Scanning Microscopes Probe Local Details of the Quantum Hall State

Since the discovery of the integer quantum Hall effect in 1980, many physicists have been intrigued by this special state, in which electrons confined in a two-dimensional world execute tiny orbits about magnetic flux lines. Much as we may want to visualize its microscopic structure, however, most of what we have learned to date about the quantum Hall state is based on measurements of bulk properties such as the Hall conductance. Microscopic measurements of more local properties have eluded us because the electrons that form the quantum Hall state reside at an interface between semiconducting layers that are buried tens of nanometers below the surface. And the quantum Hall behavior shows up only when the sample is cooled to temperatures below a few kelvin and placed in a high magnetic field, on the order of several teslas.

Nevertheless, a number of researchers have been tempted to apply to the quantum Hall state some of the scanning probe microscopy techniques that have been so successful in making detailed microscopic images of surface phenomena. At last month's meeting of the American Physical Society, held in Los Angeles, three groups were expected to present high-resolution (100 nm) color images of various local features of the quantum Hall state. On behalf of a collaboration between MIT and Purdue University, Stuart Tessmer (now at Michigan State University) presented a map of subsurface charge accumulations near a plateau in the Hall conductance, showing mysterious dark filaments swirling around brighter regions.[1]

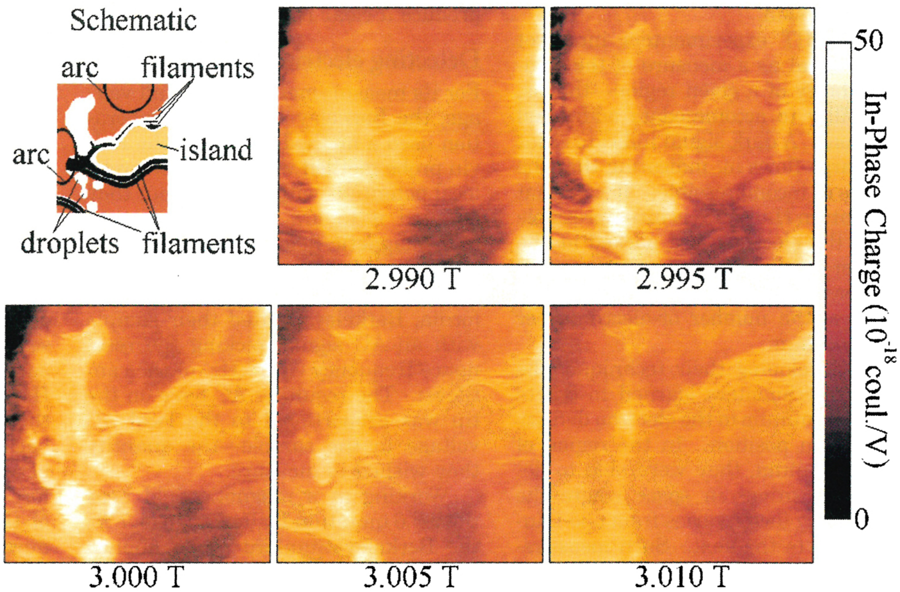
The other images shown at the meeting reflected the variation of the Hall potential across a sample. The data are of interest to theorists, who have studied the possibility that the current might flow preferentially at the edges of a sample when the quantum Hall state has an integer number of electrons for each magnetic flux quantum.[2,3] Two groups have approached the problem in different ways—and with different results—as discussed by Kent McCormick, representing a collaboration between the University of California, Berkeley, Lawrence Berkeley Laboratory and Stanford University, and by Amir Yacoby of the Weizmann Institute, speaking for his colleagues from Bell Labs and from Phase Metrics in San Diego. The California team used a variant of the atomic force microscope (AFM) while the Bell Labs group had built a unique scanning microscope whose tip is a single-electron transistor.[4]

> Researchers are finding ways to peer tens of nanometers below the surface of an insulator to image some properties of two-dimensional electron gases.

