Tunnel Vision

"We think of this little beam of ballistic electrons as a tiny searchlight. It goes down through the metal . . . and we can use it to illuminate the interface structure."

Ballistic electron emission microscopy illuminates the interface between gold and a gallium arsenide substrate. (From the JPL Digital Image Animation Lab's production of "Gallium Arsenide: The Movie".)

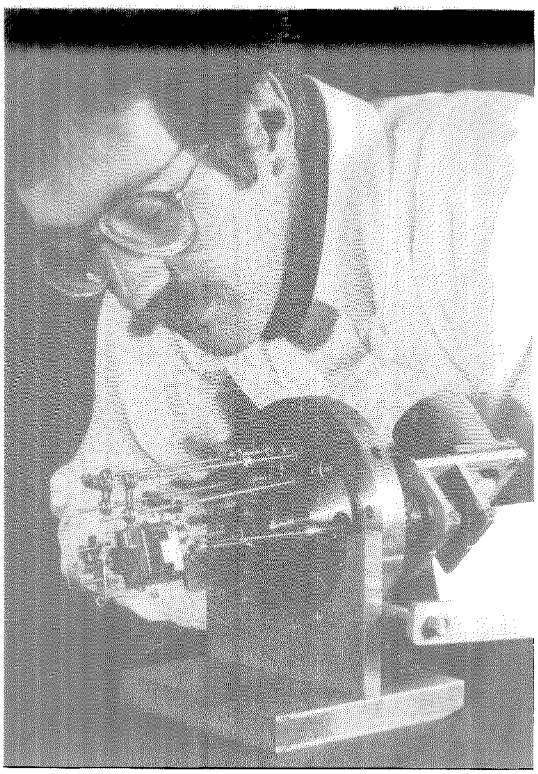
In an article in the February 1960 *E&S*, which has been massively photocopied and recirculated in the intervening decades, the late Richard Feynman prophesied a new field of physics—"manipulating and controlling things on a small scale." He meant a very small scale—angstroms (ten-billionths of a meter). The article, "There's Plenty of Room at the Bottom," described this new field as "not quite the same as the others in that it will not tell us much of fundamental physics (in the sense of, 'What are the strange particles?'), but it is more like solid-state physics in the sense that it might tell us much of great interest about the strange phenomena that occur in complex situations. Furthermore, a point that is most important is that it would have an enormous number of technical applications."

Feynman's predictions did come true; nanotechnology is very big, so to speak, these days, and is indeed finding "an enormous number of technical applications." But nowhere is this dramatic downsizing more pertinent, perhaps, than in space—at least in the things human beings send into space. To exploit these possibilities JPL's Center for Space Microelectronics Technology (CSMT) was established in January 1987, under the directorship of Carl Kukkonen.

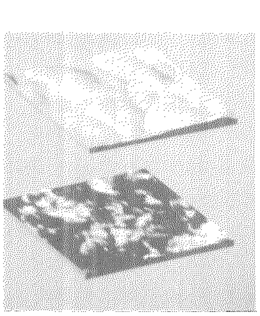
CSMT (pronounced Kismet) is divided into four research areas: photonics, custom microcircuits, computer architecture, and solid-state devices. Photonics (optoelectronics) involves devices that marry laser and integrated-circuit technologies; such devices can generate, detect, modulate, and switch electromagnetic radiation and in space can be used for communication, guidance and control, and robotic vision. The custom microcircuits program develops specialized chips for communication and for image and signal processing; it's also investigating what happens to microcircuits subjected to the ionizing radiation in space. CSMT's efforts in computer architecture include groups working on neural networks (see the article beginning on page 4) and in parallel computing (see page 28).

Research on solid-state devices (such as sensors for the very-far-infrared and submillimeter portions of the electromagnetic spectrum, and other electronics for space) is housed, along with the photonics group, in the Microdevices Laboratory, built just last year. The NASA-funded laboratory contains state-of-the-art equipment for fabricating and characterizing both semiconductors and superconductors. Its laboratories and various categories of clean rooms (located on the vibration-isolated floors necessary for submicron device fabrication) are home to a bevy of advanced instruments and techniques, among them scanning tunneling microscopy.

Scanning tunneling microscopy (STM), which won the 1986 Nobel Prize for its inventors, Gerd Binnig and Heinrich Rohrer, is scarcely a decade old, although the phenomenon was predicted by quantum mechanics and the idea for building such an instrument has been around since the thirties. Its realization had to wait until technology was capable of bringing two surfaces together and holding them at a constant separation of just a few atom diameters. According to



The ballistic electron emission microscope (BEEM), shown here with Bill Kaiser, provides a new view below the surface. Below: The surface of a gold/gallium arsenide structure is revealed by STM (top) and the interface of the two materials by BEEM (bottom).



