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Powering the Telecosm
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Quantum Power

Power devices built on SiC perform fantastically well. And Cree knows more about SiC than anyone else.

Over 650 scientists and engineers showed up for the bi-annual International Conference on silicon carbide (SiC) in October 1999. The techs were looking at the next big opportunity in Quantum Power–but irrational exuberance being what it was, Wall Street somehow got *Power* mixed up with *Logic*. Very soon after, shares of the world's largest vendor of SiC wafers took off. They would soar 300 percent before tumbling back down to earth in the first quarter of this year.

The company was Cree (CREE). And as best we can fathom it, that particular spasm of ebullience can be traced to the fact that quantum power capabilities of SiC are sometimes used to make light, which sometimes takes the form of a coherent laser beam, which sometimes is used to convey bits–all of which apparently got Cree hitched to the boom-bust vendors of telecom equipment, and their vaporous dot.com clients. If that was in fact behind Cree's rise and fall in the last 24 months, why then we have learned something important–about Wall Street, if not about Cree itself. Wall Street, it seems, has not yet assimilated the fundamental difference between power and logic. It will.

But haven't we been arguing all along that logic–the whole digital economy–depends on supplies of high-9s power? We have, and it does. To say that A depends on B, however, is not to say that B depends on A. Power moves atoms as well as bits, and the more precise, focused, and controlled the power, the better it moves them both. The digital economy defines the leading edge of demand for Powercosm technologies, but only the edge. Digital power is taking over wherever we move atoms, and wherever we merely look at them, too–from under the hoods of cars (*December 2000 DPR*) to medical implants (*April 2001 DPR*), to detectors and imaging technologies of every kind.

Which brings us back to silicon carbide. It's found in meteorites, but does not occur naturally on earth; it was first synthesized a century ago, by chemists in search of diamond-like materials. Growing pure SiC crystals, and then building gates on them took a lot longer. The first SiC electronic devices didn't emerge until 1991. Until very recently, SiC's only toehold in the Powercosm was in the manufacture of blue light-emitting diodes (LEDs).

Companies like Microsemi (MSCC) and Infineon ((IFX) *December 2000 DPR*) are now building the first commercial SiC diodes, and SiC transistors are not far behind. And difficult though SiC is to work with, no other semiconductor holds out similar promise to push the powerchip up the performance curve of higher power, higher power density, higher frequency, and higher temperature applications.

Cree is the world's biggest supplier of SiC. Our *April 2000 DPR* took note of Cree's pioneering work with SiC, and that material's potentially huge implications in the Powercosm. We were drawn back to Cree this past January, when the company acquired UltraRF (the subject of our *November 2000 DPR*) from Spectrian (SPCT). But we assumed at the time that too little of the rest of Cree's business was directly anchored in the Powercosm to earn Cree the place that Spectrian had just surrendered on our Power Panel. We spoke too soon.

The thing to grasp about SiC, and Cree–and also Advanced Power Technologies ((APTI) *October 2000 DPR*), Fairchild ((FCS) *January 2001 DPR*), International Rectifier (IRF) and IXYS ((SYXI) *April 2000 DPR*)–is that the semiconductor market has been cleaved in two. Semiconductor power and semiconductor logic both descended from the first primeval transistor that took shape in Shockley's lab in 1949, they are as far apart today as microbe and mastodon. Cree ranks as a Powercosm company, all right, because SiC's destiny centers primarily on power, not logic. Power devices built on SiC perform fantastically well. And Cree knows more about SiC than anyone else.

Quantum Light Bulb on a Quantum Scaffold

In 1987, Cree's first business plan sketched out potential military applications for SiC, along with a projected $14-million-a-year market for blue light-emitting diodes (LEDs). The military applications have emerged–but blue LEDs came faster. Cree now owns about 40 percent of the $120 million global market, and the business currently generates roughly half of Cree's $110 million annual revenues. Cree substantially expanded its engineering capabilities and intellectual property with its May 2000 acquisition of Nitres Corp., a private developer of gallium nitride (GaN) semiconductors, and has steadily expanded its manufacturing capacity to meet demand (42,000 sq ft added in late 1999, 125,000 sq ft in December 2000).

Cree isn't alone in this business–Nichia Chemical has about the same market share; other manufacturers include Toyoda GESI and AXT (AXTI). Nichia, Toyoda, and Cree all developed GaN epitaxy as a viable light emitter. They apparently did so independently and contemporaneously, but they are now embroiled in patent litigation–a potentially significant legal factor for investors, though one that falls well outside the scope of this technology newsletter.

