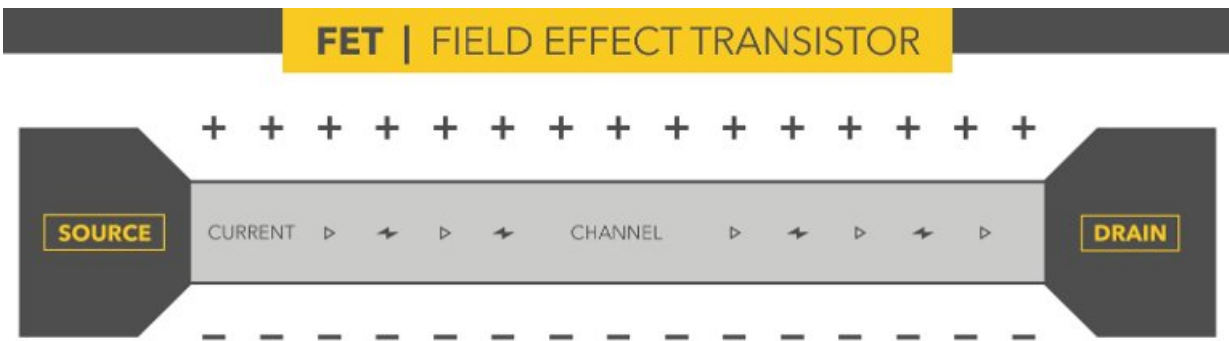


# Probing quantum phenomena in tiny transistors

July 7 2016, by Allison Mills

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A field effect transistor (FET) uses a gate bias to control electrical current in a channel between a source and drain, which produces an electrostatic field around the channel. Credit: Michigan Technological University

Nearly 1,000 times thinner than a human hair, nanowires can only be understood with quantum mechanics. Using quantum models, physicists from Michigan Technological University have figured out what drives the efficiency of a silicon-germanium (Si-Ge) core-shell nanowire transistor.

## Core-Shell Nanowires

The study, published last week in *Nano Letters*, focuses on the quantum

tunneling in a core-shell nanowire structure. Ranjit Pati, a professor of physics at Michigan Tech, led the work along with his graduate students Kamal Dhungana and Meghnath Jaishi.

Core-shell nanowires are like a much smaller version of electrical cable, where the core region of the cable is made up of different material than the shell region. In this case, the core is made from silicon and the shell is made from germanium. Both silicon and germanium are semiconducting materials. Being so thin, these semiconducting core-shell nanowires are considered one-dimensional materials that display unique physical properties.

The arrangements of atoms in these nanowires determine how the electrons traverse through them, Pati explains, adding that a more comprehensive understanding of the physics that drive these nanoscale transistors could lead to increased efficiency in electronic devices.

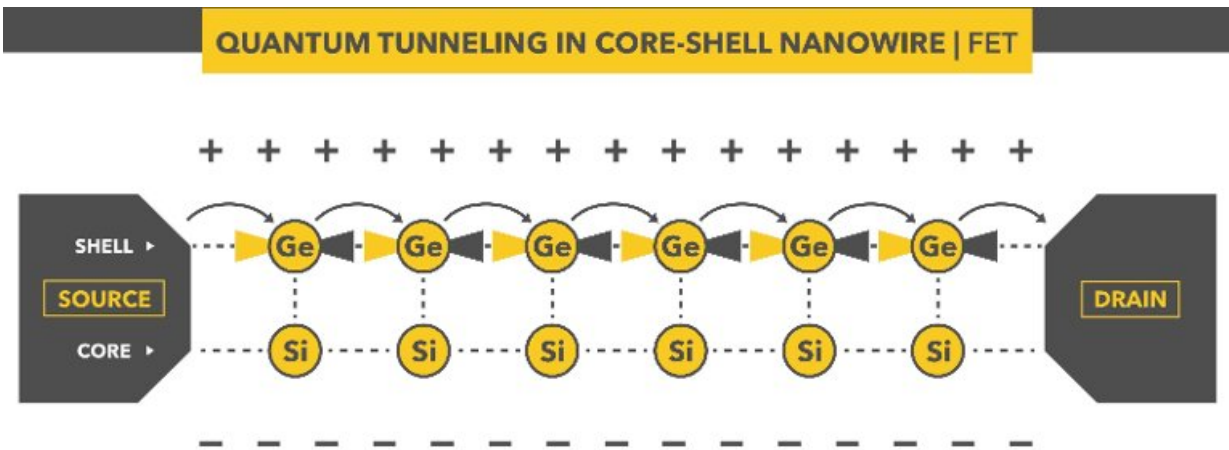
"The performance of a heterogeneous silicon-germanium nanowire transistor is much better than a homogeneous silicon nanowire," Pati says. "In our study, we've unraveled the quantum phenomena responsible for its superior performance."

