Metal–Insulator Transition Unexpectedly Appears in a Two-Dimensional Electron System

When the temperature approaches 0 K, can a two-dimensional electron system become a metal? Some recent experiments suggest it can.

For roughly the last two decades, it has generally been believed among those interested in two-dimensional disordered electron systems that, in zero magnetic field, such systems do not undergo a metal–insulator transition at 0 K. In an influential 1979 paper, Elihu Abrahams, Philip Anderson, Donald Licciardello and T. V. Ramakrishnan, who became known as the Gang of Four, had used scaling arguments, assumed there were no electron–electron interactions and found that an electron in a two-dimensional random potential at 0 K would not diffuse. So, if the temperature were lowered toward 0 K, no transition from insulator to metal would occur in a disordered system. Even if the two-dimensional electron systems were conducting at high temperatures, the disorder and the two-dimensionality would be sufficient to localize the electrons, preventing metallic behavior at T=0.

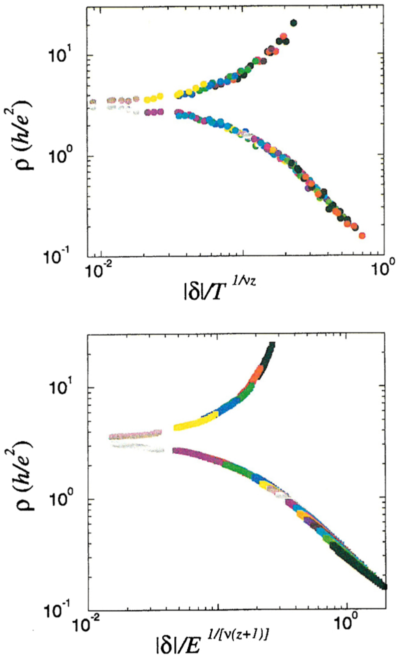
Experiments done in the early 1980s at Bell Laboratories and at the University of Cambridge, with silicon metal oxide semiconductor field-effect transistors (MOSFETs), generally confirmed the Gang of Four's predictions.

However, in 1994, Sergey Kravchenko, George Kravchenko and John Furneaux (all then at the University of Oklahoma), and Vladimir Pudalov and Marie D'Iorio (National Research Council of Canada), studied silicon MOSFETs with much higher electron mobilities than the other experimenters had used, and they reported evidence for a metal–insulator transition at very low electron density.[1] Although that report was met with great skepticism, additional experiments done in the last few months are confirming a metal–insulator transition and causing theorists and experimenters to attempt to elucidate and explain this unexpected behavior.

Scaling theory of localization

Anderson in 1958 had introduced the idea of localization, which occurs in a static disordered system, where electron interactions don't matter. Later, David Thouless and Franz Wegner applied the idea of scaling from the theory of critical phenomena to localization. In their 1979 paper, the Gang of Four, using a scaling approach, considered the conductance of a tiny block of a material. Then they doubled the block size and asked, What's the value of the conductance? If the conductance is only a function of the smaller block's conductance, it's called one-parameter scaling. Says Abrahams, "It's independent of the nature of the material, independent of the exact microscopic quality of the disorder, and so forth. You construct a function that tells you how the conductance changes as you change length scale or temperature. It was a surprise when it turned out that you couldn't have any metallic states at zero temperature in two dimensions. Therefore, ultimately, at sufficiently low temperature in the presence of disorder, if there were no phase transition to superconductivity, all 'metals' would be insulating at zero temperature."

The Gang of Four and shortly thereafter Lev Gorkov, Anatoly Larkin and David Khmelnitskii (then at the Landau Institute), did perturbative calculations based on scattering of electrons from static impurities. They found that in two dimensions there was an enhancement of back scattering, which means that if you send an electron along the x axis, it'll start scattering, and if it scatters backward, that gives rise to resistance. So the total scattering from impurities is enhanced in the backward direction in such a way that you always get insulating behavior in two dimensions at 0 K. Explains Abrahams, "This particular effect was well known in one dimension beforehand. It's much weaker in two dimensions, but the same thing happens. It's an interference effect from electron waves that interfere constructively in the backward direction. In three dimensions, there's more phase space for the charge to escape from the place where you put it, so it does get away."



SCALING BEHAVIOR of temperature (T) and electric field (E) for a two-dimensional silicon MOSFET. Resistivity, ρ, normalized by h/e^2, versus $|\delta|/T^{1/\nu z}$ (top panel) and $|\delta|/E^{1/[\nu(z+1)]}$ (bottom panel) where δ is the difference between electron density and its critical value; z and ν are critical exponents. Different colors represent data for different fixed δ. (Figure courtesy of Dmitri Simonian; adapted from refs. 1 and 2.)

