Smaller, faster, tougher

Silicon carbide will soon supplant silicon in hybrid cars and the electric grid

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Some technological revolutions are flashy. And some are almost invisible. We're quite familiar with the flashy ones; they've given us powerful computers we can hold in the palms of our hands, devices that can pinpoint our location by way of orbiting satellites, and the ability to bank and shop without leaving our homes.

But none of these innovations would have occurred without the technology that delivers power to them. Over the last half century, a more subtle revolution in power electronics has provided us with compact and efficient semiconductor devices that can manipulate, regulate, and convert electricity from one form to another.

Silicon has long been the semiconductor of choice for power electronics. But soon this ubiquitous substance will have to share the spotlight. Devices made from silicon carbide (SiC)—a faster, tougher, and more efficient alternative to silicon—are beginning to take off. Simple SiC diodes have already started to supplant silicon devices in some applications. And over the last few years, they've been joined by the first commercially available SiC transistors, enabling a new range of SiC-based power electronics. What's more, SiC wafer manufacturers have succeeded in steadily reducing the defects in the material while increasing the wafer size, thus driving down the prices of SiC devices. For the first time last year, according to estimates made by wafer maker Cree, the global market for silicon carbide devices topped US $100 million.

Within five years, we should see this market balloon as SiC devices find their way into power electronics for hybrid and all-electric vehicles, creating simpler and more efficient power systems. SiC power devices also could become vital in solar and wind energy creation, by reducing the energy lost as electricity is converted to a form that can be used on the power grid. Eventually, silicon carbide could remake the grid itself by eliminating the need for bulky substation transformers, thereby saving an enormous amount of energy that is now wasted as electricity makes its way from the power plant to its final destination. Although the field of SiC power electronics is still quite immature, we expect it's in for a big growth spurt.

Silicon-based devices are, by comparison, so mature and inexpensive to manufacture, it might be hard to believe that any material could shake silicon from its perch. But silicon carbide is quite special. Many of the material's most attractive properties stem from a single physical feature: SiC's bandgap, the energy needed to excite electrons from the material's valence band into the conducting band. Silicon carbide electrons need three times as much energy to be excited into the conduction band, a property that lets SiC devices withstand far higher voltages and temperatures than their silicon counterparts.

One of the biggest advantages the wide bandgap confers is in averting electrical breakdown. Silicon devices, for example, can't withstand electric fields in excess of about 300 kV/cm. Anything stronger will tug on electrons flowing in the device with enough force to knock other electrons out of the valence band. These liberated electrons will in turn accelerate and collide with other electrons, creating an avalanche that can cause the current to swell and eventually destroy the material.

Because electrons in SiC require more energy to be pushed into the conduction band, the material can withstand much stronger electric fields, more than 10 times the maximum for silicon. As a result, an SiC-based device can have the same dimensions as a silicon device but withstand 10 times the voltage. What’s more, a silicon carbide device can be less than a tenth as thick as a silicon device but carry the same voltage rating, since the voltage difference does not have to be spread across as much material. These thinner devices are faster, and they boast less resistance, which means less energy is lost to heat when a silicon carbide diode or transistor is conducting electricity.

Because of these features, silicon carbide could be used to replace slow silicon switches with alternative designs that are faster and more energy efficient. To sustain voltages beyond about 200 V, a silicon transistor has to be quite thick, which boosts resistance and cuts down on switching speed. To circumvent the low speed, high-voltage silicon switches tend to be bipolar transistors: They use both holes and electrons to carry current. The design carries more current, but it takes time for all the charges to fully exit the device. When the transistor is being switched from its “on”, current-carrying state to its “off”, voltage-blocking state, there is a period of overlap where remaining charged carriers are exposed to high voltage and dragged through the device, dissipating heat.

Using silicon carbide instead of silicon in high-voltage devices will allow slow silicon bipolar transistors to be replaced by single carrier, or unipolar, devices such as power MOSFETs. Fewer charge carriers are left behind in such devices, so the transistors can be switched quickly and far more efficiently. The faster devices also have the added benefit of more compact circuits, since their higher frequency operation allows the use of smaller inductors and capacitors.