All of the blue LED manufacturers, Cree included, are pushing blue photons out of gallium nitride not silicon carbide. The color of the light you can get out of a semiconductor junction depends on the material's "band gap." Aluminum gallium arsenide (AlGaAs) shines red; GaN is blue. Cree is different, however, in that it grows its GaN on a SiC substrate; its competitors all grow it on sapphire. The SiC provides a better scaffold because it more closely matches the GaN lattice structure, and thus yields more uniform GaN layers; that has an important impact on power output and device longevity. The SiC is also an excellent conduit for moving electrons on to the GaN layer, and heat out of it. Sapphire, by contrast, is an insulator.

Bottom line: a SiC-base LED is half the size, a lot more reliable, and very much more efficient. By continuously refining the complex recipes, Cree continues to increase the brightness of its blue LEDs, and to lower their power consumption (a 50 percent drop in just the last two years). Until last year, Nichia had built the most efficient blue LEDs. Then the Cree-Nitres team demonstrated a device with a stunning 28 percent conversion efficiency. The efficiencies of incandescent bulbs, by contrast, typically run in the single digits.

It is here–in this most humble possible application of SiC, and in the passing shadow of "single digits"–that we get a first hint of the possibilities that lie ahead. All center on semiconductors, which is to say, on *quantum engineering*. All advance power, not logic. And a very important subset of them center on SiC–as it makes the leap from quantum "scaffold" to the heart of the "skyscraper" itself.

Quantum Technology

Edison invented his filament light bulb in 1879. The addition of a second and then a third filament produced the tube diode (1905), and then the tube amplifier (1906), and then … then nothing fundamental until 1949, when Shockley's team at Bell Labs built the first semiconductor-based diodes and triodes. The semiconductor "light bulb"–a red LED–wasn't invented until 1969. The blue LED took another 25 years after that. Which–if it proves nothing else–does establish that the quantum engineering of even light-bulb-power devices is quite a challenge.

All quantum technologies depend on the engineering of atomic-scale layers with extraordinary precision. Quantum physics happens in the electron orbits around atomic nuclei–a negative charge (n) situated in quantum proximity to a positive (p) one. A semiconductor junction provides the equivalent–the spherical atom unrolled (so to speak) into a flat n-p layer, that is much larger and that can therefore handle much more total power. It won't work, however, without crystals and junctions that are very close to atomically perfect.

This isn't easy–least of all on SiC–but it is indubitably real. While the digital-logic crowd dreams of building a quantum computer at some distant point in the future, the digital-power engineers are building quantum power switches, variable resistors, and transformers today–building them commercially, and selling them by the millions–they call them diodes, power transistors, and lasers. Even when it serves merely as a scaffold, the SiC crystal systematically exploits quantum phenomena: the near-perfect atomic lattice makes possible the near-perfect transport of electricity and heat through it, with a wave-like transfer of energy replacing the chaotic, diffusive transfers that govern in other materials.

Building functional power devices out of atomic-scale junctions and perfect crystals is extremely difficult–but the payoffs are commensurately big–orders of magnitude improvements in power density, speed, and overall efficiency. Electron-to-photon conversion efficiencies, for example, that suddenly leap from single digits to 28 percent. "Bulbs" that suddenly shrink from

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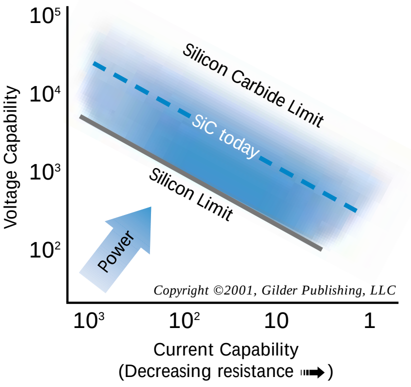
the size of a pear to the size of a poppy seed. Per unit of area and of energy used, semiconductor "bulbs" are far brighter than Edison's, which means they can be far more compact, efficient, and cool.

So much so that it is now reasonable to project that solid-state light will almost completely supersede Edison's filaments within the next few decades. Electron-to-photon transitions can now be accomplished much more compactly and efficiently at quantum junctions than in heated filaments or excited gas cavities. The transition has already occurred wherever it is important to supply more light with less power. In battery-powered devices of every description, from wristwatches to emergency exit signs, to traffic lights. In cars, from the dashboard to the taillights, and soon the headlamps too. Full color LED displays are possible now that the blues have joined the more common reds and greens. Baseball parks are now erecting huge ones for instant replays. Some 18 million LEDs light the NASDAQ's huge display in New York's Times Square.

But again, what is significant here isn't any single product, however conspicuously it may assail New Yorkers. Silicon carbide is much bigger than any second-to-second hiccups in the NASDAQ ticker, or even than the difficult line that has been crossed between the red and the blue quantum light bulb. The key point is that quantum physics is ruled by atomic structure, and atomic-scale architectures–which means that it inevitably comes down to *materials*. Silicon (Si) is different from gallium, which is different from silicon carbide. SiC, it turns out, has some of the most attractive physical properties of any semiconductor yet developed.

