Beyond 1 and 0: Engineers boost potential for creating successor to shrinking transistors

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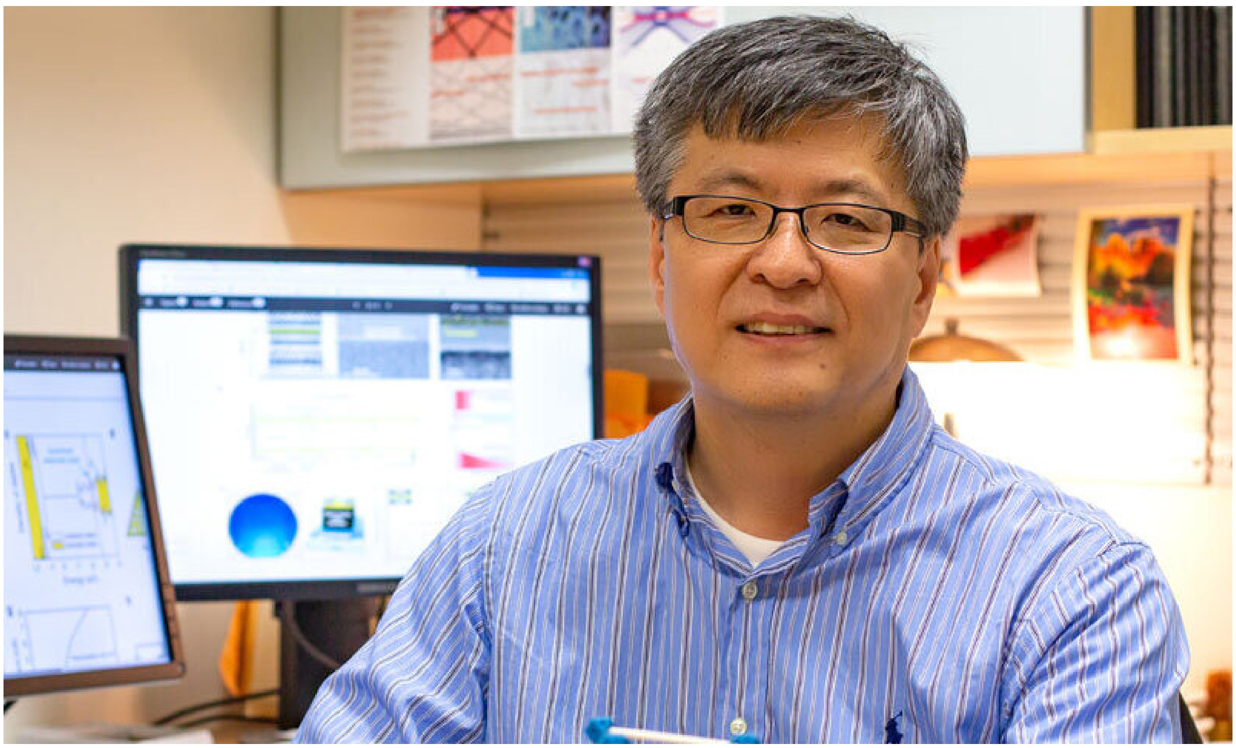


Dr. Kyeongjae Cho, professor of materials science and engineering, and his UT Dallas collaborators developed the fundamental physics of a multi-value logic transistor based on zinc oxide. Credit: University of Texas at Dallas

Computers and similar electronic devices have gotten faster and smaller over the decades as computer-chip makers have learned how to shrink individual transistors, the tiny electrical switches that convey digital information.

Scientists' pursuit of the smallest possible transistor has allowed more of them to be packed onto each chip. But that race to the bottom is almost over: Researchers are fast approaching the physical minimum for transistor size, with recent models down to about 10 nanometers—or just 30 atoms—wide.

"The processing power of electronic devices comes from the hundreds of millions, or billions, of transistors that are interconnected on a single computer chip," said Dr. Kyeongjae Cho, professor of materials science and engineering at The University of Texas at Dallas. "But we are rapidly approaching the lower limits of scale."

