RESEARCHERS TACKLE A GRAND CHALLENGE: REDUCING POWER CONSUMPTION OF ELECTRONIC SYSTEMS

Readers who grew up in the 1950s and 60s may remember the sense of excitement and modernity that the terms "transistor" and "solid state" evoked at that time. Transistors were the key to new electronic products that were transforming people's lives. To a teenager in the 1960s, a transistor radio was definitely "cool."

The advent of the integrated circuit, which put many tiny transistors onto a single computer chip, eventually propelled an explosion of personal computing and communications technologies that continue to shape our society.

Fast-forward to 2010, and our appetite for electronic products had grown to the point that information-processing devices of all kinds—including consumer electronics, computers, office equipment, network equipment, data centers, servers, and supercomputers—were using a growing fraction of the total electricity production in the U.S.

Researchers at the Center for Energy Efficient Electronics Science (E^{3}S) are concerned that the inexorable expansion in the role of information in society will place an increasing burden on the U.S. energy economy and ultimately will limit functionality. But reducing power consumption will mean rethinking the very component that has been the iconic mainstay of electronics since the middle of the 20th century.

Current electronic systems are dependent on the transistor, which requires a powering voltage close to 1 volt. But the wires of an electronic circuit can function adequately even at voltages as low as a few millivolts. If a transistor also could be made to operate in that range, that is, if its operating voltage could be reduced by a factor of about one thousand, then the power consumed by the transistor would be reduced by a factor of one million, since power scales as the square of the voltage.

E^{3}S researchers aim to reach this target. They are working to develop the fundamental and conceptual breakthroughs in the underlying physics, chemistry, and materials science that form the foundation of information-processing technologies in order to make novel electronic components with dramatically lower power consumption.

Headquartered at the University of California Berkeley and led by Eli Yablonovitch, the Center for E^{3}S brings together an interdisciplinary team from UC Berkeley, MIT, Stanford University, and Tuskegee University, to tackle the grand challenge of reinventing the transistor. They are focusing on four interrelated themes: nanoelectronics for solid-state millivolt switching; nanomechanics methods of zero-leakage switching; nanomagnetic logic; and nanophotonics for optical communication in support of new energy-efficient devices.

Hit the Wall? Go Through It

To understand how conventional transistor technology has "hit the wall" in terms of power reduction requires a refresher on some of the fundamentals of computer processors.

Today's consumers likely are familiar with microprocessor chips, the "brain" of electronic products. "Information is stored in computers in binary form, in other words there are two states, high or low voltage, representing a 1 or 0," explains E^{3}S researcher Tsu-Jae King Liu, professor of electrical engineering and computer sciences at UC Berkeley. "Basically, a microprocessor chip is largely comprised of transistors that simply act as switches. There are a bunch of 1s and 0s–that is, high and low voltages–being routed through logic gates throughout the chip to perform some computation.

"So a state-of-the-art microprocessor chip today might contain multiple billions of these transistors, most of them simply acting as switches. They either make or break a connection. And we do this in a solid-state transistor by raising or lowering a barrier to current flow.

"The problem is that as the transistors are scaled down to really small dimensions, the two terminals are coming so close together that it's really hard to turn off the current; there's always some leakage. That leakage leads to power consumption. We could raise the switching voltage of the transistor to stem this leakage; however, if the switching voltage is high, then it's actually hard to get a lot of current to flow freely when the transistor is on, and to compensate for that, then you have to apply an even higher voltage.

"So this is the fundamental issue: when you scale transistors down in size, you can't really scale down their operating voltage and still get low leakage. You can't scale the switching voltage down for a transistor, otherwise the leakage will go up, and also the operating voltage of the transistor cannot scale down, simply because otherwise the transistor won't conduct a lot of current when it's turned on."

