Making the new silicon: Gallium nitride electronics could drastically cut energy usage

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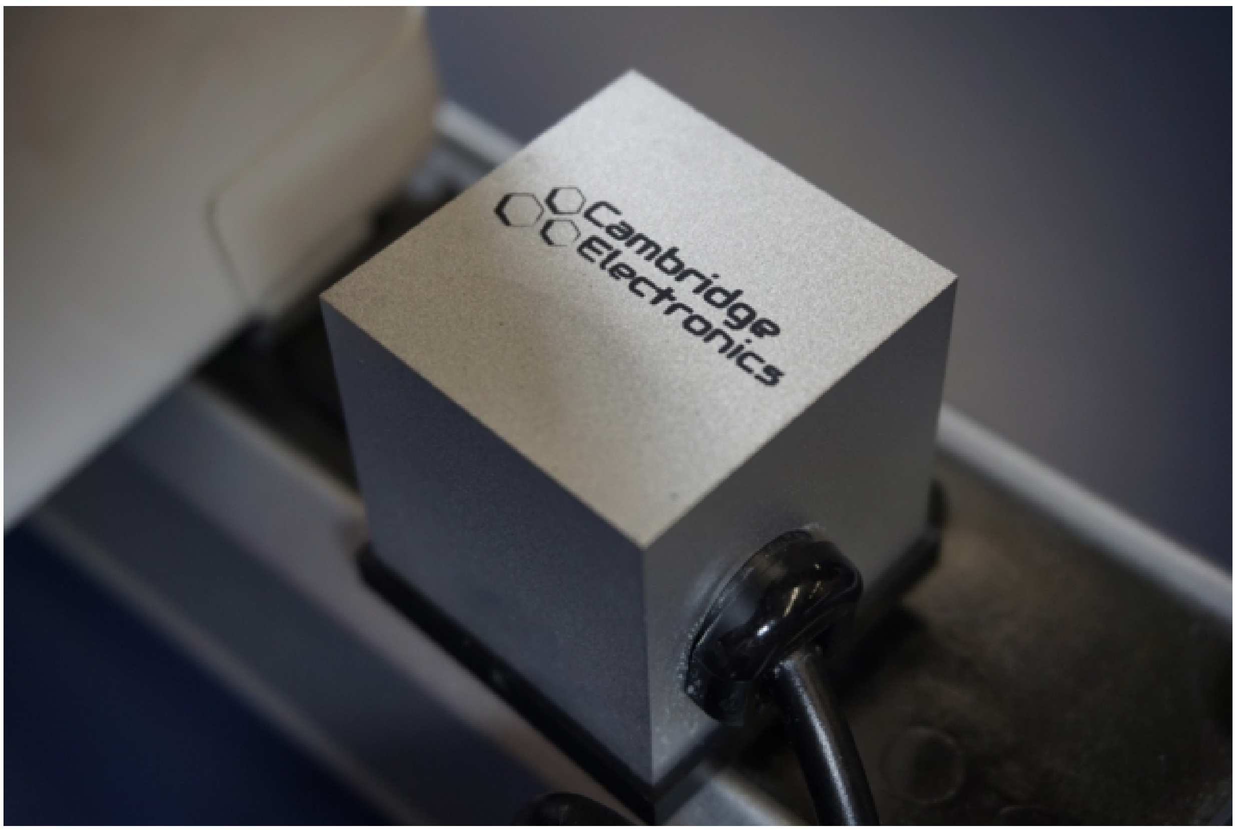

Shown here is a prototype laptop power adapter made by Cambridge Electronics using GaN transistors. At 1.5 cubic inches, this is the smallest laptop power adapter ever made. Credit: Cambridge Electronics

An exotic material called gallium nitride (GaN) is poised to become the next semiconductor for power electronics, enabling much higher efficiency than silicon.

In 2013, the Department of Energy (DOE) dedicated approximately half of a $140 million research institute for power electronics to GaN research, citing its potential to reduce worldwide energy consumption. Now MIT spinout Cambridge Electronics Inc. (CEI) has announced a line of GaN transistors and power electronic circuits that promise to cut energy usage in data centers, electric cars, and consumer devices by 10 to 20 percent worldwide by 2025.

Power electronics is a ubiquitous technology used to convert electricity to higher or lower voltages and different currents—such as in a laptop's power adapter, or in electric substations that convert voltages and distribute electricity to consumers. Many of these power-electronics systems rely on silicon transistors that switch on and off to regulate voltage but, due to speed and resistance constraints, waste energy as heat.

CEI's GaN transistors have at least one-tenth the resistance of such silicon-based transistors, according to the company. This allows for much higher energy-efficiency, and orders-of-magnitude faster switching frequency—meaning power-electronics systems with these components can be made much smaller. CEI is using its transistors to enable power electronics that will make data centers less energy-intensive, electric cars cheaper and more powerful, and laptop power adapters one- third the size—or even small enough to fit inside the computer itself.

