction," where two atomically sharp electrodes are moved with atomic precision between each other, allowed for a detailed study of the conducting properties of one-atom contacts. This technique makes use of a piezo (as in a STM) to bend a substrate and to move two, closely mounted metal electrodes with respect to each other. This technique has two unique advantages over a STM: (i) the system is statically stable, so it need not use a feedback system, and (ii) there is a mechanical advantage in the design (such as in a lever), which can increase the obtainable resolution of the driving piezo,

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often by a factor of 100 to 1000.

If we can measure one conductance unit at the jump to contact, we should be able to measure conductance quantization in integer multiples of $2e^2/h$ if we increase the constriction atom by atom. Recent progress has shed some light on this issue. By using the MCB junction to change the constriction size atom by atom, we observe conductance steps every time atoms are forced into the constriction region (5, 6). The measurements indicate that all of the atomic positions inside the constriction region are relevant for determination of the conductance. In semiconductors, the electron wavelength is much too large for the measurements to be sensitive to the individual atomic positions. In metals, the electron wavelength is on the order of the interatomic distance; thus, the atomic configuration is responsible for electron interference effects in the constriction, just as in the quantum coral measurements of Crommie *et al.* (3).

The MCB junction offers another interesting difference: Each time the wire is broken, a new atomic arrangement is, in general, formed; unlike the semiconductor case of a configuration fixed by the lithography, the MCB performs a unique measurement each time. Thus, although a specific atomic configuration may not yield an integer quantization for its conductance, the average over many measurements should. This averaging is exactly what Olesen *et al.* (7) did. They found that integer conductance values are favored over other values in this ensemble of contacts. MCB results on gold and copper contacts (8) confirmed their finding. Other measurements indicate that besides the atomic positions, the metal's electronic character (that is, the extent to which electrons feel the atomic potential) also plays a role in these microscopic contacts (9). Although the measurements showed that an accurate description of atom-sized constrictions is complex and needed, they also showed that confinement of the electrons in the two dimensions perpendicular to the electron current leads to quantization effects very similar to those of 2D electron gases.

Also, in the tunnel regime, when the MCB is broken, impressive results have been obtained. Small tunnel sensors have been fabricated where the electrodes are held stable within a few atomic distances. The way these gadgets work is simple: two electrodes can move to and from each other by means of an electrical steering signal. Because the dependence of the tunnel resistance on the electrode separation is exponential, it is essential that electrodes in a tunnel sensor be placed initially close together, otherwise the tunnel resistance becomes immeasurably high. In one type of sensor, electronics continuously monitor the tunnel resistance and correct the steering signal to maintain a constant tunnel resistance and thus a constant distance between the electrodes under all circumstances. When a force is exerted on one electrode, the steering signal counterbalances it. Thus, the mechanical force is transduced into an electrical signal. These devices can be used in a microphone, accelerometer, infrared detector, or magnetometer (10). Another type of tunnel transducer has been introduced by Zhou *et al.* (11), who showed that by making a very small MCB junction in silicon, no force rebalancing is necessary. The two electrodes are designed so that the separation never exceeds a few angstroms (which can be measured by the tunnel resistance). In contrast with the force-rebalancing device, the actual movement of one electrode over a few angstroms provides the signal. The small size gives the device exceptional stability because of the mechanical advantage; the distance noise between the electrodes was ~0.01 atomic diameters (11).

In addition, these silicon microfabricated sensors can be mixed with other chip electronics, for applications such as sensors, actuator control, and basic physical measurements. The field is only at the beginning of its development, but it offers great potential in a number of industries. As these new technologies continue to develop, Feynman's microworld continues to expand.

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Glacial Climate in the Tropics

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One of the many unresolved puzzles about Earth's climate during the Pleistocene glaciations concerns the tropics. In a report on page 1930 of this issue, Schrag *et al.* (1) describe oxygen isotope results that directly indicate greater cooling in the tropics during glacial cycles than previously believed.

The findings of the now famous CLIMAP (2) program conducted during the 1970s convinced most paleoclimatologists that the ecology of the planktonic foraminifera implied a glacial cooling in the tropics of only 1° ± 1°C. However, over the last several years, evidence based on strontium-calcium ratios in corals (3) suggests that the ocean cooling might have been as much as 5°C. Further, the descent of snow lines on tropical mountains (4) and noble gas temperatures from Brazilian ground waters (5) point to a similar cooling for tropical land masses and islands. Finally, the combination of the lowered snow lines (4) and the large glacial-to-Holocene ^{18}O shift found by Thompson *et al.* (6) in an ice core drilled at an elevation of 6 km in the Andes appears to demand a substantially lower water vapor content for the tropical atmosphere during glacial time.

These new results have caused the pendulum to swing toward a consensus that during times of glaciation, climatic conditions in the tropics were quite different from those today. But, as the evidence in hand is not self-consistent, the pendulum is by no means locked. Still to be explained is why strontium-calcium measurements on corals (3) and noble gas measurements on ground waters (5) suggest a tropical cooling of 4° to 6°C while foraminifera speciation (2), oxygen isotope (7, 8), and alkenone results (9–11) suggest a cooling of no more than 3°C. Does this disagreement reflect regional differences in the extent of cooling, or is one group or the other of these proxies misleading us?

My thoughts on this subject have been strongly influenced by the oxygen isotope results on planktonic foraminifera. The glacial-to-interglacial change for these surface dwellers is equal to or less than that for deep

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