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The Tunable Powercosm

The intervening year has been no kinder to Intersil than to most of the rest of NASDAQ. But so far as Powercosm technology goes, Intersil has the goods.

Electricity is broadband power. A high-voltage electric line a few inches across conveys more power than the massive engine struts that link four giant turbines to the wings of a jumbo jet. Yet the moment you try to move power out of an electric wire and into a moving shaft (through a motor), or into another electric wire at a different voltage (through a transformer), the jumbo-scale hardware reappears – metal and more metal, in armatures, magnets, and coils of wire.

Think of them all as antennas and radios – though often, humongous ones. A radio projects power from an electric wire into whatever's nearby – the ether, a frozen pizza (in a microwave oven), or a magnet of one kind or another (in an electric motor or transformer). The out-of-the-wire power may be called a "magnetic flux," "radio wave," radar, light, or X-rays, and it can move atoms or bits, but so far as the basic physics goes, it's all the same.

The more power you want to project, and the more precisely you want to control it, the harder it gets. Until very recently, more power and more control invariably meant more jumbo-scale hardware. But another option has recently emerged: more silicon. Add silicon by the ounce, lose metal by the ton.

A small cluster of companies has been developing the silicon that can make that happen at higher powers, where the largest opportunity now lies. Four of them are already on our Power Panel: International Rectifier (IRF), Infineon (IFX), Advanced Power Technologies (APTI), and IXYS (SYXI). They are now joined by Intersil (ISIL), the company that invented the Insulated Gate Bipolar Transistor (IGBT) in 1982. Until 1999, Intersil remained buried inside Harris Corporation (HRS), the big electrical defense contractor. A management buyout, followed by an IPO in February 2000, gave Intersil new independence and innovative vigor. The intervening year has been no kinder to ISIL than to most of the rest of NASDAQ. But so far as basic Powercosm technology goes, Intersil has the goods.

Maxwell's Chasm

Broadband power – electricity – runs at the speed of light. Narrowband power, in the click-click bang-bang world of shafts, linkages, and pneumatic systems, runs at the speed of sound. These two worlds are thus separated by a performance chasm that is three to five orders of magnitude wide (see our special issue *Powerchip Paradigm II: Broadband Power*). Call it Maxwell's Chasm, after the man who worked out the physics that defines it.

To get orderly power – anything better than raw heat – out of current-carrying wire you have to oscillate the current, or the wire itself, or the wire's surroundings. The faster you oscillate electrons back and forth, the more power they project into their surroundings. James Clerk Maxwell wrote down the basic equations in 1873.

One way to oscillate them is to pump current into a naturally-resonant analog circuit. Heinrich Hertz did that in his laboratory in 1887, and Guglielmo ("G.M.") Marconi followed with the first practical "wireless telegraph" in 1895. Alternating-current motors were developed about the same time by Nikola Tesla (a contemporary and fierce competitor of Thomas Edison) and subsequently commercialized by George Westinghouse. From radio to electric motor, it's the same basic principle every time: pump current into an array of magnets and wires that have a natural propensity to oscillate at a particular frequency. Such systems work just fine – but they aren't flexible. They favor one particular frequency and speed. They're hard to "tune" and hard to control.

The other option is to control frequency digitally – to build up the current profile you want by brute, digital force. Put four (or more) switches in a suitable array, flip them back and forth just so, and you can convert just about any input power profile into just about any desired output profile. (If you can flip the switches fast enough to build the waveform you want, at the power levels you need.) Until very recently, you couldn't. The switches that could handle a lot of power were electromechanical, and therefore slow. The switches that were fast were semiconductors, that couldn't handle much power, at least not efficiently.

Now they can. The leading-edge manufacturers, Intersil prominent among them, are pushing the power-chip transistor, the IGBT, up the two-dimensional performance curve – higher power and faster switching speeds. The inevitable result: IGBTs are progressively taking control of just about every system that produces or consumes significant amounts of power.

The Distant Drummer

Most of the electrical world is tuned to just two stations on the dial. One is way off to the left – no frequency at all, *i.e.* flat-line direct current. The other is at 60 Hz, the ubiquitous frequency of the U.S. power grid. One station accommodates the twenty-first century smartchip. The other plays only nineteenth century tunes, to a rhythm established a century ago by Westinghouse, Telsa, and their pioneering colleagues.

The DC station exists for a very good reason. A bit exists only so long as there are electrons around to define it. If the electrons disappear, however briefly, the bit does too, and it doesn't come back. AC power "disappears" twice every cycle – which means that 60 Hz AC power would wipe out every bit in a Pentium 120 times per second. Frequency is the enemy here; arrays of power-conditioning electronics are deployed to make sure that no hint of "alternating" corrupts the flow of current to the microprocessor, not 60 Hz AC, nor any of the other spikes, blips, dips, sags, and longer interruptions that so often hitch a ride on the 60 Hz train.