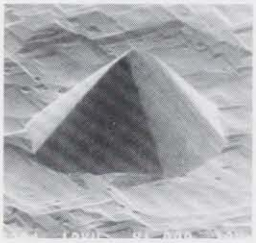
"A major fraction of the world economy depends upon the silicon-silicon dioxide interface."

quantum mechanics, when you do that with two metal electrodes in a vacuum, there is some probability that a few of the electrons that are propagating back and forth at high velocity in the electrodes will leak out into the vacuum; they won't all be trapped inside as classical physics would have it. Of course, they don't leak very far. The electron distribution in the vacuum is a function of distance and it decays to zero very quickly—about a factor of 10 for every angstrom out from the surface. But if you have these little clouds of electrons floating above two surfaces that are, say, 10 angstroms apart (about three atom diameters), some of those electron probabilities will overlap, allowing electrons to "tunnel" through the vacuum and across to the other surface. Although tunneling would normally occur in both directions, applying a voltage difference to one of the electrodes unbalances this symmetry, giving more of the electrons on one side the kick to jump the potential-energy gap between the metal and the vacuum, and prompting a one-way flow. So an electrical current is created, even though classical physics would say the circuit is open.

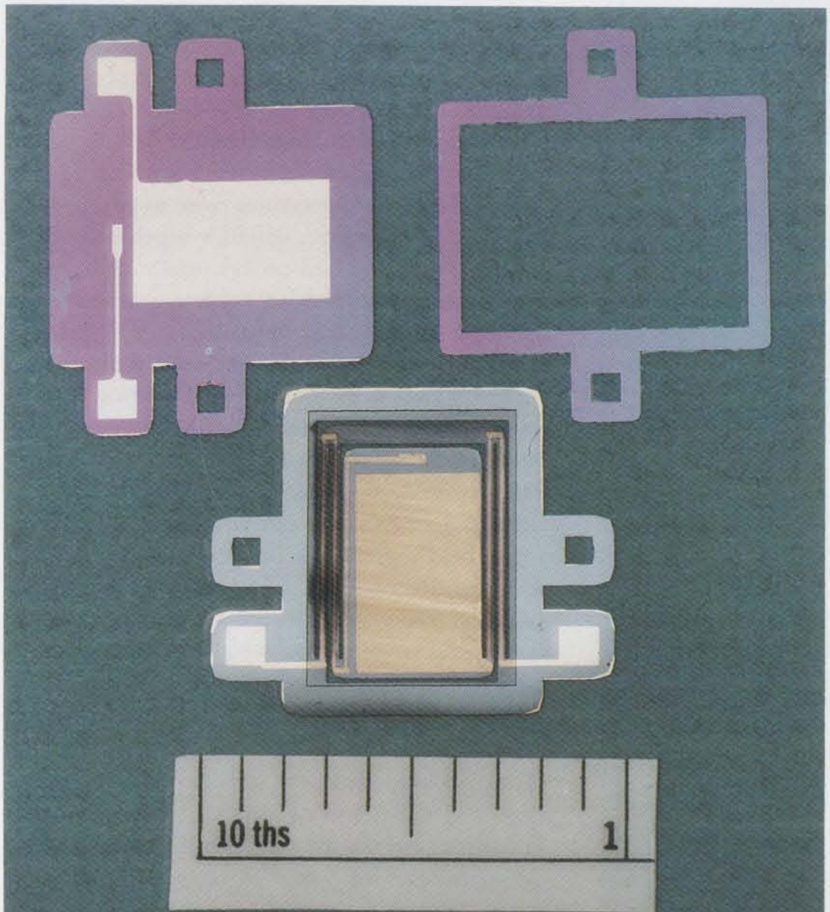
In a scanning tunneling microscope, one of these electrodes is a very sharp metal tip; the other is a conducting surface, say a semiconductor, to be studied. A piezoelectric servomechanism (one that can change its dimensions in response to voltage) uses feedback-controlled tunnel current to keep the tip hovering at a constant altitude of a few angstroms above the sample. Because the tunneling phenomenon decays so quickly, it's extraordinarily sensitive to changes in distance of even a fraction of an angstrom; so measuring the tunneling current while scanning with the tunnel tip can provide an atomic-resolution image. The current flows only through the atom on the very end of the tip, making the STM an extremely sensitive position detector. When the tip scans across the layer of atoms on the sample surface, its trajectory follows the contours of the individual atoms and reveals the electronic structure of the surface.

Bill Kaiser, now a senior research scientist at JPL, did some of the early work in studying surfaces by STM. But even more interesting than surfaces are the inaccessible interfaces below the surface, for example, where a semiconductor and a metal (or two semiconductor materials) meet. "A major fraction of the world economy depends upon the silicon-silicon dioxide interface," says Kaiser.

