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Using Imperfections to Build Better Nanowire Networks

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Electronic devices have evolved from a novelty to an integral part of modern life, and with each new generation their dimensions get smaller. But as device interconnects or current leads shrink with them, there comes a point where the current-carrying capabilities of these wires will reach their miniature limit. In light of this hurdle, UT's condensed matter physicists are growing wires at the nanoscale, taking a bottom-up approach and learning more about how physics works at the atomic level. They've recently published two papers on this research, and what they've found is that it's actually the defects in nanowires that play a key role in how they function.

Given their scale, nanowires can be tricky to make (consider that a sheet of paper is about 100,000 nanometers—or nm—thick). Working with Professor Hanno Weitering, Graduate Student Saban Hus set out to grow ultrathin wires made from yttrium and silicon on a silicon-(110) surface. Silicon is the material of choice for microchips, and when it's cut into wafers, each surface has a certain orientation labeled according to the resulting planes; e.g., (100), (111), etc. Hus used (110) as the substrate, or base layer, to grow wires with cross sections as small as 1.5 nm^2.

"On the technologically important (100) surface you have two equivalent growth directions for the nanowires, which are perpendicular to each other," Hus said. "However, on the (110) template, all wires grow in the same direction. So you don't have wires crossing each other. That means that when you want to put electrical contacts on them, you know which direction the current is flowing."

Defects, it turns out, play an important role in creating these nanowires. In a crystalline-structured material like silicon, the surface is far from perfect. There are flat areas, called terraces, but depending on how the atoms line up, there may be neighboring terraces of different heights, with a step in between them. In this study, Hus and Weitering found that the wires showed a clear preference for growing along these edges, especially if the steps are oriented in the preferred growth direction. That tendency could have practical applications, as designing intentional mis-cuts on silicon wafers could mean controlling the spaces between wires.

"Typically when you grow nanowires, you don't know what you're going to get; what direction they'll take," Weitering said. "Saban found the recipe to grow them in one direction; and also how to control separation between the wires."

Growing wires with equal distances between them can help streamline the process of making integrated circuits, Hus explained, because they create a sort of template.

"When you make integrated circuits, you put masks on top of each other," he said. "So you can have a mask which has contacts with a given distance, and you just align the mask and you know that they are all in the same position."

Hus is first author on the paper detailing this work: "Formation of uni-directional ultrathin metallic YSi_2 nanowires on Si(110)," which was featured on the August 12 cover of *Applied Physics Letters*. Silicon-based nanowires are interesting to scientists because they're a close representation of a one-dimensional electrical conductor, a concept of great interest in condensed matter physics as illustrated in another recent paper by UT physicists and colleagues, this one published in *Nano Letters*.

As Weitering explained, a truly one-dimensional system is a line: "It has no width; it has no height. If you talk about a wire that has a thickness and a height; you're already assuming three dimensions."

Moving electrons through a one-dimensional system, he continued, is like putting down a bunch of billiard balls in a row, with each ball representing an electron.

"And now you try to move an electron," he said. "The only way an electron can move is if they move all together. You cannot even define a single electron or single 'quasi-particle.' By definition, it's totally collective: they move all together. And that is what's referred to as a Luttinger Liquid."

Weitering, Postdoc Violeta Iancu (now at the University of Leuven), and colleagues from Oak Ridge National Laboratory and the University of North Carolina tested whether the Luttinger Liquid model would still apply in a system that, although not strictly one dimensional, comes pretty close. They grew nanowires with cross sections down to 1 x $0.5nm^2$ on a silicon surface.

"Those wires are about as one dimensional as you can get," Weitering said. "You'd think they might be the closest representations of the Luttinger Liquid, (which) is a purely theoretical construct. We did detailed electrical measurements on those wires. And we found that we understand how electrons move through the wires, but it's not like a Luttinger Liquid; it's a totally different mechanism."

What they discovered is that, as in the *Nano Letters* paper, electrons moving in reduced dimensions have their own ideas about what they want to do, and that behavior is significantly influenced by imperfections. As Weitering explained, consider that if you're moving in a three-dimensional system, you have options when you encounter a bump in the road, so to speak.