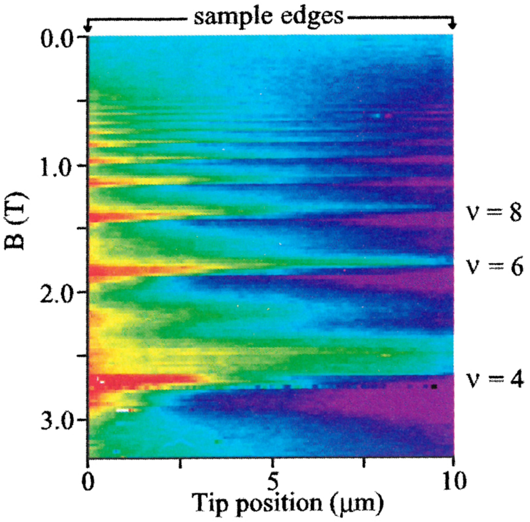
In all the scanning probe techniques, the researchers position a small probe near the surface of a sample to detect some local feature of the two-dimensional electron gas below the surface. (That two-dimensional gas is the system that manifests the quantum Hall behavior.) The researchers then move the probe systematically across the surface to sample other regions of the two-dimensional electron gas.

Detecting charge accumulations

The probe developed by the MIT team was used essentially to measure the ease with which charge flows in and out of a given region of the electron gas (in a sample provided by colleagues at Purdue University). With a conducting tip held 5 nm above the surface, the experimenters excited the subsurface two-dimensional gas with an AC voltage (a few millivolts at 100 kHz), which caused charges to enter or leave the electron gas. The flow of charge into a given region induced a charge in the probe tip positioned above it. The experimenters made AC rather than DC measurements to screen out the effects of all the static charge embedded in the surface and dopant regions above the electron gas.



FILAMENTS, DROPLETS AND ISLANDS are some of the features that researchers have labeled in these images of a quantum Hall state for different magnetic fields just below the value (3.040 tesla) where there is an integer number of electrons for each flux quantum. The colors code the "in-phase charge" (see scale on right), a measure of each region's compressibility. (Adapted from ref. 1.)



THE ELECTRICAL POTENTIAL along a path transverse to the current flow in a quantum Hall system, for a range of magnetic fields. Far away from integer filling factors ν, the potential drops linearly across the sample. At fields just below an integer filling factor, most of the potential drop occurs near the edges of the Hall state, as seen by the high voltage (red) on the left and low voltage (purple) on the right. (Courtesy of Paul McEuen, University of California, Berkeley.)

Ray Ashoori, who heads the MIT team, confessed to us that these images were the hardest measurements he has made. The tip had to be scanned at a fixed distance above an insulator, but there was no feedback to warn when the tip was approaching a mountain on the surface. "It's like flying in the dark," he said.

The MIT experimenters interpret their signal as a measure of the compressibility of a given region—that is, its ability to accommodate additional electrons: A dark signal indicates that no charge flows in, indicating that the region is incompressible. Recall that a quantum Hall state is incompressible when the electrons are packed at the highest possible density—that is, at an integer filling factor ν, where the filling factor is the number of electrons per flux quantum.

In developing their technique, the MIT experimenters learned to create a local minimum in the electron density at a given position. In the region of that minimum, they were able to delineate positions in space where the local filling factor varies from one Landau level to the next. Such measurements showed, asserts Ashoori, that their scanning probe microscope could resolve quantum Hall features.

The MIT experimenters were then ready to study an unperturbed region where the electron density in the two-dimensional electron gas is nearly constant. The images they took showed complex patterns of compressibility, but only when the magnetic field was very close to an integer filling factor, which, in the case of the MIT experiment, was just below 3.04 tesla (see the figure on page 17). Ashoori notes that the patterns they found displayed a striking coherence; they showed filamentary structures and other fine features that extended across regions as large as several microns. Although the observed structures were reproducible at any given field, they were highly dependent on magnetic field: When the field changed by as little as 1%, the new pattern bore little resemblance to the previous one. The data support those theorists who have felt that the quantum Hall state is uniform away from integer filling factors.