What's the solution? One approach under development at the center is based on the quantum mechanical phenomenon of tunneling. Instead of raising and lowering a "wall" as the switching mechanism, researchers are controlling the energy levels of the materials, aligning them to allow electrons to tunnel through the wall to start the flow of current and then misaligning the levels to stop the current.

"This is a switching principle that's completely different from the principle that's used in all conventional transistors," says Yablonovitch. "To turn the tunnel transistors on and off, we'll simply move the energy levels from being in coincidence to being misaligned. That shift is done with voltage, so if the energy levels are very sharp, then a small voltage will misalign the energy levels, and that's the secret," he says. "The energy levels have to be very sharp, and if they are not very sharp, then we won't get the full benefit." More fundamental research will be needed to develop materials and systems to make the tunnel transistor a reality.

On another front, Center researchers are focusing on the design of nanoelectromechanical switches that will have zero off-state leakage current. With a tiny mechanical switch, "you don't have any material in between the two electrodes when it switches off, so really, no current can leak. And then to turn on the switch, you just bring two electrodes into physical contact. So the challenge is how to make devices with very small gaps, so that they can operate with very low actuation voltages," explains King Liu.

However, opening and closing a physical structure is slower than having electrons flow through a material. "The speed of the mechanical devices is about a thousand times slower than electrical devices," says King Liu. "But our research in the Center is also looking at how to design the circuits quite differently for mechanical switches to overcome this disadvantage. Even though the switches are switching at a lower speed, the overall system can be operating with the same performance by taking advantage of parallel processing.

"A lot of the computers you've seen nowadays have multiple cores–dual core or quad core–and in the future, you may have thousands of cores working in parallel, so

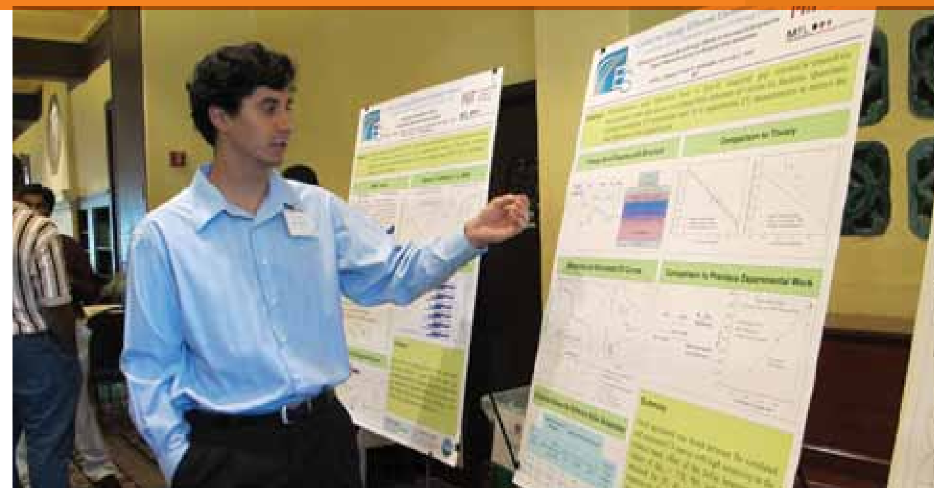
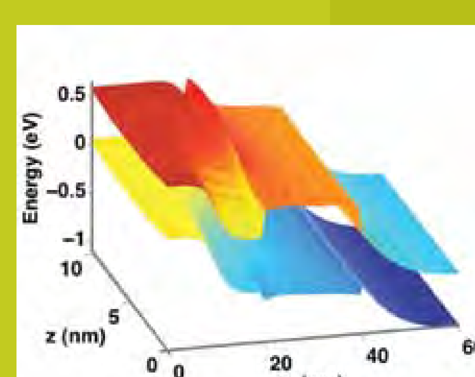


Photo: J. Peng, E^3S

the switches can be permitted to switch a thousand times slower. The key is that if each switch can operate at lower energy, the energy efficiency can be orders of magnitude better. The prototype devices we've made so far are on the order of tens of microns long," says King Liu. A micron is a thousandth of a millimeter in length, or about 0.00004 inch. "The gaps are on the order of tenths of microns. We're aiming now in the Center for the next few years to really aggressively scale down the lateral dimensions to be sub-microns and the vertical dimension approaching 10 nanometers or less, permitting lower energy operation."