"Let's say if you're on the highway and there is a traffic jam in one lane," he said. "You can pass left or you can pass right; you have another degree of freedom, as we say. If you're up in the sky and you encounter an obstacle, you can pass left, right, above, or below."

If you're moving in a one-dimensional system and you suddenly encounter a roadblock, however, you've more or less reached the end of your journey. So it might follow that an electron moving in a one-dimensional (or nearly so) environment would simply stop if it encountered an obstacle—or defect—and that would put an end to the flow of current.

In their *Nano Letters* research, however, scientists found that defects will indeed tend to trap the electron. However, it can still escape the trap and move along the wire through a mechanism of 'thermally assisted quantum tunneling.' This trapping and tunneling of a particular electron, in turn, influences how the other electrons propagate, especially in a network of wires. This understanding would be necessary for wiring future nano-scale electronics.

"Suppose you have two parallel wires and the current can go through both," Weitering said. "The current can flow unimpeded through one wire and then there is suddenly a defect, so essentially the defect traps the electron. When the electron is trapped, then the electrons in the other wire will start to feel the trapped electron, and that will affect their behavior. In the *Nano Letter*, we first analyzed the role of what a defect does in a single wire, and then we figured out that if we have a high density of wires there starts to be some crosstalk between (them). What causes the crosstalk is actually the defects."

They not only concluded that defects play a key role in the way current behaves in nanowires, they also performed mathematical analysis of the electrical measurement data to determine exactly *how many* defects are in a single wire. Using a scanning tunneling microscope—which provides topological images of a surface at the atomic level—they were able to count defects one by one and found that those numbers were in sync with their mathematical analysis. The results are published in the paper "Polaronic transport and current blockades in epitaxial silicide nanowires and nanowire arrays."

"I think that's a big step forward in the interpretation of how you deal with defects in these one-dimensional systems," Weitering said.

Dealing with defects is crucial because, as he explained, the laws of thermodynamics simply won't allow for defect-free circuits. The options, then, become minimizing the number of defects or maybe learning to tune them to get unique device characteristics.

As Hus said, if scientists and engineers can find a way to control nanowires individually, “you can use one wire as a gate for the second wire, which gives you the ultimate transistor. You can turn it on or off with one or two electrons.”

Exploring the growth of nanowires is one research avenue to circumvent the constraints on developing nanotechnology, where the current generation is at 22 nanometers in terms of the smallest possible feature size.

“The way devices are made right now is through lithographic processing,” Weitering said, “and there are limitations as to how small you can go with conventional lithography methods. They start out with a wafer and then they start etching, and they have some very complicated steps. They’re actually removing material to make features smaller. What people like us are doing is to try to create these devices from the bottom up, using ‘the LEGO method’ instead of top-down and etching things away. We’re trying to build materials using atoms as our LEGO blocks.”

Despite the promise of nanowires as an alternative to conventional device production, there’s still the matter of making the leap from the lab to the commercial sector.

“That’s an enormous challenge, to integrate different devices and then eventually, if you get something working, to compete with this current generation of devices which are just mass produced,” Weitering said, “and also to get quality control anywhere close to what we currently have in silicon manufacturing.”

For scientists like him and Hus, however, the physics behind the work provides an interesting problem to sort out.

“You can pursue an avenue where you try to minimize the number of defects and try to improve the recipes,” he said. “But in the end thermodynamics is pretty tough on you. You’re going to get defects. Those are the odds you have to fight. (But) if we can understand how these defects affect the electrical properties of a device, then maybe one day if we have better control of how to place them, you can use them to your advantage as well.”

Both papers are available online:

- “**Formation of uni-directional ultrathin metallic YSi_2 nanowires on Si(110) (http://dx.doi.org/10.1063/1.4817529)**” (*Applied Physics Letters*)
- “**Polaronic transport and current blockades in epitaxial silicide nanowires and nanowire arrays (http://dx.doi.org/10.1021/nl401574c)**” (*Nano Letters*)