Imaging Electron Flow

New scanning probe techniques provide fascinating glimpses into the detailed behavior of semiconductor devices in the quantum regime.

Mark A. Topinka, Robert M. Westervelt, and Eric J. Heller

Semiconductor heterostructures have revolutionized solid-state physics and its applications. Most of us use the fruits of this revolution every day in CD and DVD recorders and players, cellular telephones, laser-based telecommunications, satellite television, and much more. The technology, based on atomic layer-by-layer growth using molecular beam epitaxy (MBE), is sophisticated, remarkable, and marketable.

One class of semiconductor heterostructures, the two-dimensional electron gas (2DEG), has been a focal point for theorists and experimentalists and a wellspring of new physics. A 2DEG can be produced at low temperatures at an interface of two distinct layers (a so-called heterojunction) doped nearby with atoms that donate electrons. The electrons at such a junction are confined to the lowest quantum state in the direction normal to the interface; by charging gate electrodes on the top surface of the heterostructure some distance away to repel them, the electrons can be further confined in the other directions to make dots, wires, resonators, and other shapes. That technology has led to celebrated discoveries including the integer and fractional quantum Hall effect (QHE),\(^1\) the Coulomb blockade and single-electron transistors, and conductance quantization in quantum point contacts (QPCs).\(^2\) The potential for exploiting these and many other quantum effects is spawning new fields of single-electronics\(^3\) and spintronics\(^4\)—new approaches to logic that use single electron charges and spins to represent bits of data and the new area of quantum information processing, based on the coherent interaction of quantum mechanical qubits.\(^5\)

Despite all the beautiful experiments already performed on 2DEGs and all that is riding on the new science and phenomena made possible by them, researchers have been blind until recently as to how electrons actually move through them. Most of the knowledge of electron flow in 2DEGs is indirect, based on electron-transport measurements of macroscopically averaged quantities. To be sure, many of the statistical properties are known, such as the electron mean free path. But macroscopically averaged parameters do not reveal the details of the fascinating behavior to be found on the nanoscale. For that, imaging is needed.

Imaging a system is essential to understanding its fundamental properties and developing new electronic and magnetic devices. Imagine the difficulty of designing and fabricating an integrated circuit from a silicon crystal without the use of an optical or electron microscope. As device sizes continue to decrease, quantum behavior becomes important and offers new research and application opportunities. To understand the fundamental behavior of electrons in this quantum regime and to make functioning devices based on this behavior, one must develop ways to visualize the flow of electron charges and spins through semiconductors. The invention of the scanning tunneling microscope (STM) allowed researchers to directly view the pattern of atoms on a material’s surface. Additional methods are needed to image the flow of electrons beneath the surface.

Obtaining images of 2DEGs inside semiconductors is no easy matter, because the electrons are buried beneath the surface and because the samples must be cooled to low temperatures to show quantum behavior. Nonetheless, a number of groups have recently developed liquid-helium–cooled scanning probe microscopes (SPM) for this purpose.

Making a two-dimensional electron gas

Figure 1 illustrates how a 2DEG can be created inside a gallium arsenide–aluminum gallium arsenide heterostructure. During growth by MBE, atomic layers are added to the heterostructure at a rate of about one layer per second. Conduction-band profiles can be engineered from GaAs to AlGaAs. Switching abruptly from GaAs to AlGaAs creates a very clean, sharp barrier that keeps electrons inside the GaAs layer. Silicon atoms in the AlGaAs layer act as donors; the electrons ionized from the Si fall over the barrier and are trapped at the GaAs–AlGaAs interface, where they can move freely for long distances. At low temperatures, movement in the z-direction (normal to the interface) is frozen out, but the electrons, trapped in a 2D “flatland” sheet, are free to move and interact in the x- and y-directions.

