THE UNIVERSITY OF TEXAS AT AUSTIN
TEXAS ADVANCED COMPUTING CENTER

Tunneling Transistors

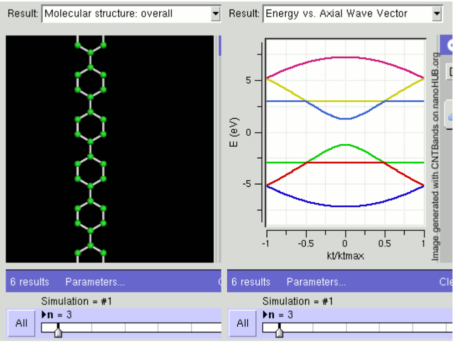
Quantum effects in “III-V” materials allow for faster, lower-energy nanotransistors

Imagine if the rapid technological progress we’ve become accustomed to suddenly leveled off. Many experts believe this could occur if silicon transistors — the basis for nearly all electronics — reach their miniaturization limit, which is believed to be less than a decade away.

This scenario may come as a relief to some — no need to buy the latest gadget. But economically it would be a disaster for the United States. Not only has the semiconductor industry been the U.S.’s biggest export over the last five years, it is widely recognized as a key driver for economic growth globally.

According to the Semiconductor Industry Association, in 2004, from a worldwide base of $213 billion, semiconductors enabled the generation of some $12 trillion in electronic systems business and $5 trillion in services, representing close to 10% of world gross domestic product.

Economic progress like this cannot be slowed without a fight. Consequently, a massive scientific effort is underway to find new materials, new methods, or even new paradigms that can replace silicon transistors in a fast, cost-effective way.



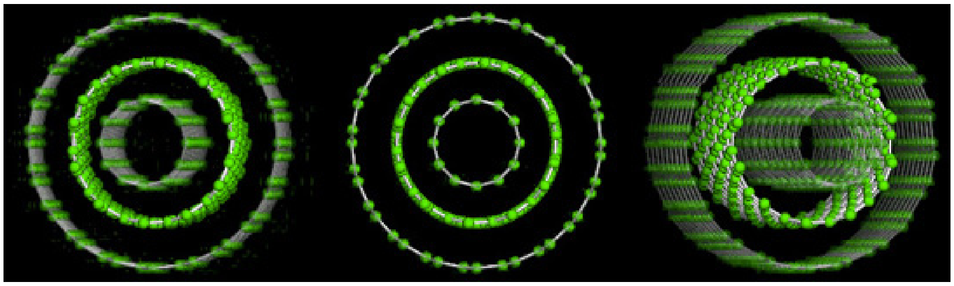
Result: Molecular structure: overall

Result: Energy vs. Axial Wave Vector

Simulation = #1

n = 3

Animations and visualization are generated with various nanoHUB.org tools to enable insight into nanotechnology and nanoscience. Above, a simulations shows a graphene nanoribbon that can be either a zig-zag (left image) or arm-chair (right image) type. Both zig-zag and armchair type GNR are shown with varying widths. Additional animations are also available at http://nanohub.org/resources/8882



Carbon nanotubes have novel properties that make them potentially useful in many nanotechnology applications, including electronics, optics and other fields of materials science. Simulations of new nanoscale materials help advance research and assist industry in the transition from silicon to alternative transistors materials.

This race, inside the R&D centers of multinational corporations like Intel, IBM, GlobalFoundaries, Advanced Micro Devices, Samsung, and others, and also in academia, has led to several promising ideas. Nanotransistors made of graphene and quantum computers [featured in Part 1 and 2 of this series] are leading contender for future devices, but both involve unproven materials and processes.

A promising design being explored at the Midwest Institute for Nanoelectronics Discovery (MIND) are “tunneling” transistors that use “III-V” materials, comprised of elements from the 3rd and 5th columns of the periodic table. These materials consume less energy and can be made smaller than silicon without degrading.

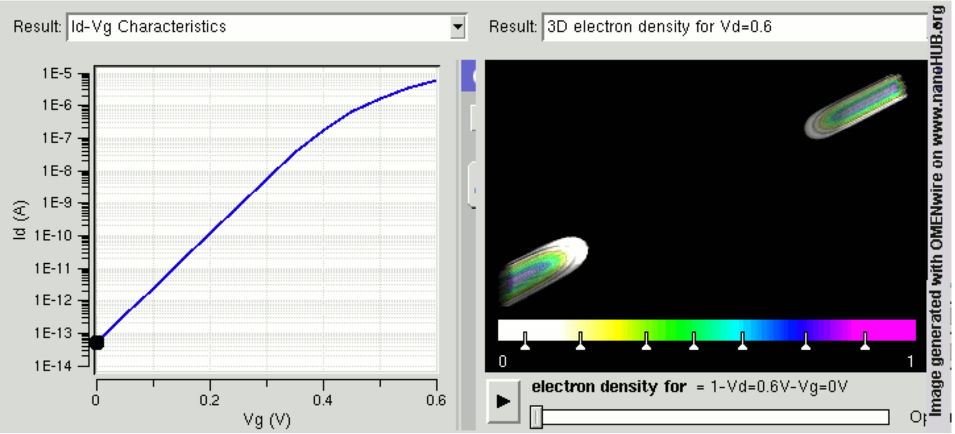
“III-V materials have been studied extensively,” said Gerhard Klimeck, director of the Network for Computational Nanotechnology (which hosts nanohub.org) and a professor of electrical and computer engineering at Purdue University. “But they have not reached Intel or IBM because industry has been able to build transistors with silicon and it’s expensive to completely retool.”