For all its fine qualities, silicon carbide has been a difficult material to master. One of the biggest hurdles to its widespread use in power electronics has been in wafer manufacturing. When engineers first started working with the material in the 1970’s, they struggled to grow large single crystals of the stuff—the silicon and carbon atoms had a habit of separating from one another to form polycrystalline structures.

Over the years, researchers succeeded in creating larger and larger single crystal wafers. And in 1991, a few years after the company was founded, Cree released the first commercially available SiC wafers. They were just an inch across and used mostly for research, but it was a start. Since then Cree and other manufacturers have made steady progress in boosting the size of the wafers; these days 4-inch SiC wafers are common, and six-inch wafers are on the horizon. A larger wafer size means more devices can be built on each wafer, which drives down device cost.

At the same time, companies have been working to overcome another early stumbling block: a high number of defects in SiC crystals. Unlike silicon, SiC doesn’t have a liquid phase. As a result, SiC crystals are grown layer by layer from vapor at roughly 2500°C. This process is difficult to control and can easily give rise to tiny, tornado-like tunnels called micropipes that arise from dislocations in the crystal early in the wafer formation process.

Devices that are built atop these micropipes don’t perform as designed. Even a few micropipes per square centimeter is enough to erode device yield and thus boost cost. But as wafer producers continued to fine-tune manufacturing processes, they made steady strides in eliminating such defects, too. In 2005, the Swedish firm Intrinsic Semiconductor, later acquired by Cree, debuted four-inch SiC wafers with zero micropipes.

Of course, wafers would be nothing if there weren't devices to build on top of them. In 2001, more than 50 years after the first silicon power electronic devices emerged, Munich-based Infineon Technologies released the first commercial SiC device. It was a Schottky diode, a simple junction made from metal and SiC. Although they cost more than silicon diodes, these SiC devices offer a range of benefits, including better energy efficiency and reliability and cooler operation. They also eliminate the need for devices like snubbers, which would otherwise be used to protect silicon circuitry from current spikes. In less than 10 years, SiC Schottky diodes have all but replaced the silicon p-n diodes in switched-mode power supplies for computers, particularly those in large data centers. Manufacturers now offer Schottky diodes that can withstand voltages as high as 1200V, four times the maximum voltage of comparable silicon devices.

But to truly revolutionize power electronics, you need a second component: transistors. These more sophisticated devices have taken longer to realize in silicon carbide. It wasn't until 2008 that the first SiC transistors—junction field-effect transistors (JFETs) manufactured by Mississippi-based SemiSouth—finally hit the marketplace. The number of transistor offerings has since boomed. SiC transistors with a range of architectures are now offered by the likes of Cree, SiCED, Rohm, and TranSiC. Each design has its advantages, and the jury's still out on which one will get the biggest share of the market, but competition is clearly heating up.

At Oak Ridge National Laboratory, we've been exploring how well SiC diodes and transistors work as the power electronics devices for all-electric and hybrid electric vehicles. After the battery, electronics is the key added cost to these vehicles. They're needed to convert wall power into battery power, to recharge the battery from the engine or from the brakes, and most importantly, to operate the traction drive, which transforms battery power into electricity for running the motors that propel the vehicle. Of all the electronics in an electric vehicle, the traction drive draws the most power.

The drive has two main parts: a boost converter that increases the voltage of DC current from the battery and an inverter that converts this electricity into three-phase AC needed by the motor. The three-phase inverter in turn consists of roughly a dozen diodes and transistors. In computer and laboratory simulations at Oak Ridge, we've shown that simply swapping silicon diodes with SiC Schottky diodes cuts the inverter's energy loss by 33 percent. The reduction doubles if you also replace the silicon transistors with SiC transistors. This boost in efficiency results mainly from SiC's lower electrical resistance, which means it loses less power to heat, and from faster, more efficient switching.