## **Field Effect Transistors**

Transistors power our digital world. And they used to be large—or at least large enough for people to see. With advances in nanotechnology and materials science, researchers have been able to minimize the size and maximize the numbers of transistors that can be assembled on a microchip.

The particular transistor that Pati has been working on is a field effect transistor (FET) made out of core-shell nanowires. It manipulates the [electrical current](#) in the nanowire channel using a gate bias. Simply put, a

gate bias affects electric current in the channel like a valve controls water flow in a pipe. The gate bias produces an electrostatic field effect that induces a switching behavior in the channel current. Controlling this field can turn the device on or off, much like a light switch.



Quantum tunneling of electrons across germanium atoms in a core-shell nanowire transistor. The close-packed alignment of dumbbell-shaped p<sub>z</sub>-orbitals direct the physics of tunneling. Credit: Michigan Technological University

Several groups have successfully fabricated core-shell nanowire FETs and demonstrated their effectiveness over the transistors currently used in microprocessors. What Pati and his team looked at is the quantum physics driving their superior performance.

## Quantum Tunneling

The electrical current between source and drain in a nanowire FET cannot be understood using classical physics. That's because electrons do

strange things at such a tiny scale.

"Imagine a fish being trapped inside a fish tank; if fish has enough energy, it could jump up over the wall," Pati says. "Now imagine an electron in the tank: if it has enough energy, the electron could jump out—but even if it doesn't have enough energy, the electron can tunnel through the side walls, so there is a finite probability that we would find an electron outside the tank."

This is known as quantum tunneling. For Pati, catching the electron in action inside the nanowire transistors is the key to understanding their superior performance. He and his team used what is called a first-principles quantum transport approach to know what causes the electrons to tunnel efficiently in the core-shell nanowires.

The quantum tunneling of electrons—an atomic-scale game of hopscotch—is what enables the electrons to move through the nanowire materials connecting the source and drain. And the movement gets more specific than that: the electrons almost exclusively hop across the germanium shell but not through the silicon core. They do so through the aligned pz-orbitals of the germanium.

Simply put, these orbitals, which are dumbbell-shaped regions of high probability for finding an electron, are perfect landing pads for tunneling electrons. The specific alignment—color-coded in the diagram above—makes [quantum tunneling](#) even easier. It's like the difference between trying to burrow through a well with steel walls versus sand walls. The close-packed alignment of the pz-orbitals in the germanium shell enable electrons to tunnel from one atom to another, creating a much higher electrical current when switched on. In the case of homogeneous silicon nanowires, there is no close-packed alignment of the pz-orbitals, which explains why they are less effective FETs.

## Nanowires in Electronics

There are many potential uses for nanowire FETs. Pati and his team write in their Nano Letters paper that they "expect that the electronic orbital level understanding gained in this study would prove useful for designing a new generation of core–shell nanowire FETs."

Specifically, having a heterogeneous structure offers additional mobility control and superior performance over the current generation of transistors, in addition to compatibility with the existing silicon technology. The core-shell nanowire FETs could transform our future by making computers more powerful, phones and wearables smarter, cars more interconnected and electrical grids more efficient. The next step is simply taking a small quantum leap.

**More information:** Kamal B. Dhungana et al. Unlocking the Origin of Superior Performance of a Si–Ge Core–Shell Nanowire Quantum Dot Field Effect Transistor, *Nano Letters* (2016). [DOI: 10.1021/acs.nanolett.6b00359](https://doi.org/10.1021/acs.nanolett.6b00359)

Provided by Michigan Technological University

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