The first two-way, 2-D, ultra-high mobility Si (111) transistor

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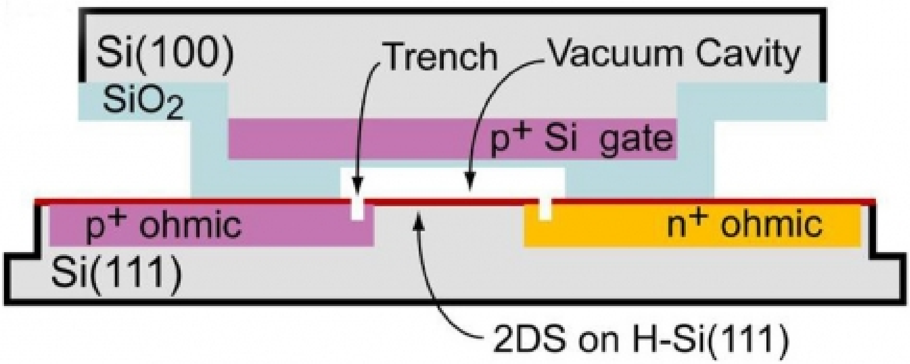

The upper half of the structure (using a different kind of silicon, Si100), constitutes the gate. Beneath the gate (the white region) is a small vacuum cavity. Directly beneath the vacuum region is the slab of silicon (111) material. The very topmost layer is impregnated with hydrogen atoms (H) is the crucial real estate. This layer supports a 2-dimensional electron system (2DES) of charges running between the source and the drain.

The two-dimensional physical properties of semiconductor materials depend keenly on a number of factors, such as material purity, surface orientation, flatness, surface reconstruction, charge carrier polarity, and temperature. JQI scientists have optimized a number of these parameters to produce the first ever ultra-high mobility, two-dimensional Si(111) transistor that allows charge carriers (electrons or holes) to flow through the same conduction channel by merely changing an external gate voltage.

The JQI device was made in the form of a field effect transistor (FET). In this design, ubiquitous among electronic products, currents pass from a semiconductor pad (the source) to another pad (the drain) but only by going through a slender region in between; electric charge will flow only if the electric field applied to that region from an external gate electrode is of the right magnitude.

The JQI device won't be replacing existing transistors in commercial electronic products but it might lead to new possibilities for fundamental research exploring such phenomena as the fractional quantum Hall effect (FQHE), and topological states. Some scientists believe that these fascinating research areas—-involving the existence of exotic, partially-charged, collective motions of electrons in a flat material and the persistence of currents around the edge of the sample—-might become just as important for condensed matter physics as the study of superconductors and superfluids was earlier.

Semiconductor properties

Let's review some of the parameters mentioned above and how the JQI experiment grapple with them:

- Temperature—in general as the material is cooled its conductivity will improve. Electrons flowing through the material will be more mobile since they would be buffeted less by the thermal agitation of the atoms bobbing about some average position. The JQI research takes place in a cold regime around 1 K.

- Purity—Electron mobility is reduced by scattering in a material from impurity atoms. The JQI sample consists of a high-purity form of silicon.
- Flatness—For studying the fractional quantum Hall effect, restricting electron flow to two dimensions is essential. Only then strange quantum effects be manifested. The JQI sample has an atomically flat surface.
- Reconstruction—silicon atoms adopt a diamond-like configuration in three dimensions. A unit cell of atoms (see figure 1) will look very different depending on what kind of planar view you adopt. For the silicon lattice, the Si(111) surface is the only atomically smooth face which can be produced though the process of simple wet chemical etching, with each dangling bond terminated by a hydrogen atom. Compared with the Si/SiO2 interface in a typical MOSFET (a metal-oxide-semiconductor FET), the vacuum/H-Si(111) interface is atomically flat and has many fewer defects. This leads to much higher carrier mobilities. The JQI experiment was designed with this in mind.
- Multi-valley—Electrons (or holes) moving through a crystal can be thought of as waves. A graph of the wave energy versus wave momentum reveals an interesting property. Depending on nature of the crystal, the graph will be a valley-shaped curve, or even a set of valleys nested within each other. In a two- dimensional electron system (2DES) based in Si111, the electrons enjoy a sixfold valley degeneracy—-the word degeneracy here meaning that the electrons have the same energy but as many as six equivalent sets of momentum values. This plentiful degeneracy helps electron mobility (there are more modes of travel through the crystal) and might be exploited in creating multi-valued