In the 1980s, the late William McMillan (then at the University of Illinois) wrote a paper in which he introduced scaling for both disorder and electron–electron interactions. Boris Al'tshuler, Arkady Aronov (then both at the Leningrad Institute of Nuclear Physics) and Patrick Lee (then at Bell Labs) pointed out that the electron–electron interaction in a disordered medium plays an important role and produces an effect on conductivity that mimics the localization effect. At about the same time, a whole raft of experiments could be explained by combining coherent backscattering scaling theory of localization with the interaction effect of Al'tshuler, Aronov and Lee. They included experiments on silicon MOSFETs by David Bishop, Daniel Tsui and Robert Dynes at Bell Labs and by M. J. Uren, R. A. Davies, Moshe Kaveh and Michael Pepper at the University of Cambridge, and on disordered metallic films by Gerald Dolan and Douglas Osheroff at Bell Labs.

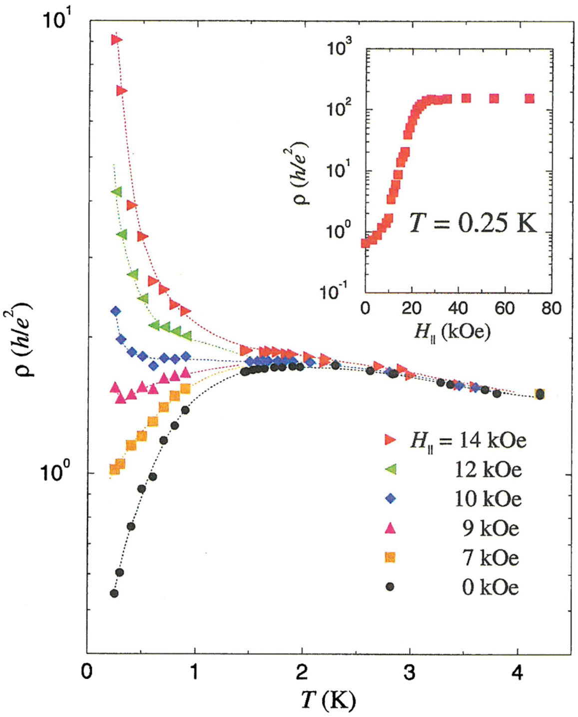
"Many theorists realized that to describe the metal–insulator transition, you needed to incorporate the effects of interactions," recalls Lee. "The most important work was by Alexander Finkel'stein of the Landau Institute in the early 1980s, but the theory was incomplete in that in many cases the interaction parameter scales to strong coupling and one loses control. The problem got so hard that people just abandoned it. In a few cases, such as in high magnetic field, we were pretty confident there should be no metallic states." However, Abrahams notes, "in Finkel'stein's theory, as the length scale increases (or temperature goes to zero), the resistivity decreases. So the metallic phase could be stabilized. However, prior to the recent experiments, no one was paying attention to this possibility."

High-mobility silicon MOSFETs

The silicon MOSFETs studied by the Bell Labs and Cambridge experimenters in the early 1980s had electron mobilities that were typically 2000 to 6500 $cm^2/(V\ s)$. But the silicon MOSFETs used in 1994 by Sergey Kravchenko and his collaborators had mobilities of 35 000, and in one case 75 000 $cm^2/(V\ s)$. The mobility is a rough measure of the amount of disorder and is primarily determined by the number of impurities in the oxide and by the roughness of the silicon and oxide interface. The experimenters' results were quite unexpected and were met with great skepticism. Kravchenko had obtained his samples from an industrial lab in the Soviet Union that subsequently caught fire. And, rumor has it, when the lab was rebuilt, the workers could no longer produce high-mobility samples.

To make a silicon MOSFET, one starts with a layer of very lightly doped silicon, then adds an oxide layer and a gate. A lead is attached to the gate and two other leads to contacts at the interface between the silicon and the oxide. When a potential is applied to the gate, the valence band and the conduction band both bend downward so that a potential well is created at the interface. Some of the electrons from the interior spill into the well, and that layer, 2–3 nanometers thick, serves as a trap for a two-dimensional system of electrons that can't move into the silicon or the oxide; but they can move on the layer between them—in two dimensions.