To get down to this interface, known as the Schottky barrier, Kaiser (along with Doug Bell and Michael Hecht at JPL) invented BEEM—ballistic electron emission microscopy. BEEM gets a little more mileage (angstromage?) out of the tunneling electrons. To accomplish this, Kaiser has made use of an unusual phenomenon that is "almost always neglected in tunneling, but it's always operating." That is, the electrons don't stop when they hit the other electrode surface—some of them scatter, losing energy in collisions, but some of them continue to propagate through the electrode with all the energy they arrived with. They can actually travel a relatively long distance in microscopic terms—up to several hundred angstroms—before petering



The tunnel sensor consists of three tiny (the scale is 1 inch) silicon plates sandwiched together (but shown separately here). The bottom plate incorporates the folded gold springs on either side of the gold pad, and the tunnel tip, barely visible as a black dot on the horizontal arm above the pad (and magnified at left). Any slight vibration will jiggle the spring-supported plate and disturb the current from the tunnel tip to the opposite electrode (upper left). The third plate is a spacer between them.



out. Since the top layer of a semiconductor is 100–200 angstroms thick, the electrons can quite easily make it to the buried interface. A little extra voltage difference injects these electrons "ballistically," giving them enough oomph to shoot straight through to the Schottky barrier and surmount the potential-energy step, similar to the one between electrode and vacuum, that exists between metal and semiconductor. To do this the BEEM device requires a third electrode (where an STM has only two)—a thin metal film deposited on the back of the semiconductor target to collect the electrons that make it through the Schottky barrier. Varying the tunnel voltage controls the energy of the ballistic electrons, which allows detailed spectroscopic analysis of the fundamental interface properties as a function of electron energy.

"We think of this little beam of ballistic electrons as a tiny searchlight," says Kaiser. "It goes down through the metal even though the metal is normally opaque, and we can use it to illuminate the interface structure." What they have seen has also been illuminating, and scientists who have been studying invisible Schottky barriers for 20 years are doing some revising now that they can actually see them. One colleague claimed that BEEM has set the field back ten years, because it revealed that the semiconductor interface was not nearly as simple as had been assumed. Beyond semiconductors, BEEM makes it possible to bring to light the properties of all kinds of buried interfaces that have hitherto been hidden from direct study. BEEM research has grown rapidly and is now being pursued at many laboratories in the United States, Europe, and Japan; the first international BEEM workshop was held at JPL in March with more than 70 participants.

Kaiser, Steven Waltman, and Tom Kenny have also adapted the tunneling phenomenon to a very sensitive motion detector—a tiny silicon sandwich that functions as an accelerometer. The tunnel sensor is accurate to 1 nano-g (10^{-9} g) and can be fabricated as a 50 × 50-micron square on a silicon chip. "Typically a nano-g accelerometer is something the size of several shoe boxes," says Kaiser, "and weighs tens of pounds and has expensive electronics associated with it."

Three parallel plates—micro-machined from single crystals of silicon—form the guts of the tunnel sensor. The bottom plate contains a microscopic gold STM tip and tiny, folded, cantilever springs, also of gold. This plate levitates at the bottom of the sandwich, and when the plates move within tunneling range, current flows

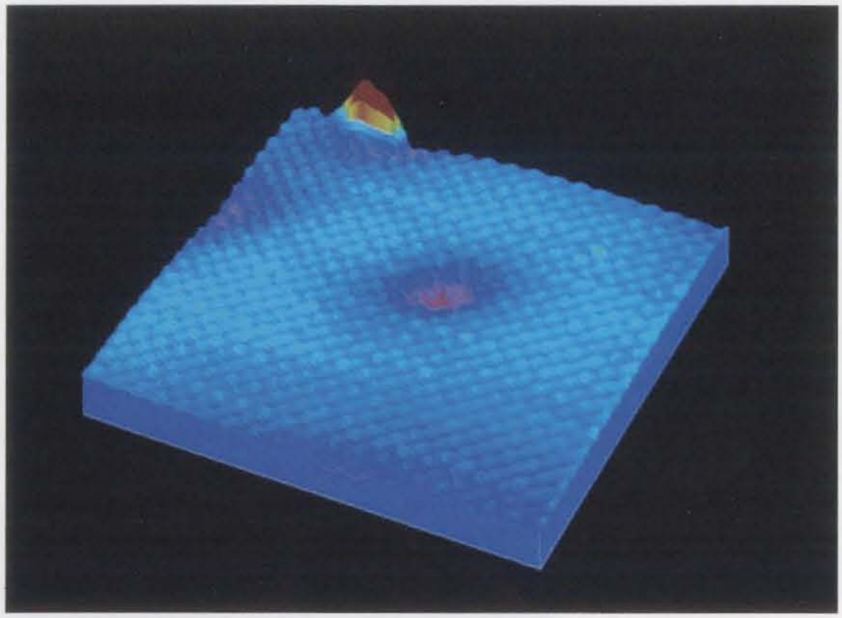
John Baldeschwieler's group made this STM image of DNA (far left), magnified approximately 25 million times, the sharpest image ever obtained of the molecule. It's compared to a computer model of DNA. Below: Baldeschwieler (right) and Mike Youngquist examine an STM instrument designed and built by Youngquist to operate immersed in liquid helium.