Two-dimensional electron gases possess a unique combination of parameters that together make an ideal laboratory in which to explore the fascinating and often surprising behavior of such systems. The electron’s de Broglie wavelength at the Fermi energy is unusually long, typically 20–100 nm, and it can be an appreciable fraction of the size of a typical device. (Electron wavelengths in metals, by comparison, are typically well under 1 nm.) The Fermi wavelength can be tuned by changing the electron density with a planar gate electrode located beneath the 2DEG. Because they do not collide often with other particles, the

Mark Topinka, now an Urbanek Postdoctoral Fellow in the applied physics department at Stanford University, received his PhD from Harvard University under Bob Westervelt, Mallinckrodt Professor of Applied Physics and of Physics. Rick Heller is a professor of chemistry and physics at Harvard.
The QHE profoundly changes the way electrons move through a 2DEG. In a strong magnetic field applied perpendicular to the 2DEG, the electrons no longer travel as free plane waves but instead occupy a series of discrete Landau levels separated in energy by $\hbar \omega_c$, the energy associated with the cyclotron frequency $\omega_c$ ($\hbar$ is Planck’s constant). Both the number of states in each Landau level and the spacing between the levels scale with the applied field. Motion along the field lines cannot occur, because the electron gas is two-dimensional. At a magnetic field for which the quantum states in the highest occupied Landau level are half filled, the familiar classical Hall resistance and nonzero longitudinal resistance are observed. Quantum Hall plateaus occur at magnetic fields for which the highest occupied Landau level is almost completely filled. The number of filled Landau levels is called the filling factor $\nu$.

On a quantum Hall plateau, electrons in the middle of the sample form an incompressible liquid (see PHYSICS TODAY, August 2003, page 38). The longitudinal resistance of the sample goes to zero, and the transverse Hall resistance is quantized on plateaus of height $\nu \hbar/e^2$ with integer values of the filling factor $\nu$, where $e$ is the electron charge. All of the current through the sample is carried by edge states that pass around its circumference. These edge states correspond to classical skipping orbits that repeatedly hit the edge as the electron tries to move in a circle in the magnetic field. The fractional QHE, which produces plateaus in the Hall resistance at values $(1/\nu) \hbar/e^2$ for certain fractional numbers, such as $1/3$, is also associated with edge states, but its source is the correlated motion of electrons in the 2DEG.

The QHE is associated with remarkable spatial structures in the 2DEG. The structures include predicted spatially striped phases of the quantum Hall liquid that have been investigated using macroscopic measurements. Imaging the properties of a 2DEG in a strong magnetic field at low temperatures is a particularly useful way to understand the QHE, and a number of groups have developed cooled scanning probe microscopes for this purpose.

Raymond Ashoori’s group at MIT has developed a way to image electron flow in the quantum Hall regime using a subsurface charge accumulation (SCA) probe. An STM tip held above the surface capacitively couples to the 2DEG immediately below. When a small AC voltage is applied between the tip and the 2DEG, the resulting flow of charge in the gas induces an oscillating image charge on the tip; that oscillation is detected by a sensitive electrometer. Adding a positive DC voltage to the tip allows spatial profiling of the 2DEG by creating a small bubble composed of a few electron charges beneath the tip. The bubble is surrounded by an insulating ring of incompressible fluid in the quantum Hall regime, and it forms an electrically isolated quantum dot that holds a fixed, discrete number of electron charges.

Figure 2 is an image of the SCA signal obtained as the bubble is moved through the 2DEG by scanning the STM tip above the surface. As the number of electrons in the bubble changes, the signal intensity oscillates, which results in bright strips that form a contour map of the random electrostatic potential inside the quantum Hall liquid.
This image directly demonstrates how, thanks to the 2DEG's incompressibility, the QHE can block the flow of electrons inside the electron gas.

Amir Yacoby (now at the Weizmann Institute of Science) and his colleagues at Lucent Technologies' Bell Labs developed an alternate way to image the charge of an electron gas. They successfully fabricated a single-electron transistor (SET) on the tip of a glass fiber and used it as a scanning electrometer probe. The SET was sensitive enough to detect changes in the 2DEG potential and density variations corresponding to tiny fractions of a single electron. With their probe, they imaged edge states that pass around the circumference of the electron gas in the quantum Hall regime (see figure 3a). The image was produced by measuring the charge induced on the SET electrometer when a voltage was applied to a gate electrode beneath the 2DEG. The incompressible strips of electron gas next to the edge states allowed the electric field to pass through the 2DEG to reach the SET; the result was the bright strips in figure 3a. The SET tip was also used to image the Hall potential, as shown in figure 3b for a magnetic field near the \( \nu = 2 \) plateau. The Hall potential appears at the edges of the 2DEG, but no longitudinal potential is seen. These results show how edge states occur in the quantum Hall regime and directly confirm earlier theoretical predictions. The scanning electrometer tip was also used at Bell Labs to image, in a manner similar to the Ashoori group, localized 2DEG electron states in the quantum Hall regime.