The patterns disappeared completely and the sample charged uniformly when the magnetic field was more than about 0.15 T away from a filled Landau level. For a range of fields very close to an exactly filled (incompressible) Landau level, insufficient charge entered the sample to produce a clear image.

Detecting electrical fields

For its measurements of the Hall voltage, the Berkeley–Stanford collaboration used a method similar to the Kelvin probe method widely used to probe local potentials with an AFM, but they adapted it to low temperatures and high magnetic fields. Like the MIT–Purdue group, the researchers, led by Paul McEuen of the University of California, Berkeley, excited their sample with an AC signal, picking the resonance frequency (150 kHz) of the cantilever. The resulting AC force on the tip was proportional to the local AC voltage in the sample—the quantity they wished to measure.

Working at a magnetic field near the $\nu = 6$ quantum Hall plateau (1.7 T), the Berkeley–Stanford group applied an AC voltage drop along the length of their electron gas and measured the transverse voltage across the 10 μm width of the two-dimensional gas. The results are shown in the figure above. The potential drops linearly across the sample at magnetic fields well below the Hall plateau, indicating that the current flow is fairly uniform throughout the gas. As the magnetic field approaches the Hall plateau from below, the voltage drop occurs increasingly at the edges, which therefore carry the majority of the current. At the quantum Hall plateau, the current is carried predominantly in the bulk. Above the plateau, the voltage drop is once again linear. These results are consistent with earlier, electro-optical measurements,[5] but the new data have a spatial resolution between 10 and 100 times better.

Detecting static fields

Unlike the two scanning probe microscopes just described, the instrument developed at Bell Labs measures DC fields. The researchers there have managed to mount onto the end of a fine glass fiber a single-electron transistor—essentially a submicron-sized metallic island connected to metallic leads on both sides by small tunnel junctions. This single-electron transistor microscope represents a marriage between a scanning microscope built at Bell Labs by Harald Hess (who has since moved to Phase Metrics), and a single-electron transistor provided by Ted Fulton, who pioneered the minuscule transistors[6] in the late 1980s. Hess and Fulton told us that the sensitive microscope was extremely delicate and required painstaking and patient development.

The presence of an electical field changes the rate of tunneling into this metal island, so that monitoring the current flow into the single electron transistor is a way to detect small changes in the electrical potential. Thus the device has a charge resolution of 1% of an electron charge with a spatial resolution of 100 nm.

Because it makes DC measurements, this sensor will register all the static charges, including those that reside on the surface and in the dopant layer above the two-dimensional electron gas. Indeed, in their first report of this device,[4] the Bell Labs researchers described the fluctuating surface distributions of these charges. Hess pointed out to us, however, that the experimenters can eliminate this background by taking the difference between two static images, made before and after each such perturbation of the system. Following this procedure allowed them to image individual electron charges that had moved between images. Related low-frequency perturbation schemes can allow various physical properties of the quantum Hall state to be directly imaged.

At the APS meeting, Yacoby, who is now at the Weizmann Institute of Science in Rehovot, Israel, presented the results of their studies of the Hall voltage near the $\nu = 2$ filling factor. Like the Berkeley–Stanford collaboration, Yacoby and his colleagues find that the voltage drop is linear when the magnetic field is far from the $\nu = 2$ state, but there the similarities stop. The Bell Labs data suggest that, as the field passes through the Hall plateau, there is a strong voltage drop near the edges of the channel and almost none in the center. Under certain conditions, the experimenters see other nonuniform Hall voltage distributions that suggest more complex Hall current distributions.

What does the structure mean?