Kravchenko and his collaborators reported clear signatures of a metal–insulator transition in their high-mobility silicon MOSFETs in zero magnetic field.[1] The experimenters studied resistivity as a function of temperature for various fixed gate voltages (fixed electron density). They fixed electron density at some low value and found that the resistivity tended to infinity as the temperature was decreased. Then they increased the electron density a little bit, fixed it, and mapped the resistivity, and even though it did so more slowly, the resistivity still tended to infinity. So the experimenters obtained a whole family of such curves. Beyond a critical value of electron density, instead of tending to infinity, the resitivity began to go down to a finite or perhaps a zero value (nobody knows for sure). "That indicated," Kravchenko explains, "two regimes—a regime of low electron density, where the sample is an insulator, and a regime of higher electron density, where resistivity tends to a finite value and the sample is a conductor. It turned out that the data can be scaled—one can find a single multiplicative factor for each curve, which, if chosen correctly, makes all the data collapse onto two separate branches—an insulating branch that tended to infinity and a conducting branch that tended to something else. That was a real surprise."



EFFECT OF PARALLEL MAGNETIC FIELD in a two-dimensional silicon MOSFET. Main figure is normalized resistivity, ρ, versus temperature, T, for fields ranging from 0–14 kilo-oersteds. Inset shows a rapid increase of resistivity as field is increased, followed by saturation beyond about 20 kOe. (Figure courtesy of Dmitri Simonian; adapted from ref. 3.)

When Kravchenko moved from Oklahoma to the City College of New York in the fall of 1995, he joined up with Myriam Sarachik and her student, Dmitri Simonian. The earlier experiments were done in a linear regime. But when the electric field is strong, the effective electron temperature becomes different from the lattice temperature. Very general scaling arguments based on gauge invariance suggest that resistivity should also scale with the electric field, and that's what the City College–Oklahoma group showed.[2]

According to Sarachik, "The electric field scaling is easier to measure than the temperature scaling and gives really clean, beautiful results. When people saw the two forms of scaling, one under the other (see the figure on page 19), it convinced many that they might want to take this thing seriously."

Very recently, Simonian, Kravchenko, Sarachik and Pudalov have done similar experiments with an applied magnetic field. Sarachik explains, "Once you put a perpendicular field on, the transport is dominated by orbital effects, which lead to oscillations in the resistivity and the quantum Hall effect at large field values. If the field is instead applied parallel to the plane of the electrons, the coupling is presumably to spins only, and one avoids the additional complications associated with orbital motion." As the team applied a magnetic field parallel to the plane of the electrons, increasing the field caused the resistivity to increase sharply until it reached a constant value (see the figure on this page). The parallel magnetic field produced a dramatic effect on the transition–above about 20 kilo-oersteds the field appeared to entirely eliminate the conduction mechanism for the conducting phase seen in zero magnetic field, the experimenters said.[3]

Says Sarachik, "The field dependence in our new paper looks very much like what happens when you quench a superconductor. However, it may not be superconductivity at all. It could be some other sort of collective phenomenon." Superconductivity has been raised by a number of people—by Philip Phillips and Yi Wan (University of Illinois) and by Dietrich Belitz (University of Oregon) and Theodore Kirkpatrick (University of Maryland). Simonian, Kravchenko, Sarachik and Pudalov note in their preprint that the magnetic field behavior, as well as the critical behavior in zero magnetic field, bears a strong resemblance to behavior near the superconductor–insulator transition in thin metal films reported by Arthur Hebard and Mikko Paalanen (both then at Bell Labs) in 1990, by Ying Liu, Kenneth McGreer, Brant Nease, David Haviland, Gloria Martinez, Woods Halley and Allen Goldman (University of Minnesota) in 1991 and Ali Yazdani and Aharon Kapitulnik (Stanford University) in 1995.

Now Dragana Popović (City College and Florida State University), Alan B. Fowler (IBM Thomas J. Watson Research Center) and Sean Washburn (University of North Carolina at Chapel Hill) have analyzed data they've had for years, using a recent analysis based on scaling near a zero temperature metal–insulator transition done by Vladimir Dobrosavljević (Florida State University), Abrahams (Rutgers University), Eduardo Miranda (Florida State) and Sudip Chakravarty (UCLA).[4] Popović and her collaborators used silicon MOSFETs and applied a substrate bias to vary the mobility of their samples. They found no metallic phase at mobilities in the range covered by the Bell Labs and Cambridge experiments. However, as they increased mobility to 10 000 $cm^2/(V\ s)$, a metallic phase appeared, consistent with the results of Kravchenko and his collaborators.

The reports of a two-dimensional metal–insulator transition have caused a lot of head scratching among theorists and experimenters. As Gordon Thomas (Bell Labs) says, "It changes our view of what two-dimensional systems are like." Although the scaling theory of localization had a great deal of success over the last two decades, it now appears that Coulomb interactions can play a larger role in two-dimensional systems, he says, and "that's exciting. It's interesting to consider classes of materials where you move from dominant effects of disorder to significant effects of Coulomb interactions."

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References

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