The quantum Hall regime imaging by the MIT and Bell Labs teams—as well as by Paul McEuen at the University of California, Berkeley and Cornell University, by Jürgen Weis and Klaus von Klitzing at the Max Planck Institute for Solid State Research in Stuttgart, Germany, and by Klaus Ensslin at ETH Zürich—represents groundbreaking achievements that have enriched theories of the QHE and revealed intriguing new effects.

**Imaging electron flow in low magnetic fields**

Although many insights have come from imaging the quantum Hall regime, the majority of semiconductor devices operate without an applied magnetic field, making it important to image in that regime, too. Recent imaging by our group at Harvard University, by McEuen, by Charles Smith and David Ritchie at the University of Cambridge, and by Ensslin has focused on electron flow patterns in a 2DEG with no applied magnetic field or with small magnetic fields. Mark Eriksson, working with two of us (Topinka and Westervelt), led the charge in 1996 by directly imaging the mean free path in a 2DEG for electrons passing through a wide constriction. Four years later, Rolf Crook and colleagues at Cambridge imaged cyclotron orbits in a 2DEG at 4.2 K and interpreted features of their images in terms of the deflections in electron trajectories caused by donor atom density fluctuations and impurities. Using a charged atomic-force microscope tip...
to bend the trajectories of electrons traveling between two QPCs, they achieved glimpses into the spatial details of electron flow in 2DEG nanostructures. Those early experiments set the scene for more recent high-resolution images that revealed surprising and important details about electron flow in 2DEGs.

At Harvard, we used scanning probe microscopy to image the coherent flow of electron waves through a 2DEG with no applied magnetic field.\(^{15,16}\) We focused on the pattern of electron flow through one of the most fundamental and widely used nanostructures: a QPC,\(^ {17}\) a narrow constriction whose width is comparable to the electrons' Fermi wavelength \(\lambda_F\) (see PHYSICS TODAY, July 1996, page 22). As its width is increased, the conductance of a QPC increases in steps of height \(2e^2/h\) because the electrons travel through individual transverse modes, each of which contributes \(2e^2/h\) to the total conductance.

Figure 4a illustrates our technique for imaging the flow of electron waves in a GaAs–AlGaAs 2DEG. Gates on the surface form a QPC whose width could be adjusted by changing the gate voltage. A charged SPM tip capacitively couples to the electron gas below; for negative tip-to-gas voltages, it can deplete a small, round divot in the 2DEG that scatters incoming electron waves, as shown in the simulations (blue). The change in conductance induced by the tip is proportional to the flux of electrons hitting the divot under the tip. As the tip is scanned over the sample, the QPC conductance images the electron flow through individual transverse modes, each of which contributes \(2e^2/h\) to the total conductance.

Figure 5. Electron flow through a two-dimensional electron gas from a quantum point contact on the first conductance step. The image shows surprisingly narrow branches that are produced by small-angle scattering from charged donor atoms in the donor layer, as shown in figure 1. The interference fringes, demonstrating quantum mechanical coherence, extend throughout the image. The arrow points to a cusp produced by the focusing effect of a nearby impurity atom. (Adapted from ref. 16.)
electron flux that was there before the tip was present.

With this technique, we could image the patterns of electron flow through the individual transverse modes of the QPC that are responsible for the conductance steps shown in figure 4b. Figures 4c–e compare experimental images of the flow of electron waves through the first three modes of the QPC (outside), with theoretical simulations (inside). The spatial character of the modes is clearly visible: Electron flow through the first mode shows one angular lobe; flow through the second mode shows a V-shaped pattern with two angular lobes and a zero down the center; and flow through the third mode shows three angular lobes with two zeros. In addition, the experimental images show interference fringes, spaced by $\lambda_F/2$ (about 20 nm), that demonstrate that the flow of electron waves is quantum mechanically coherent over the imaged distances.