The III-V materials have made inroads in certain niche applications like optical and high-speed communications. However, it has not cracked the CPU market where estimates for building fabrication plants based on new materials or technologies are in the range of several billion dollars. Because of the size of the investment, a great deal of preliminary research needs to be done before any manufacturer will make the leap.

What’s wrong with silicon? you ask. First, silicon chips use unsustainable amounts of power; second, by packing so many transistors on a chip, they can reach temperatures high enough to melt metal; and third, an odd quantum characteristic called tunneling allows electrons, at small length scales, to burrow under a barrier and leak charge.

Tunneling is considered a major problem in CMOS semiconductor design. "It's a leakage path that we don't want," Klimeck said. "But maybe tunneling can turn from an obstacle into a virtue in these devices."

A transistor's actions are two-fold. Not only does the device have to switch on and off, it must also be able to distinguish between the two states. Since the off state is always little leaky, the goal is to increase the ratio of "on" current to "off" current to at least 10,000.



With the scaling down of metal oxide semiconductor field-effect transistors (better known as a MOSFET), researchers are looking at new transistor designs. Among them is the gate-all-around nanowire MOSFET. Due to quantum mechanical confinement in both the transverse directions, an inversion channel is formed at the center of the device. This phenomenon iscalled volume inversion. Threshold voltage for the simulated nanowire device in the accompanying image is ~0.45V.

There are fundamental limits in this regard for today’s CMOS technology, but III-V materials, and specifically the tunnel FET (TFET) transistors that Klimeck is exploring, can perform better. They are often called “steep sub-threshold swing devices,” because they swing from almost no current to full current with a very steep slope. As a consequence, they would require less power while still performing the same number of operations.

Recent simulations on the Ranger supercomputer at the Texas Advanced Computing Center (TACC) and the Jaguar supercomputer at the National Center for Computational Sciences, led to a greater understanding of the quantum, and atomic-lever dynamics at play in the nanoscale device. Determining the energetics and electron pathways of these new nanoscale forms of III-V materials required more than 15 million processor hours on Ranger and 23 million hours on Jaguar between 2008-2011.

The research group, led by Alan Seabaugh of the University of Notre Dame, found that the sub-threshold conduction problem is related to the way electrons gather in the device. The group started out with a design developed at the University of California, Berkeley that was released to much excitement in Nature magazine in 2010. Using the computational tools they developed, the researchers found that the off current for the transistor was extremely high — a big problem for the device design.

To explain the physics of the problem, Klimeck likened the electrons involved in computing to water molecules in a bucket. The bucket has a hard bottom, but it has a fuzzy upper layer where electrons act like water vapor. The vapor cannot be controlled or "gated," resulting in a large voltage range to turn the switch on and off.

Band-to-band tunneling transistors have (figuratively speaking) a top on the bucket. Therefore the flow of the electrons can be tightly controlled without any temperature dependent "vapor" and the devices can turn on and off with a smaller voltage swing.

Klimeck et al filed a patent sponsored by the Nanoelectronics Research Initiative (NRI) for their improved tunneling design, and published several papers on the subject in the Journal of Applied Physics and the IEEE Electron Device Letters in 2010-2011.

"If you can switch from on to off in a smaller swing, you can reduce the whole swing from .9 volts, which we have today, to .5 or .4, volts, which is what we're aiming for," Klimeck said. That factor of two reduction in voltage results in four times less power required. "That's a huge improvement if you can maintain the same current flowing through your valve."

Computer modeling and simulation help the researchers explore the design space and physical properties of the materials, showing how one constructs a real device, atom by atom, in terms of geometries and growth.

“We try understand on the simulation side what can be done and provide the experimentalists with ideas,” Klimeck said.

“The tunnel FETs look fairly similar to the CMOS transistor that we see today, though they use very different materials and actually turn off and on by a quantum effect called tunneling,” said Jeff Welser, Director of the Nanotechnology Research Initiative, which funds the studies at the MIND center. “It turns out that by using tunneling, you can get transistors to turn on much more quickly.”

Though esoteric, the search for new nanotransistors is incredibly important for national competitiveness and economic security. Semiconductors are not only the U.S.’s largest export, they are the foundation for the last four decades of incredible growth in wealth, health and scientific advancement.

“Making sure that the nation continues to be on the leading edge of this export is of utmost importance, and it’s timely to do that because we know that the industry does not have a solution at the 8 nanometer level,” Klimeck said. “If we do not find a solution to continue to improve computers, the technical advancement that we’ve seen in the last 40 years will stop.”

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Gerhard Klimeck, director of the Network for Computational Nanotechnology and a professor of electrical and computer engineering at Purdue University.