"This is a once-in-a-lifetime opportunity to change electronics and to really make an impact on how energy is used in the world," says CEI co-founder Tomás Palacios, an MIT associate professor of electrical engineering and computer science who co-invented the technology.

Other co-founders and co-inventors are Anantha Chandrakasan, the Joseph F. and Nancy P. Keithley Professor in Electrical Engineering, now chair of CEI's technical advisory board; alumnus Bin Lu SM '07, PhD '13, CEI's vice president for device development; Ling Xia PhD'12, CEI's director of operations; Mohamed Azize, CEI's director of epitaxy; and Omair Saadat PhD '14, CEI's director of product reliability.

Making GaN feasible

While GaN transistors have several benefits over silicon, safety drawbacks and expensive manufacturing methods have largely kept them off the market. But Palacios, Lu, Saadat, and other MIT researchers managed to overcome these issues through design innovations made in the late 2000s.

Power transistors are designed to flow high currents when on, and to block high voltages when off. Should the circuit break or fail, the transistors must default to the "off" position to cut the current to avoid short circuits and other issues—an important feature of silicon power transistors.

But GaN transistors are typically "normally on"—meaning, by default, they'll always allow a flow of current, which has historically been difficult to correct. Using resources in MIT's Microsystems Technology Laboratory, the researchers—supported by Department of Defense and DOE grants—developed GaN transistors that were "normally off" by modifying the structure of the material.

To make traditional GaN transistors, scientists grow a thin layer of GaN on top of a substrate. The MIT researchers layered different materials with disparate compositions in their GaN transistors. Finding the precise mix allowed a new kind of GaN transistors that go to the off position by default.

"We always talk about GaN as gallium and nitrogen, but you can modify the basic GaN material, add impurities and other elements, to change its properties," Palacios says.

But GaN and other nonsilicon semiconductors are also manufactured in special processes, which are expensive. To drop costs, the MIT researchers—at the Institute and, later, with the company—developed new fabrication technologies, or "process recipes," Lu says. This involved, among other things, switching out gold metals used in manufacturing GaN devices for metals that were compatible with silicon fabrication, and developing ways to deposit GaN on large wafers used by silicon foundries.

"Basically, we are fabricating our advanced GaN transistors and circuits in conventional silicon foundries, at the cost of silicon. The cost is the same, but the performance of the new devices is 100 times better," Lu says.

Major applications

CEI is currently using its advanced transistors to develop laptop power adaptors that are approximately 1.5 cubic inches in diameter—the smallest ever made.

Among the other feasible applications for the transistors, Palacios says, is better power electronics for data centers run by Google, Amazon, Facebook, and other companies, to power the cloud.

Currently, these data centers eat up about 2 percent of electricity in the United States. But GaN-based power electronics, Palacios says, could save a very significant fraction of that.

Another major future application, Palacios adds, will be replacing the silicon-based power electronics in electric cars. These are in the chargers that charge the battery, and the inverters that convert the battery power to drive the electric motors. The silicon transistors used today have a constrained power capability that limits how much power the car can handle. This is one of the main reasons why there are few large electric vehicles.

GaN-based power electronics, on the other hand, could boost power output for electric cars, while making them more energy-efficient and lighter—and, therefore, cheaper and capable of driving longer distances. "Electric vehicles are popular, but still a niche product. GaN power electronics will be key to make them mainstream," Palacios says.

Innovative ideas

In launching CEI, the MIT founders turned to the Institute's entrepreneurial programs, which contributed to the startup's progress. "MIT's innovation and entrepreneurial ecosystem has been key to get things moving and to the point where we are now," Palacios says.

Palacios first earned a grant from the Deshpande Center for Technological Innovation to launch CEI. Afterward, he took his idea for GaN-based power electronics to Innovation Teams (i-Teams), which brings together MIT students from across disciplines to evaluate the commercial feasibility of new technologies. That program, he says, showed him the huge market pull for GaN power electronics, and helped CEI settle on its first products.

"Many times, it's the other way around: You come out with an amazing technology looking for an application. In this case, thanks to i-Teams, we found there were many applications looking for this technology," Palacios says.

For Lu, a key element for growing CEI was auditing Start6, a workshop hosted by the Department of Electrical Engineering and Computer Science, where entrepreneurial engineering students are guided through the startup process with group discussions and talks from seasoned entrepreneurs. Among other things, Lu gained perspective on dividing equity, funding, building a team, and other early startup challenges.

"It's a great class for a student who has an idea, but doesn't know exactly what's going on in business," Lu says. "It's kind of an overview of what the process is going to be like, so when you start your own company you are ready."

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