Silicon Carbide's Lure



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Silicon carbide has some of the most attractive properties of any semiconductor yet developed. It withstands voltages 8 times higher than silicon can; it conducts current up to 100 times more freely; and it conducts heat better than gold.

Silicon Carbide

Silicon carbide lines the brakes of a 911 Porsche Turbo–because it reduces rotor weight by 35 pounds, increases friction 25 percent, eliminates fade, and lasts over 185,000 miles. It makes excellent sand paper too. And a good SiC crystal looks like a diamond to the untrained eye–Cree itself still supplies a tiny percent of its SiC output to jewelry manufacturers. But not the really good crystals. Quantum power devices require levels of crystalline perfection much higher than those demanded in the adornment of fingers and ears.

The strength, hardness, and high thermal conductivity that make it so attractive to Porsche's brake designers also make SiC enormously difficult to engineer at any scale, with smaller even harder than bigger. Pure SiC crystals are very difficult to grow at all. Like all other semiconductors, SiC tends to acquire all sorts of bulk and surface defects when grown into a crystal; unlike others, SiC also tends to form "micropipe" defects that act as electrical short circuits straight through the crystal. Growing thin "epitaxial" layers on top of a SiC substrate surface is an equally big challenge.

Why then bother with SiC at all? Because it's a fantastic semiconductor. Silicon carbide can withstand voltages 8 times higher than silicon can. It can also conduct current up to 100 times more freely. And its extraordinary thermal conductivity beats everything, including even gold's. Random thermal fluctuations generate electron-hole pairs that cause current leakage and noise in all semiconductor-based electrical devices–but the problem is 16 orders-of-magnitude lower in SiC than in Si.

So if you can in fact manage to grow perfect enough SiC crystals, and if you can then add perfect enough epitaxial layers, and then if you manufacture functional devices on them, you get enormous pay offs in overall performance. The "ifs" are daunting in practice–but the potential pay-offs have long tantalized the engineers of logic chips. SiC DRAM memory chips would hold their charge for a century or so, which would get them through most power outages, even in California. Build a Pentium on SiC, and you could immediately boost clock speed to 75 GHz, three times the limit theoretically achievable on Si.

While the logic engineers have salivated over a distant SiC menu, the power engineers have already begun to dine. Two members of our Power Panel, Infineon and Microsemi, already buy SiC from Cree, and manufacture it into commercial diodes. The SiC power switches now coming to market can operate 10 times as efficiently as Si equivalents–which means they can run 10 times faster, or occupy 1/10th the space for the same power rating. The performance gains multiply out from there, because higher efficiency in one chip often lets you shrink adjacent chips, boost frequencies, and thus further shrink the (often very bulky) inductors, magnetics, and heat sinks. Build a grid-level power switch out of SiC and shrink the module from a U-Haul to a breadbox.

Researchers at Purdue University's Wide Band Gap group, and at Cree itself, have managed to make laboratory versions of SiC memory and logic–but we don't expect one imminently from Intel. Within the next few years, however, we do expect to see commercial SiC-based power MOSFETs, microwave amplifiers, microwave oscillators, charge-coupled devices, and photodetectors chips. Yes, as Wall Street surmised last year, Cree's SiC lands in telecom equipment; indeed, Cree itself purchased UltraRF from Spectrian last December to push the SiC-based development of wireless RF power amplifiers and datacom power supplies. But as the UltraRF acquisition confirms, SiC great promise is–precisely–to amplify and convert *power*, and lots of it, in applications spanning a wide range of frequency bands, from static switches to RF amplifiers, to optical light-emitting (or light-absorbing) diodes.

Wafers

The scheme for growing high quality SiC crystals wasn't conceived until 1955, and it took another 30 years of research before anyone came close to mastering the "seed sublimation" technique that yields semiconductor grade wafers. North Carolina State University was home to the team that achieved one of the key breakthroughs. One member was Eric Hunter. In 1987, his brother Neal (himself a recent graduate of NC State) persuaded the team to set up Cree Research–Neal had the funding all lined up, in the form of a second mortgage and a pyramid of credit cards. An IPO followed in 1993. Neal Hunter remains Chairman and CEO.

A few other SiC manufacturers have emerged, among them Sterling (Sterling, Virginia, acquired by Uniroyal in May 2000), and Litton Airtran (still precommercial, bought the SiC assets of Northrop Grumman). Cree itself, however, supplies 90 percent of the world's semiconductor-grade SiC.