from the STM tip to a gold pad on the top plate (the middle plate serves as a spacer). Instead of positioning these plates with a piezoelectric drive (which has thermal drift and noise detrimental to a sensor) as in STM, these plates are brought within tunneling range of each other and held there by an electrostatic field; applying a voltage creates an attractive force that moves them closer together. Any slight vibration, say a seismic wave, will cause the spring-supported plate to wobble, changing the tunnel current. Inexpensive and easy to manufacture with current lithography techniques, the tunnel sensor could be used for miniature seismometers, pressure sensors, microphones, and a variety of applications in space and on the ground. The JPL group is also investigating using it as the transducer in a pneumatic infrared detector.

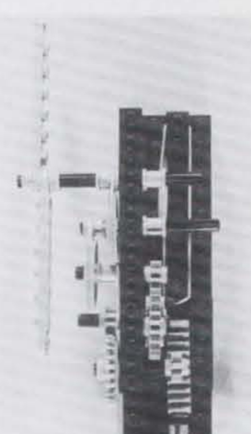
Kaiser's innovative adaptations of STM technology has also kindled a campus collaboration with Professor of Chemistry John Baldeschwieler, who is interested in using the technique to look at molecular structure. "We couldn't have done it without Kaiser, because the support from his group in terms of designing this kind of instrumentation was crucial. It would have taken us years to learn," says Baldeschwieler.

What Baldeschwieler needed was an STM that worked in temperatures close to absolute zero, and Rick LeDuc, of JPL's superconductivity group, and Kaiser had providentially built just such a device for studying superconductors. It operated perfectly well immersed in a dewar of liquid helium. Baldeschwieler needed low temperatures (which give tunneling electrons a narrower energy distribution) for an experiment in "inelastic electron tunneling spectroscopy," looking at how electrons interact with molecular vibrations. Molecules can be thought of as atoms held together by little springs that vibrate at certain frequencies. Chemists observe the radiation a sample emits (or absorbs) at those frequencies to determine what molecules are present in a complicated mixture. When an electron collides inelastically with a surface molecule, some of the electron's energy goes into exciting vibrations in the springs. This causes a change in the tunneling current. These changes in current provide the vibrational spectrum of the molecule with a field of view of a single atom. Chemists are interested in molecular surface structures because the reactive sites on catalyst surfaces are often an atomic step or dislocation that changes the reactivity of a molecule that binds to it.

Baldeschwieler and Kaiser are coprincipal investigators on the NSF-funded experiment,



Top right: STM reveals the surface atomic lattice of gallium arsenide. The 125-angstrom-square image, made by grad student Robert Driscoll, resolves the gallium atoms along with an adsorbed electronegative defect (magenta depression in center). The height of the atomic corrugation is 0.03 angstroms.
Below right: Youngquist obtained this large-scale topographic image of graphite, 7,500 angstroms square, on the first test run at room temperature of his low-temperature STM. The vertical scale is exaggerated to enhance surface features. Smaller-scale images (not shown) resolved individual carbon atoms. Youngquist also built a functioning STM out of Lego blocks.



and have collaborated both on the experiment's design and its theory of operation. "This is a project where there's a significant sharing of time, energy, and talent," according to Baldeschwieler. Initially Mike Youngquist, a grad student in Baldeschwieler's lab, spent several months up at JPL studying the technology with LeDuc. Youngquist has since built several prototypes of his own (including the functional but facetious Lego-block instrument shown in the photo at left), and the Caltech group has significantly advanced low-temperature STM instrumentation.

They are now testing the instruments by looking at well-known molecules. They have achieved atomic-resolution images of graphite with their system, and plan to look at the stretching of the bonds holding hydrogen atoms to silicon (in a thin layer of silicon hydride on the surface), an experiment that promises a good chance of success. "This is the most straightforward experiment we can design at the moment, and that's because the hydrogen will cover the whole surface; we won't have any trouble finding it. We'll be looking for the appearance of the inelastic tunneling transition, and then we'll verify that this is real by substituting deuterium for hydrogen, so the vibrational frequency should shift. This whole experiment is very difficult. In the beginning it's a challenge to prove that it's even working. If it does work, we'll be able to understand what the sensitivity of the technique really is, and then, of course, optimize it for molecules that are of chemical interest." □ *—JD*