Another research thrust of the Center is focusing on optical connections for computer chips rather than conventional wiring. "If we look at the current energy consumption in a chip, a large portion of that is spent on communication between transistors, the so called 'interconnect.' So we cannot solve the entire problem without tackling the interconnect energy consumption," explains Ming Wu, professor of electrical engineering and computer sciences at UC Berkeley. Today, a bit of information is represented by 20,000 photons per bit. This needs to be reduced to 20 photons per bit in nanotechnology systems, he says.

This goal will require new kinds of ultra tiny light sources and receivers that can be integrated into microprocessor chips. "So that's our step one: making miniature lasers. Step two is to look at whether we can accomplish the mission without lasers. We are looking at light emitters that are much more efficient than traditional LEDs and we have some theoretical framework on how to achieve that. And so that is part of the center research." □



Above: In search of millivolt switch.
Image: M.J. Yuen, E^3S
Right: Tunneling transistor simulation.
Image: K. Ganapathi, UC Berkeley

A CONVERSATION WITH THE DIRECTOR

Eli Yablonovitch

Why did you seek to create a Center focused on this particular theme?

There was a real need to address the most pressing question, which is: what will replace the transistor? We need to have a replacement that operates at much lower voltage. How could we resist a challenge like that?

When I investigated it, I learned surprisingly that there is no reason why transistors should be operating at the high voltage that they're operating at today. They operate at around 1 volt, but they could operate at a few millivolts and still perform the required digital functions.

We are creating of a new field of electronics which I think will eventually be regarded as an important avenue, aimed toward reducing the energy per bit-function–I'm trying to get people to accept that as a figure of merit.

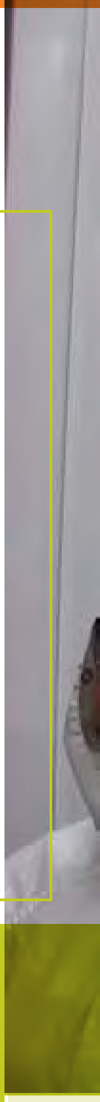
And that's why it's irresistible: it's very much a grand challenge. And it's going to take a while. I knew the only way to achieve something like that would be with a Center.

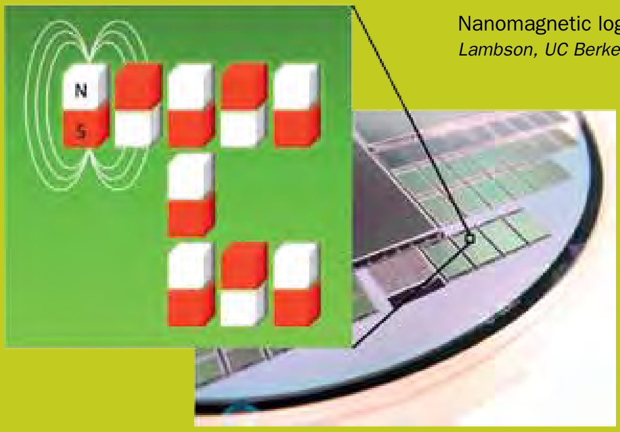
How does industry get involved?

We have a relationship with industry. They came to the site visit and expressed their need for this type of research, and they're participating very strongly. This is very long-range for them. They're monitoring it very carefully.