What did Cree get right? With smartchips, the prize goes to the company that puts the most gates on to the wafer. With powerchips, the winner is the company that most successfully pulls the most defects out. To handle more power, more efficiently, you have to build a bigger gate, not a smaller one. And how big you can build it, at what cost, depends on how often micropipe defects in your wafer punch a short-circuit right through your gate. Cree has managed to push down SiC crystal defect density by some fifty-fold from their first wafers a decade ago, and the reductions continue apace–which is to say, roughly at a Moore's Law rate. Cree's earliest SiC wafers averaged hundreds of defects per square centimeter; they're running well below 10 today.

Cree's first key insights related to the specific composition of the starting material, and the process for growing a solid SiC crystal directly out of a gas. Electronic grade silicon is happy to melt, and then resolidify; SiC, by contrast, forms such a tight lattice that it's either a solid, or it's a vapor, it refuses to go gentle into the liquid night. That creates a very difficult chasm for crystal builders to cross. John Palmour, one of Cree's founders, and its current chief technologist, ranks the basic starting chemistry and the ultra-high-temperature heating process as crown jewels among Cree's many trade secrets.

The second challenge involves growing an epitaxial layer on the SiC base. This is the layer in which dopants make the junctions that form diodes and transistors. The substrate acts, in effect, as a scaffold of atomic-scale precision for the quantum engineering that follows on its surface. But until recently, it was all but impossible to build any kind of epitaxial layer on SiC. Few other semiconductors match the SiC lattice closely enough to form properly on that base. Gallium arsenide, widely used to make RF devices, can't hack it. Gallium nitride (GaN) can–but it's hard to manage, and it's horrendously prone to defects when grown as an epitaxial layer. Only a few companies in the world have found ways to beat the problem, Cree among them. And Cree is the only one growing them on SiC; the rest are growing GaN on sapphire.

The other option is to grow an epitaxial layer of doped SiC on the pure SiC base. Why not just use the SiC that's already there? Because an even finer crystal lattice is required, and because it's at the epitaxy stage of things that the first of two dopants–nitrogen or phosphorus ("n"), or aluminum or boron ("p")–is introduced into the SiC. It has to go in very uniformly, and SiC's prohibitively strong lattice structure again makes things difficult. Cree developed a unique process for cleaving the SiC scaffold at a very slight angle off the crystal's axis. That creates a new surface with far more points of attachment within the crystal structure as a foundation for the ultra-precise, atomic-scale "chemical vapor deposition" that follows.

As Cree has pushed defect densities down, it has been able to push wafer sizes up. The company's first, 1-inch diameter SiC wafers became commercially available in 1991. Defect densities have since fallen to the point that Cree gets reasonable yield across its current 2-inch SiC wafers, and expects to shift to commercial production of 3-inch wafers in 2002. Moving from 2 to 3 inches reduces cost per device by almost 50 percent. That's still a far cry from the 12-inch wafers the pure silicon industry is now headed for, but the trend is clear: Cree is now moving along the same falling-cost, rising-yield curves that have made logic chips as cheap as jelly beans.

From here on out, SiC wafer costs should drop as fast as the market for SiC devices grows. Cree now owns some 80 patents, and much more IP in the form of experience and trade secrets. Defect formation in the epitaxial layer is exquisitely sensitive to numerous variables including pressure, temperature, and gas flow rates, and there's no possibility of reverse engineering process details out of the final product.

Quantum Diode

In the past 12 months, Cree's SiC has made the transition from scaffold to integral component in the most basic of quantum devices, the Schottky diode. The diode is a ubiquitous, fundamental building block in virtually every type of power-handling circuit at every level of power, from microwatts to megawatts. And rising power densities, power levels, and speed have pushed diodes to the limits of conventional semiconductors–especially in applications like medical implants (which have to be extremely compact, reliable, and power efficient), satellites (similar requirements), and high-power systems for high-9s data centers, silicon factories, control systems for large factory motors, and the grid.

The simplest diode architecture is the heterostructure Schottky, in which the junction is created by directly bonding a metal wire to a semiconductor crystal. Microsemi and Infineon have both introduced SiC-based Schottky diodes built on Cree's SiC, and Cree will be shipping its own Schottky by year's end. Microsemi's SiC Schottkys are targeted for implantable defibrillators and high-speed modems where small size and high efficiency are critical, as well as for satellites and military radar where the additional virtue of radiation robustness is prized. Another early application has been to replace conventional silicon PIN diodes in high-powered MRI units. Infineon has just completed its internal qualification of the fab process for its own Cree-SiC Schottky diode. The company is initially targeting high-end (datacom and telecom) power supplies. Infineon sees very strong demand here for technologies that sharply boost efficiency and shrink footprint.