But SiC's advantages don't end there. SiC's big band gap also makes the material much more heat resistant than silicon, since it takes more energy to kick electrons into the conduction band. Excess heat can excite so many electrons that it can interfere with a device's operation. For silicon, this thermal breakdown occurs at around 150 °C, but SiC devices can withstand temperatures of more than 600 °C. This thermal resistance makes SiC attractive for a range of rugged applications, including military electronics, electronics for oil wells, and geothermal plants, and robotic spacecraft.

In hybrid and electric vehicles, SiC's operating temperature is high enough that it could eliminate one of the most bulky components in hybrid and all-electric vehicles: the water cooling system. Hybrid vehicles need two cooling loops: one for the gasoline engine, which runs at 105 °C, and another to cool the power electronics and traction motor. Because silicon-based electronics stop performing at around 150 °C and because some physical space separates the electronics from the coolant, this second loop needs to run even colder than the gasoline loop, or at roughly 65–70 °C.

Water cooling adds significantly to the overall size of the engine, and if the water leaks out, it can destroy the electronics. Our simulation results suggest that SiC inverters, because they can operate at higher temperatures, could reduce the size of the cooling system by 60 percent. If we combine these inverters with other high-temperature components like high-temperature capacitors, we might be able to eliminate the second loop altogether, and simply cool the electronics with air. First, though, the packaging and peripheral components—the capacitors, control circuits, and drivers that turn transistor gates on and off—must also be made to withstand high temperatures. We've slowly been making progress on this front and have built drivers from scratch that work up to 200 °C.

How efficient could SiC ultimately make electric vehicles? Electric traction drives already convert more than 85 percent of their power into usable mechanical energy, more than double the raw efficiency of a gasoline engine. But the U.S. Department of Energy has set some ambitious goals for boosting the efficiency even further. Specifically, the agency has said that by 2015, drives should convert 93 percent of their power into mechanical work, and by 2020, more than 94 percent. In other words, it wants future drives to lose half as much energy as present-day drives.

These efficiency targets wouldn't be hard to reach by themselves, but the DOE also expects that electric traction drives in 2020 will be half the size and less than a fifth of the cost. These ambitious targets will be all but impossible to hit with silicon alone, but we think SiC has the potential to get us at least most of the way there.

One area where SiC devices are already making inroads is solar power. Photovoltaic panels, whether they're mounted on a roof or spread across hectares of land, require inverters that can convert the DC electricity produced by the panels into AC electricity that can be fed into the power grid. This conversion process is already quite efficient: Silicon-based inverters lose just 2-3 percent of the energy they process. But inverters that contain SiC diodes and transistors can easily cut that loss in half. Over the 20-year lifetime of a 10-megawatt solar plant, that could add up to hundreds of thousands of dollars in savings.

That's just for starters. The U.S. Department of Energy estimates that improvements in power electronics could eventually reduce U.S. electricity consumption by as much as 30 percent. To get there, the department's Advanced Research Projects Agency—Energy program last year awarded grants to several projects that aim to rebuild power electronics from the ground up. Two grants went to teams led by Cree and GeneSiC that are investigating ways to make SiC devices that can operate up to 15,000 V.

This voltage range is well beyond the capabilities of silicon devices, and it will require SiC components that don't yet exist, including high-voltage bipolar transistors and p-n diodes. But if such research succeeds, it could one day revamp the electric grid by allowing for solid-state devices that can directly connect distribution lines to higher voltage transmission lines. At present, that job is performed by massive, multi-ton transformers, which dominate power substations. Someday, though, utility companies could replace these behemoths with far more efficient solid-state transformers, each the size of a suitcase.

Of course, that's still a long way off. One key technical hurdle will be continuing to improve the quality of SiC device channels. Current SiC transistors have channels that carry charges a factor of 10 slower than their theoretical limits, but modifications such as better surface quality should help.

Right now, silicon carbide is experiencing the same sorts of growing pains that silicon did in the 1950s and 1960s, when physicists and engineers saw it as a replacement for germanium. Despite the fact that SiC devices are still relatively new and more expensive than their silicon counterparts, the material has already demonstrated clear advantages over the alternatives. As more and more such devices come to market and their capabilities expand, they could start a revolution of their own.