qubits in future quantum information devices. The prospective science of utilizing the valley effect is (in analogy to spintronics) called "valleytronics."

- Polarity—In the ambipolar FET, both electrons and holes flow through the same conduction channel. However, electrons and holes are very different charge carriers, with different effect masses, valley degeneracies etc. The JQI setup tried to gather the information about the behavior of both electrons and holes.

Setup and results

The JQI scientists measured the density of electrons and holes in the 2DS region, their mobility, and the conductivity of the device (related to the mobility) for various values of temperature and gate voltage.

When the gate voltage is positive, the researchers observe a 2D electron system (2DES). When the voltage is negative, the Si(111) plane supports a 2D hole system (2DHS). This is the first time ambipolar behavior has been studied in a 2D system with very different valley degeneracy.

The JQI scientists are publishing their results in the journal *Physical Review Letters*. The first author on the paper, experimenter Binhui Hu, sees the achievement this was: "The great advantage of such an ambipolar device is that the 2DES and the 2DHS feel precisely the same bare disorder, and therefore a direct comparison between the conductivity data between electrons and holes in the same device should give us considerable insight into the essentially metallic behavior of the Si (111). The ability to switch between electrons and holes in the same device would be of interest for studies of scattering, interaction effects and spin related phenomena, since these two types of charge carriers have very different effective masses, energy band structures, and spin properties."

The JQI 2D sample is remarkable in another way. As the temperature is cooled from 4 K to an even colder 0.3 K, the electron conductivity improves by a factor of 8. For holes the improvement is a factor of 2. (The difference here is that the valley degeneracy of electrons is 6, while the valley degeneracy of holes is 1, so the temperature dependence of the effective screening of the disorder is much stronger for electrons.) This large increase is "by far the largest temperature-induced fractional change in the metallic conductivity ever reported in any non-superconducting system in such a small temperature window," said Hu.

Theory

The high charge mobility of the JQI transistor and its ambipolar versatility will make it a useful platform for studying fundamental condensed matter phenomena, such as the existence of two-dimensional (2D) metals and the fractional quantum Hall effect. Also high mobility means that electronic transactions can proceed faster, an important consideration for future quantum computers, where the lifetime of qubits—-the units of information in a quantum environment—-can be fleeting.

One of those who provided theoretical input into this work was JQI scientist and University of Maryland physics professor Sankar das Sarma. In a 2008 paper (journals.aps.org/prb/abstract/ … 3/PhysRevB.77.235437) das Sarma showed that at low enough temperatures phonons—-the particle equivalent of thermal agitation—-are no longer much of a factor in the scattering of electrons in a semiconductor. "The only thing that matters at low temperature is scattering from impurities," says das Sarma, "which can be reduced by improving sample quality, that is, by getting purer samples through better material science. This is what Binhui Hu and Bruce Kane (leader of the JQI experimental part of the work) have done in this Si (111) effort."

Although das Sarma figures the mobility in the sample is not yet good enough for studying FQHE, he is optimistic: "This work shows that silicon is a candidate for performing FQHE research. Only Kane's lab can fabricate these high-mobility Si samples, with mobilities a factor of 20 higher than for other silicon materials at low temperatures."

More information: (2008) "Limit to two-dimensional mobility in modulation-doped GaAs quantum structures: How to achieve a mobility of 100 million." journals.aps.org/prb/abstract/ … 3/PhysRevB.77.235437

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