That's what SiC delivers when it replaces Si in a Schottky diode. The SiC devices make possible power supplies that operate at 500 kHz and beyond (Infineon has a 1-MHz prototype), some 5 to 10 times faster than Si-based alternatives. The SiC diode's combination of higher switching frequency and inherently higher efficiency keeps the power-switching IGBTs alongside much cooler, which lets the IGBTs themselves run more efficiently, or handle more power. A power supply can thus be shrunk five-fold or more, even though the diodes themselves occupy only a tiny fraction of the unit. The first Infineon and Microsemi commercial units are rated at a half kilovolt; prototypes are already beyond 1 kV. For now, the SiC-based diodes remain 5 to 10 times more expensive than the Si units they replace. But higher switching speed always wins sooner or later in the Powercosm, and all the trends are toward lower multiples on the SiC-device price, and higher multiples on speed pay-off.

At the grid-level of power, Cree has been working with Kansai Electric Power Company for the past two years, to produce high-power PIN diodes and power switches (MOSFETs) on SiC. Cree recently demonstrated the world's highest power (12.3-kV) SiC rectifier. That peak will continue to rise year by year, as Cree continues to push SiC crystal defect densities down. When the peak reaches grid power levels, stressed utilities (such as California's) will have compelling reasons to invest heavily in these devices; arrays of faster, electrically cleaner, high-power switches are the only devices that can be deployed directly and very quickly to increase the capacities of transmission grids (*October 2000 DPR*). Several dozen installations around the world already use grid-level powerchips, but use banks of silicon switch modules that remain physically enormous (semi-trailer sized) and prohibitively expensive. On SiC, the module sizes collapse an order of magnitude, capabilities increase–and prices drop sharply.

Beyond the Schottky lie the various device architectures in which the junction is created inside the semiconductor itself, by doping. As noted above, the first of two dopants can be introduced during the formation of a SiC epitaxy layer; the second dopant (needed to form a p-n junction) has to be blasted into the lattice with a rifle-like ion implanter. The damaged SiC lattice must then be healed in a high-temperature annealing process (one that operates at the very limits of conventional furnaces). With Si wafers, by contrast, the second dopant can be introduced by lower-energy implantation, followed by a simple, gentler diffusion process in a hot oven.

With SiC, the art lies in balancing the implantation energy (higher needed to obtain deeper junctions) with lattice damage and what repair is achievable via annealing (which is itself something of an art). Only a few players–at Purdue, ABB, Cree, Microsemi, and Infineon–appear to have mastered the art. Both Infineon and Microsemi expect to be releasing commercial PIN diodes on SiC next year. Infineon plans to manufacture its devices on Cree's 3-inch wafers, on a conventional 5-inch silicon fab line (with a couple of SiC-specific modifications). This fabrication of SiC devices will thus channel into the mature infrastructure of the silicon fabs, and piggyback on their steadily declining cost curve.

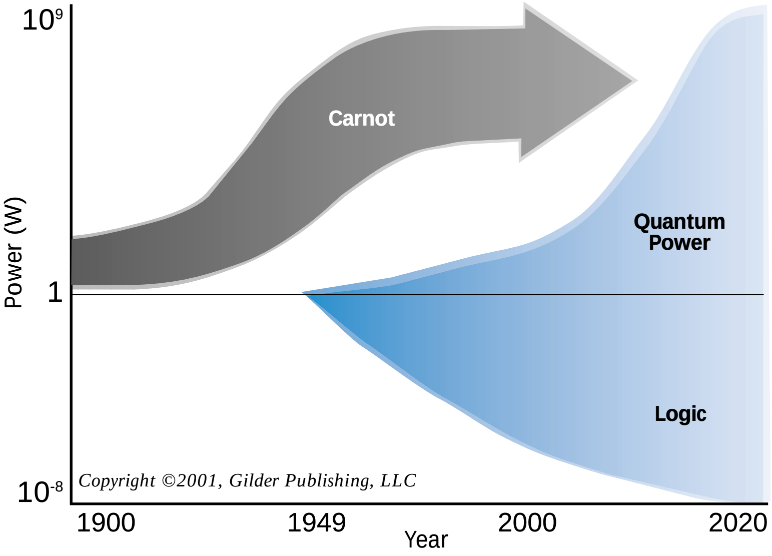
Quantum Amplifiers

SiC moves into transistors, next, the building block of all amplifiers. A transistor requires two junctions, not just one–which at least doubles the challenge.

The first architecture out of the gate here is a Metal Semiconductor Field Effect Transistor (MESFET)–an architecture already widely used in GaAs devices. The MESFET is a Schottky diode again, but this time the diode is acting as the gate of a transistor.