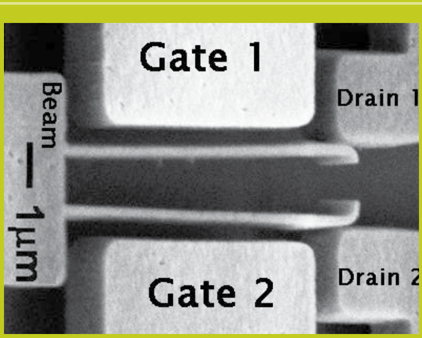
How do you view the role of director?

In a complex task like this, one that involves collaboration with industry, I'm drawing upon all of my life experiences. For example I worked for fifteen years in industry for three different companies. I'm also the founder of four startup companies, and that was a good preparation. Research like this is more long range, so it will develop a little more slowly. I do my part, but I have to encourage my co-principal investigators to dig deep and to do fantastic things. I've had a little bit of experience with that at the startup companies.





Nanomagnetic logic. *Image: B. Lambson, UC Berkeley*



Nanomechanical device.
Image: Daesung Li, Stanford U

FACULTY VIEWPOINT

Ming Wu

Professor of Electrical Engineering and Computer Sciences
University of California Berkeley

"The center really brings people together. Without a center, if I'm interested in a subject, I will be working on that, trying to find support, but it will be very difficult to find long-term support like that of the NSF center so support these long-range ideas. And it will be difficult for me to get industry support because they like to see more evidence in place before they invest in research in this area.

Right now, we have several companies that are watching the project, they are highly interested. They say 'as soon as you have some demonstration,' they would like to be involved. So a Center makes such kind of communication possible.

There are definitely more interactions. Without the Center we wouldn't be meeting as often, talking as much. I'm enjoying the interaction with Center members and still enjoying the scientific intellectual portion of our own subproject.

There is a sense of the Center, a sense of community—we are learning together."

E³S PROGRAM FOR COMMUNITY COLLEGE STUDENTS

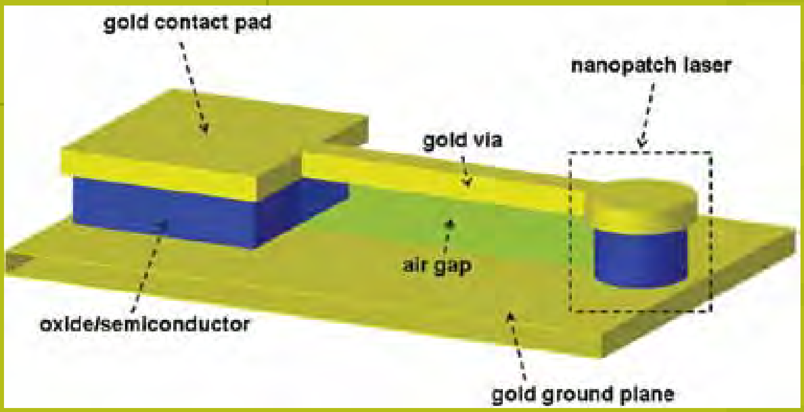
TRANSFER-TO-EXCELLENCE

Transfer-to-Excellence (TTE) is intended to inspire California community college students to ultimately transfer and complete a Bachelor's degree in science and engineering. The program consists of two components. A cross-enrollment program enables community college students to take a science, math or engineering course at UC Berkeley, and a residential summer research program brings community college students to undertake a research project hosted by a Berkeley professor.

While at UC Berkeley, TTE participants have access to academic, professional, and personal development seminars to enhance the overall preparation and confidence to pursue studies in science and engineering and, eventually, a career in the field. For the academic year following the completion of one component, participants continue to receive advising and support in their efforts to transfer to a science and engineering baccalaureate program.

TTE graduated its first cohort on August 12, 2011. Two students from the E³S partner institutions, Contra Costa College and LA Trade-Technical College, spent eight weeks doing engineering research, and one student from Chabot College completed a 4 credit lower division math course at UC Berkeley.

Undergraduate researchers in clean room at Stanford University. *Photo: S. Artis, E³S*



Schematic of tiny laser for optical interconnects. *A. Lakhani, UC Berkeley*