The spatial resolution of the images in figure 4 is excellent, considering the much larger size—about 100 nm across—of the divot of depleted electron gas. How can such great resolution occur? The tip must backscatter electrons arriving from the QPC in order to change the conductance and produce a signal. Imagine you are standing in a large room with black walls, holding a flashlight against one side of your head with its beam pointed forward. To sense the pattern of flow of light from the flashlight, a friend holds a silver ball in the light beam. Only a small glint of backscattered light, much smaller than the ball itself, will be visible to you. Similarly, the spatial resolution in images of electron flow is determined by the size of the glint, which is much smaller than the reflecting divot under the tip.

At greater distances from the QPC, we discovered that the electron flow formed remarkably narrow branches, as shown in figure 5 for the first QPC conductance step. From the experimental images and simulations close to the QPC shown in figure 4c, one might expect to see a single broad angular lobe of flow in figure 5 for the first mode of the QPC. Instead, the electron flow forms narrow branches within distances from the QPC of much less than the electron mean free path, which is 11 μm for this sample. The branches in images of electron flow are reproducible as long as the sample is kept at liquid-He temperatures. Fringes spaced by $\lambda_F/2$ are observed over the entire image; their presence again underscores the coherent wavelike nature of electron transport in 2DEGs over large distances at low temperatures.

The formation of branches is a generic feature of electron flow in a 2DEG and is associated with small-angle scattering of electrons by the random potential induced by ionized donor atoms in the donor layer (see figure 1). In macroscopic measurements of the conductance, the electron diffusion constant in 2DEGs at low temperatures is determined by small-angle scattering. As shown in figure 1, the scattered electrons travel along smoothly curved paths rather than straight lines. Because the positions of the ionized donors remain fixed at low temperatures during the time required to record an image, these curved paths can be visualized. Thus one can image spatial structures, like the branches in figure 5, that would not be visible in an ensemble average over many samples.
Ray-tracing simulations of the classical trajectories for electrons in an accurate depiction of the potential landscape in the 2DEG gives results like figure 6c, which shows a branching structure similar to the experiments. Branches in the 2DEG give results like figure 6c, which shows a branching structure similar to the experiments. Branches are also clearly seen in this month’s cover image, which shows the simulated paths of 50,000 electron trajectories.

Closer inspection of the ray-tracing simulations reveals a lensing effect that, in hindsight, might have been expected. The hills and dales in the effective potential through which the electrons in the 2DEG pass deflect the electrons this way and that, occasionally inducing V-shaped cusps in the flow that correspond to folds in the position and momentum phase space for electrons. The simulation in figure 6a shows an example of a cusp produced by a single ionized donor atom. For scattering by many ionized donor atoms, cusps form at different locations, as shown in the simulation in figure 6b. V-shaped cusps also appear in the experimental data; the arrow in figure 5 highlights an example. Once formed, cusps give rise to accumulations of trajectories that are hard to disperse, and those accumulations that are “lucky” (depending on the stability of subsequent motion) carry quite a bit of the flux and wind up looking like branches. This microscopic branching structure is perfectly consistent with the macroscopically measured mean free path and an exponential decay of momentum correlation in the diffusion of electron waves.

An imaging revolution

New ways to form and image quantum structures are developing rapidly. For example, Smith and Ritchie recently used an SPM tip to produce quantum structures in a 2DEG with erasable electrostatic lithography. In that technique, an SPM tip is used to deposit charge on the surface of a high-κ dielectric at low temperatures. Negative charge tends to deplete the underlying 2DEG and oppose the flow of electrons, and thus it creates the walls for a quantum structure. Figure 7 shows the location of the deposited charge defining a QPC; a conductance dip observed when the charged SPM tip is scanned above the QPC confirms the QPC’s location. Erasable lithography provides a new ability to change the geometry of a quantum structure during an experiment.

The success that a number of groups have had in imaging the flow of electrons—the lightest by far of all the easily accessible particles—through a 2DEG involves a subtle change of mindset, away from the ensemble and toward the individual. In condensed matter physics, there is a strong tradition of considering ensemble averages, but now researchers are increasingly confronted with a specific quantum structure, with all its warts and bumps. For example, the branching of electron flow in 2DEGs is entirely consistent with earlier work using macroscopic measurements of conductance. But the newly discovered branches put a face on the real agent of momentum decorrelation and even tell where donor atoms may be located in a particular sample.

References