The challenge with all transistors is to handle more power and higher frequencies–and to handle the power uniformly across a wide range, so that the high notes aren't amplified more or less than the low. Silicon bipolar transistors do fine with high power up to MHz fre-

Quantum Power



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The first two decades of quantum power technologies were devoted mainly to logic; smaller and lower power leads to faster and smarter processors. But the pay-off for pushing quantum technology up the power curve is even larger as high-power quantum technologies take over the old economy's Newton-Carnot systems–i.e., most of our economy.

quencies, which means up to the lower end of the radio-frequency (RF) band. Silicon LDMOS architecture takes over for high-power applications up to 2 GHz. GaAS FETs are used in cell phones because they're exceptionally compact and can handle the high frequencies–but they can't handle much power. Only SiC MESFETs can provide high power (LDMOS-like), high-power density (greater than GaAs), and high linearity, in the 1 to 7 GHz range.

Cree brought just such a device to market early last year–a commercial MESFET fabricated directly on SiC. It is suitable for 2 to 6 GHz applications–at power levels comparable to those that LDMOS chips handle at lower frequencies–some five times higher power than GaS chips can handle. Here again, SiC solves the most pressing problems that most severely limit what the best existing amplifiers can achieve. Devices have to run very fast, and emit a lot of power from a very tight space and, as it happens, the SiC devices also require less peripheral circuitry. Cree's SiC MESFETs aren't yet price competitive with the outstanding silicon-based LDMOS amplifiers developed by Cree's own UltraRF. But when they reach that point, there will be no shortage of demand.

After that, it will be back to gallium. Good as the all-SiC MESFET is, the electron mobility in any silicon-based device, including SiC, is inherently slower than it is in gallium compounds–and electron mobility is what ultimately limits a transistor's top speed. So gallium-based compounds–GaAs in particular–are the primary materials used to reach frequencies above several GHz. GaAs can't stand much heat, however, and that sharply limits how much power it can handle in current designs. The solution is to combine gallium's raw electrical speed with SiC's extraordinary thermal speed– put an epitaxial layer of a gallium compound on a SiC substrate. GaAs won't grow well on SiC. But GaN can be made to–recall that that's how Cree makes its blue LEDs.

Gallium nitride presents many of the same materials-centered challenges as SiC–Cree is numbered among the small number of companies that have learned how to work with it at the scales required for quantum engineering. Cree's acquisition of Nitres strengthened its expertise in GaN-based devices, and the union soon culminated in the development of a High Electron Mobility Transistor, based on a junction between AlGaN and GaN on a SiC substrate. That device has achieved 35-GHz speeds, and set a world record power density (9.8 W/mm), some 10 times higher than any competitive high-speed GaAs device, and double the power density of high-power silicon LDMOS. A single GaAs chip at 10 GHz can hit 15 W of power; the first generation GaN-on-SiC is already 50 W. (LDMOS can hit 120 W from a single chip, but at a lower frequency.) And for RF engineers, tiny, high-power, high-frequency devices open doors to applications heretofore out of reach–from tiny radars to high-bandwidth wireless local loops.

Quantum Engineering

Transforming energy from one form to another is a messy business. In conventional systems it almost invariably involves multiples stages. Conventional electromechanical switches, for example, use electricity to move metal to switch electricity–a typically, slow, wasteful two-stage cushion shot of old-fashioned power control.

The invention of the semiconductor transistor marked a very fundamental advance–a leap from three-dimensional, thermal, light-bulb-like vacuum tubes into the recesses of atomic junctions, where electricity acts on electricity directly. Quantum technologies like the transistor transform energy not in volumes but on surfaces–atomic-scale junctions. Because they operate at these scales, they are blindingly fast and compact. And as device engineering advances, they become extraordinarily efficient.

At the outset, they can't handle much power–atomic-scale junctions are inherently frail, and pushing them up the power curve is very hard. That is why the first two decades of quantum power technologies were devoted mainly to logic. Information is inherently light; bits can be stored in picofarad capacitors; instructions can be executed in microwatt gates. Indeed, the smaller and lower power you can make its capacitors and gates, the faster and smarter you can make the processor run. To push quantum technologies down the power curve is to swim downstream–that is where they want to go anyway. We're not saying it's easy to etch millions of microwatt gates on a silicon wafer–just that putting a single megawatt gate on the same wafer is even harder, which is why the many low-power gates got built a decade or two before the single high-power one.

But the pay-off for pushing quantum technology up the power curve is even larger than the pay-off for pushing it down. Partly because the down-scale technologies depend on the up-scale–the new digital economy requires high-power quantum technologies behind it, to deliver high-9s power for 100-MW data hotels, or high-power laser light that can push data through a fiber that circles the globe, or high-power RF signals that can punch broadband data through the airwaves. And more importantly, because high-power quantum technologies are taking over the old economy too–the century-old industrial legacies of Thomas Edison, George Westinghouse, and Henry Ford. And those segments still represent most of the economy as whole. We love cyberspace, but at the end of the day we still drive real steel down the highway, and prefer to vacation in Tuscany.