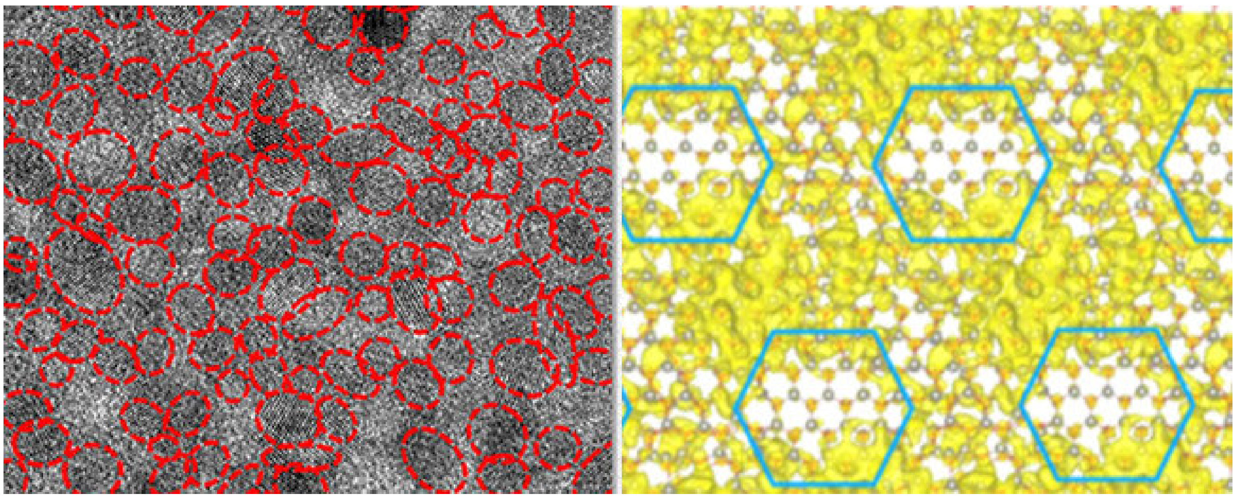
To extend the quest for faster processing speed, the microelectronics industry is looking for alternative technologies. Cho's research, published online April 30 in the journal *Nature Communications*, might offer a solution by expanding the vocabulary of the transistor.

Conventional transistors can convey just two values of information: As a switch, a transistor is either on or off, which translates into the 1s and 0s of binary language.

One way to increase processing capacity without adding more transistors would be to increase how much information each transistor conveys by introducing intermediate states between the on and off states of binary devices. A so-called multi-value logic transistor based on this principle would allow more operations and a larger amount of information to be processed in a single device.

"The concept of multi-value logic transistors is not new, and there have been many attempts to make such devices," Cho said. "We have done it."

Through theory, design and simulations, Cho's group at UT Dallas developed the fundamental physics of a multi-value logic transistor based on zinc oxide. Their collaborators in South Korea successfully fabricated and evaluated the performance of a prototype device.



The image on the left shows two forms of zinc oxide combined to form a composite nanolayer in a new type of transistor: Zinc oxide crystals (inside the red circles) are embedded in amorphous zinc oxide. The image on the right is a computer model of the structure that shows electron density distribution. Credit: University of Texas at Dallas

Cho's device is capable of two electronically stable and reliable intermediate states between 0 and 1, boosting the number of logic values per transistor from two to three or four.

Cho said the new research is significant not only because the technology is compatible with existing computer-chip configurations, but also because it could bridge a gap between today's computers and quantum computers, the potential next landmark in computing power.

While a conventional computer uses the precise values of 1s and 0s to make calculations, the fundamental logic units of a quantum computer are more fluid, with values that can exist as a combination of 1s and 0s at the same time or anywhere in between. Although they have yet to be realized commercially, large-scale quantum computers are theorized to be able to store more information and solve certain problems much faster than current computers.

"A device incorporating multi-level logic would be faster than a conventional computer because it would operate with more than just binary logic units. With quantum units, you have continuous values," Cho said.

"The transistor is a very mature technology, and quantum computers are nowhere close to being commercialized," he continued. "There is a huge gap. So how do we move from one to the other? We need some kind of evolutionary pathway, a bridging technology between binary and infinite degrees of freedom. Our work is still based on existing device technology, so it is not as revolutionary as quantum computing, but it is evolving toward that direction."

The technology Cho and his colleagues developed uses a novel configuration of two forms of zinc oxide combined to form a composite nanolayer, which is then incorporated with layers of other materials in a superlattice.

The researchers discovered they could achieve the physics needed for multi-value logic by embedding zinc oxide crystals, called quantum dots, into amorphous zinc oxide. The atoms comprising an amorphous solid are not as rigidly ordered as they are in crystalline solids.

"By engineering this material, we found that we could create a new electronic structure that enabled this multi-level logic behavior," said

Cho, who has applied for a patent. "Zinc oxide is a well-known material that tends to form both crystalline solids and amorphous solids, so it was an obvious choice to start with, but it may not be the best material. Our next step will look at how universal this behavior is among other materials as we try to optimize the technology.

"Moving forward, I also want to see how we might interface this technology with a quantum device."

More information: Lynn Lee et al, ZnO composite nanolayer with mobility edge quantization for multi-value logic transistors, *Nature Communications* (2019). DOI: 10.1038/s41467-019-09998-x

Provided by University of Texas at Dallas