The smallest length scale of interest in measurements of a two-dimensional gas is the distance between electrons (which is considerably larger in these low-density systems than the interatomic distances commonly imaged by scanning probes). Allan MacDonald of Indiana University commented to us that the ideal two-dimensional gas has no structure on this scale. Thus, the spatial variations seen in both the compressibility and Hall voltage measurements reflect the influence of either the disorder potential, caused by impurities in the underlying semiconductor, or the proximity to the edges of the sample. It would be quite intriguing, according to MacDonald, if the patterns seen in the recent experiments, or in future images made with similar techniques, were related to the fractal wavefunctions that occur in some theoretical models of the quantum Hall electrons in random potentials.

The spatial resolution in these scanning probe microscopies can be no finer than the depth of the two-dimensional gas below the surface. To improve on the spatial resolution of images below the surface, researchers from Harvard and the University of California, Santa Barbara are trying to bring the two-dimensional layer closer to the surface, but they note that it's hard to get it closer than 25 nm. This group is using low-temperature scanning probe microscopy to study current flow through subsurface ballistic point contacts.[7]

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Energy Budget of Deep-Focus Earthquakes Suggests They May Be Slip-Sliding Away

The mystery of what initiates earthquakes in Earth's mantle is as deep as ever, but the energetics of these events may help provide answers.

To understand why the Bolivian earthquake of 9 June 1994 has so rapidly become one of the most thoroughly studied seismic events in history, one must know a little about both the event and the significance of when and where it occurred. (See PHYSICS TODAY, October 1994, page 17.) To begin with, the Bolivian quake occurred in the mantle, nearly 640 km beneath the Amazon basin east of the Andes. Such a large "deep-focus" earthquake—and this one, with magnitude 8.3, was the largest such event ever recorded—can make the planet ring like a bell, exciting overtones of Earth's normal modes of oscillation that are sensitive to inhomogeneities in the core and mantle. Add in the fact that the Bolivian quake occurred after the deployment of several global and local networks of high-quality digital seismological stations, and it becomes clear that the quake offered researchers an unprecedented opportunity to illuminate the three-dimensional structure of Earth's mantle and core. (See the box at right.)

However, even as the seismographic record of the quake was illuminating the structure of Earth's interior, it was challenging prevailing ideas of how earthquakes can occur in the mantle. The mechanism of shallow quakes—brittle failure—will not work in the mantle, because high temperatures and pressures render rock more likely to flow than to fracture in response to stress. The mechanism of deep-focus earthquakes has remained mysterious since they were first discovered by the Japanese seismologist Kiyoo Wadati in the 1920s.

Because deep-focus earthquakes occur in regions where a slab of cold oceanic plate is being forced down—subducted—into the hot mantle, current theories seek to explain deep seismicity in terms of the changes undergone by minerals in the slab as it is heated and compressed during its descent into the mantle. (See the box on page 20.) The Bolivian quake posed significant challenges to any candidate mechanism,[1] because it involved a rup-

Terrestrial Tomography

To researchers who use Earth's normal modes of oscillation to map the three-dimensional structure of the planet's interior, the good fortune of having the largest-ever deep-focus earthquake occur just after the deployment of global broadband seismographic networks seemed like a dream come true. It was certainly no dream, though, and computers have been crunching data ever since. Barbara Romanowicz, Xiang-Dong Li and Joseph Durek (University of California, Berkeley) used normal modes excited by recent large deep-focus quakes in Bolivia and elsewhere to characterize the anisotropy of Earth's inner core.[3] Michael Ritzwoller and Joseph Resovsky[4] (University of Colorado at Boulder) and Jeroen Tromp and Xiong He[5] (Harvard University) used data from several recent deep-focus earthquakes to show that normal-mode studies can yield improvements in three-dimensional models of Earth, especially for the planet's mantle.

According to Ritzwoller, this work is just the beginning. "To this point, normal mode data have been well mined only up to a frequency of 3 millihertz. There is probably a factor of six more data at frequencies below 10 mHz that remain to be analyzed." A task of that magnitude ought to keep normal-mode researchers busy until the next really big deep-focus earthquake—and maybe longer.