Quantum technologies are essential for delivering high-9s power to the digital economy. They aren't quite as essential in old-economy applications–they're just vastly better than Newton-Carnot systems that they replicate. Compare today's light- and laser-emitting diodes, transistors, piezoelectric transducers, Seebeck-Peltier coolers, optical gyroscopes, and optical current and field gauges–all of which exploit quantum effects–to their traditional substitutes (like incandescent bulbs)–which don't. On the key metrics of power density, energy conversion efficiency, and raw speed, the quantum devices all perform vastly better. In another sphere, the move from vacuum tubes to transistors pushed the power of the computer processor up a billion-fold. The move from copper pipes to glass pushed bit-transmission rates up at least a million-fold. Quantum engineering of the painstakingly selected semiconductors propels similar improvements in the control and conversion of power.

Quantum engineering begins with the materials, and it is their quality that determines all that follows. The materials are plucked from favored columns of the Periodic Table, then united with atomic-scale precision: GaAs, GaN, AlGaAs, AlGaInP, GaInP, GaInAsP, InP, AlInAs, AlN, InN, BN, InSb, GaSb. Silicon is certainly not the last word in semiconductors, least of all in Powercosm applications. About 40 percent of silicon semiconductor output (by revenue) goes into the manufacture of power–not logic devices. About 95 percent of the GaAs goes to power. And 100 percent of the SiC.

And SiC is–as we have noted–a remarkable semiconductor. Because it is such a good conductor of both electricity and heat, it runs very cool, and at a relatively steady temperature. That is a very big virtue in itself. Heat is the pernicious enemy of semiconductor performance everywhere, because it introduces noise. SiC (largely) vanquishes heat. Which makes it enormously attractive even in its humblest application, as a quantum scaffold.

Scaffold applications of SiC, followed closely by smaller, lower-voltage SiC devices, have emerged first, because smaller areas of SiC crystalline perfection are easier to build than larger ones, and because micropipe leakage is quite sensitive to voltage. Higher power devices and higher voltages will inevitably follow, as Cree continues to push defect densities down. Others are counting on it to do so. In March 2000, Infineon quietly formed a wholly owned joint venture with Siemens (called “SiCED”) devoted exclusively to the development of new SiC devices. One prototype already developed: a 3500-V blocking voltage vertical junction FET.

Despite 40-plus years of post-transistor history, new semiconductors, and new applications for quantum technologies, are often greeted with deep skepticism, by engineers and companies rooted in more traditional materials and devices. There were GaAs skeptics in the 1980s too–the material seemed exotic, difficult, and daring, and it was, but today it is ubiquitous. In the early stages every new semiconductor always seems too difficult to work with, impossible to grow into defect-free crystals, just not worth all the trouble. Then it's not quite impossible, but too expensive. And then it gets cheap.

Nobody yet thinks SiC is an easy material–but everybody also recognizes that it has tremendously attractive physical properties, if only it can be shaped, bonded, and doped with enough precision to build useful devices. There are no certainties of any kind with leading-edge semiconductors, least of with a material as difficult as SiC–but SiC-based devices have already made the transition into real, pay-as-you-go commercial markets. SiC is so attractive that many more are certain to follow, if the engineers get their way. We think they will.

Peter Huber and Mark Mills
May 1, 2001

Power Panel Update

We added Calpine (CPN) to our Panel last February. We believe today, as we did then, that it's a great company that has made all the right calls on demand for grid-level power and the right technology for supplying it. But Calpine's business has become too enmeshed in California, and now national, politics for our comfort; this is a technology newsletter. At the other pole, tiny Manhattan Scientifics (MHTX) is pursuing a clever micro fuel cell architecture that we continue to believe has real promise. But, as we noted in September 2000 when we flagged MHTX, the company is an incubator. Incubators face as many non-technology uncertainties as do grid-level power companies. We have adjusted our Panel accordingly, to keep it squarely focused on companies whose futures center on viable commercial technology.

