Study explains unexpected conductivity of nanoscale silicon

February 8 2006

With her face reflected in a small glass port, physics graduate student Pengpeng Zhang peers into a scanning tunneling microscope that uses electrical current to measure atomic-sized features on the surface of nanoscale silicon membranes. Zhang is a research assistant working in the lab of materials science and engineering professor Max Lagally. She is part of the team that demonstrated how nanoscale silicone surfaces can conduct electricity — a surprising finding that will have implications for nanotechnology development. Photo by: Jeff Miller

When graduate student Pengpeng Zhang successfully imaged a piece of silicon just 10 nanometers-or a millionth of a centimeter-in thickness, she and her University of Wisconsin-Madison co-researchers were puzzled. According to established thinking, the feat should be impossible because her microscopy method required samples that conduct electricity.

"After she did it, we realized, 'Hey, this silicon layer is really thin-it's much thinner than what people normally use,'" says UW-Madison physicist Mark Eriksson. "In fact, it's thin enough that it should be very hard to run a current through it. So we began asking, 'Why is this working?'"

A team led by College of Engineering professors Paul Evans, Irena Knezevic and Max Lagally and physics professor Eriksson has now answered that question. Writing in the Feb. 9 issue of the journal Nature, they have shown that when the surface of nanoscale silicon is specially cleaned, the surface itself facilitates current flow in thin layers that ordinarily won't conduct. In fact, conductivity at the nanoscale is completely independent of the added impurities, or dopants, that usually control silicon's electrical properties, the team reports.

"What this tells us is that if you're building nanostructures, the surface is really important," says Evans. "If you make silicon half as thick, you would expect it to conduct half as well. But it turns out that silicon conducts much worse than that if the surface is poorly prepared and much better than that if the surface is well prepared."

The results also mean that the powerful concepts, methods and instruments of silicon electronics honed by scientists and the semiconductor industry over decades - many of which require conductive samples, like the scanning tunneling microscopy method employed by Zhang - can also be used to explore the nanoworld.

"We're working at the crossover between silicon electronics and nanoelectronics," says Evans. "This material is the same size as nanodevices like silicon nanowires and quantum dots. But now we can use the tools from silicon electronics we already have to probe it."

The team studied silicon-on-insulator substrates, in which a half-millimeter-thick silicon wafer is covered by a much thinner layer of insulating silicon oxide. Another silicon layer, in turn, tops the oxide layer. In the UW-Madison investigation, this uppermost layer was a "nanomembrane" just 10 nanometers thick. Silicon nanomembranes could one day become the platform for future high-speed electronics and a host of novel sensor technologies, says Lagally. But like all silicon, they naturally develop another unwanted layer of oxide on top when exposed to air, resulting in an oxide-silicon-oxide structure. And the usual means to drive off the top oxide-by heating the material to more than 1,200 degrees Celsius-causes nanomembranes to ball up.

What Zhang originally developed was a method to remove the top oxide without causing this damage. Under ultra-high vacuum, she slowly deposited several additional silicon or germanium layers, each just one atom thick, at 700 degrees C.

Scanning tunneling microscopy soon revealed that this process somehow allowed the nanomembrane to conduct electricity. To find out why, the team analyzed the resistance-the inverse of conductivity-of silicon layers ranging from to 200 to 15 nanometers in thickness. More importantly, they compared silicon's resistance when sandwiched between two oxide layers-the usual case-and when cleaned of the top oxide and exposed to vacuum through Zhang's method. Knezevic then created a model predicting resistance as a function of layer thickness in both situations.

Knezevic's model indicates that in layers thinner than 100 nanometers, the properties of silicon itself become irrelevant: what matters is the surface. Even in relatively thick layers of 200 nanometers, silicon cleaned of the top oxide was at least 10 times more conductive than silicon sandwiched between oxide layers. And as layer thickness shrunk, this difference eventually grew to six orders of magnitude.

The team has proposed that cleaning promotes conductivity by creating new electronic states on the silicon surface where electrons can reside. States are to electrons what parking spaces are to cars. In silicon sandwiched between oxide layers, every parking space-indeed, the entire space of the lot-is jammed. With no empty spaces to move into, electrons are trapped in position and current can't flow.

When new states open up on the surface due to cleaning, it's as if another level of parking spaces has been added, and a small number of electrons jump to the new spots. What they leave behind in the bulk silicon are holes-empty spaces that other electrons can fill. As electrons move into these holes, additional holes are produced. In this way, the traffic jam breaks up and current begins to flow-all because of the surface.

"It's an interesting interplay," says Eriksson. "You clean the surface so you can image it. But then the surface ends up enabling conductivity in the entire silicon layer."

Source: University of Wisconsin-Madison

Citation: Study explains unexpected conductivity of nanoscale silicon (2006, February 8) retrieved 19 April 2024 from https://phys.org/news/2006-02-unexpected-nanoscale-silicon.html