The Power Panel

Ascendant Technology	Company (Symbol)	Reference Date	Reference Price	4/30/01 Price	52wk Range	Market Cap	Customers
Powerchips:	Cree Inc. (CREE)	4/30/01	21.53	21.53	12.21 - 87.50	1.6b	Siemens, Sumitomo, Microsemi, Infineon, OSRAM, Kansai Electric Power
	Microsemi (MSCC)	3/30/01	28.00	38.36	18.94 - 52.75	531m	Lockheed Martin, Mitsubishi, Medtronic, Boeing, Motorola, Palm, Compaq
	Fairchild Semiconductor (FCS)	1/22/01	17.69	18.10	11.19 - 49.00	1.8b	GE, Emerson Electric, Rockwell, Siemens, Bosch, PowerOne, Artesyn, Invensys, IBM, Delta, Marconi
	IXYS (SYXI)	3/31/00	6.78	17.38	8.19 - 45.38	463m	Rockwell, ABB, Emerson, Still GmbH Eurotherm Ltd. (UK), Alpha Technology
	International Rectifier (IRF)	3/31/00	38.13	55.50	27.38 - 67.44	3.5b	Nokia, Lucent, Ericcson, APC, Emerson, Intel, AMD, Ford, Siemens, DaimlerChrysler, Bosch, Bose, Delphi, Ford, TRW
	Advanced Power (APTI)	8/7/00	15.00	15.23	8.44 - 49.63	129m	Alcatel, Ericsson, ITI, Power-One, Advanced Energy Industries, Emerson
	Infineon (IFX)	11/27/00	43.75	42.66	31.44 - 88.25	26.7b	Siemens, Visteon, Bosch, Mansmann-Sachs, Hella, Delphi
Network Transmission and UPS: High-temperature superconductor	ABB (ABB)	9/29/00	24.24**	18.19	16.68 - 18.30**	N/A	National Grid (UK), Microsoft, Commonwealth Edison, American Electric Power
	American Superconductor (AMSC)	9/30/99	15.38	15.60	10.75 - 61.88	316m	ABB, Edison (Italy), ST Microelectronics, Pirelli Cables, Detroit Edison, Electricite de France
Power: Heavy-Iron-Lite	General Electric (GE)	9/29/00	57.81	48.53	36.42 - 60.50	482.1b	Reliant Energy, Enron, Calpine, Trans Alta, Abener Energia, S.A.
	Catalytica Energy Systems (CESI)	9/29/00	12.38	16.50	9.13 - 20.94	203m	GE, Kawasaki Turbines, Enron, Rolls Royce, Solar Turbines
Distributed Power Generation Microturbines	Capstone Turbine Corp. (CPST)	6/29/00	16.00*	29.30	17.75 - 98.50	2.2b	Chevron, Williams ECU, Tokyo Gas, Reliant Energy
Fuel Cells	FuelCell Energy (FCEL)	8/25/00	49.88	68.90	18.00 - 108.75	1.1b	Santa Clara, RWE and Ruhrgas (Germany), General Dynamics, LADWP
Silicon Power Plants In-the-room DC and AC Power Plants	Emerson (EMR)	5/31/00	59.00	66.65	53.06 - 79.75	28.6b	Citicorp, Verizon, Nokia, Motorola, Cisco, Exodus, Qwest, Level 3, Lucent
	Power-One (PWER)	*(see below)*					
Motherboard Power Bricks, High-end DC/DC converters	Power-One (PWER)	4/28/00	22.75	17.51	12.06 - 89.81	1.4b	Cisco, Nortel, Teradyne, Lucent, Ericsson
Electron Storage & Ride-Through Ultracapacitors	Maxwell Technologies (MXWL)	2/23/01	16.72	15.70	12.06 - 22.56	156m	GM, Delphi, Visteon, Valeo, Onemocall, EPCOS, Boeing, Lockheed Martin, Rockwell
Flywheels	Active Power (ACPW)	8/8/00	17.00*	22.35	12.75 - 79.75	877m	Enron, Broadwing, Micron Technologies, PSI Net, Corncast Cable, ABC
	Beacon Power (BCON)	11/16/00	6.00*	4.00	3.90 - 10.75	169m	Century Communications, Verizon, SDG&E, TLER Associates, Cox Cable
Hydrogen Generation	Proton Energy Systems (PRTN)	9/29/00	17.00*	7.17	5.25 - 36.00	237m	Matheson Gas, NASA

Note: This table lists technologies in the Powercosm Paradigm, and representative companies that possess the ascendant technologies. But by no means are the technologies exclusive to these companies. In keeping with our objective of providing a technology strategy report, companies appear on this list only for the core competencies, without any judgment of market price or timing. Reference Price is a company's closing stock price on the Reference Date, the date on which the Power Panel was generated for the Digital Power Report in which the company was added to the Table. All "current" stock prices and new Reference Prices/Dates are based on the closing price for the last trading day prior to publication. IPO reference dates, however, are the day of the IPO. Though the Reference Price/Date is of necessity prior to final editorial, printing and distribution of the Digital Power Report, no notice of company changes is given prior to publication. Huber and Mills may hold positions in companies discussed in this newsletter or listed on the panel, and may provide technology assessment services for firms that have interests in the companies.

** Offering price at the time of IPO.*

*** Effective April 6, 2001, ABB was listed on the NYSE. The reference price has been adjusted to reflect this change. The 52-week range covers the period from April 6, 2001 only, the start date for high-low tracking on the NYSE listing.*