The grid's clock speed, however, has been pegged at 60 Hz for no very good reason at all. We owe that specific number to the state of the art in mechanical engineering around 1891, when the first AC generators and motors were being built. Westinghouse made a reasonable, practical call about how to build a functional steam turbine and AC generator with the technology he had at hand. Europe landed at an equally arbitrary 50 Hz instead. At least two dozen other frequencies were tried too, including 20, 25 and 33 1/3 Hz, and some survive to this day in isolated, off-grid applications. The huge motors used to roll very heavy steel plates through old-style steel mills ran better at 25 Hz (so did the ubiquitous nineteenth century electric trolleys). So the mill owners and trolley operators built their own facilities to generate it.

But once Westinghouse had chosen his cadence for the public grid, each successive generator or motor linked to it had to stay in tune with all the older ones already on it. All had to push and pull in synchrony, or suffer terrible consequences. So rigid was the 60 Hz cadence that wall clocks in offices and classrooms could maintain near perfect time by simply locking a tiny synchronous motor to the grid, and counting cycles. To this day, new generators that connect to the grid's gigawatts have to fall into exact step with it, or risk destruction. A Capstone (CPST) turbine *(July 2000 DPR)* spins a shaft at 1600 Hz (96,000 rpm) and produces AC power of the same frequency from its generator; an array of electronics built into the unit convert the power to 60 Hz AC (or 0 Hz DC). An Active Power (ACPW) flywheel *(August 2000 DPR)* spins at 125 Hz (7,500 rpm) when at full speed, but begins slowing down as soon as you draw on it for power; the generator attached to it therefore produces AC power anywhere between 250 Hz and 1,000 Hz, out of which the unit's electronics must rebuild a steady 60 Hz output. An American Superconductor (AMSC) Superconducting Magnetic Electric Storage System (SMES) *(November 2000 DPR)* and a FuelCell Energy (FCEL) molten carbonate fuel cell *(September 2000 DPR)* both create DC power; elaborate electronics are required to interface these units with the 60 Hz AC universe that surrounds them.

The Well Tempered Clavier

But 60 Hz is like the one-size-fits all Mao jacket in a People's Republic of Arbitrary Uniformity. Nothing much wrong with it, really, except that one size *doesn't* fit all. No single clock can or should govern the enormously varied world of atoms, electrons, and bits. The challenge is to deliver tunable power and variable bandwidth, to transform clock speed from master to servant.

For powering a Pentium, 0 Hz is a whole lot better than 60 Hz. To project power through the ether from a radio or television, you need power beginning in the dozens of kHz and up (your AM radio tops out at 1,500 kHz). The new 3G broadband wireless systems operate around 2,500 MHz. The optimum "clock speeds" of mechanical systems range all over the map. In current

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designs, for example, a typical car engine red-lines somewhat below 100 Hz (6,000 rpm). The alternator or next-generation integrated starter-motor *(see December 2000 DPR)* will convert that power into a widely varying AC frequency – so the power electronics have to bridge between the varying mechanical clock speed and the emerging 42 V DC bus.

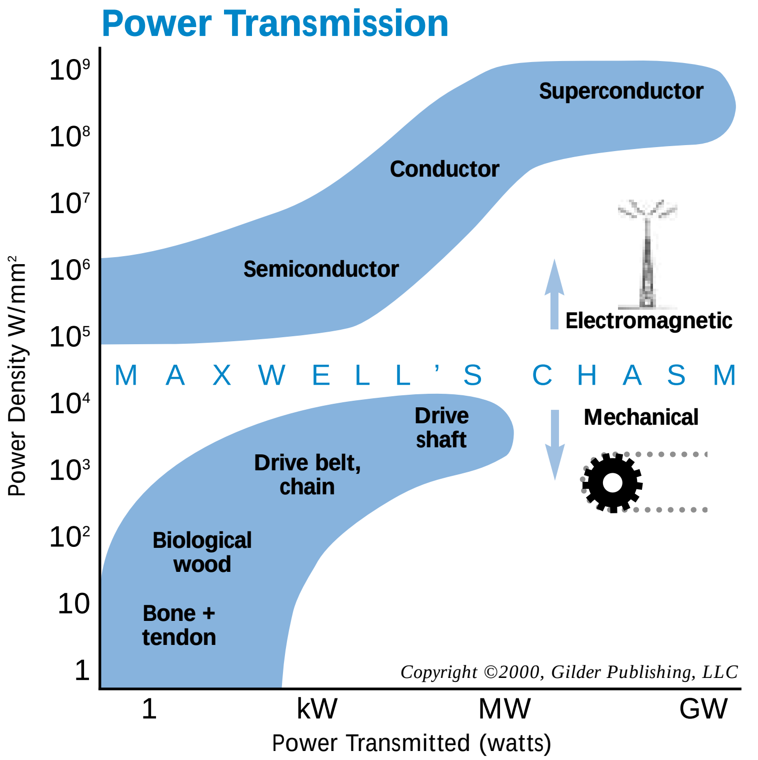
As a general matter, the higher the clock speed of a mechanical or electrical system, the higher its power density. Very high shaft speed (5,000 to 10,000 rpm) is what makes turbines compact enough to power a jumbo jet. An electric motor can be shrunk almost indefinitely by boosting the AC frequency of the electrical current that feeds it. By doing just that, Satcon's (SATC) high-performance motor group, Magmotor, makes a 100 kW motor that weighs in at 45 pounds, spins at 1,500 Hz and is the size of a large coffee can; it delivers more power than a standard 600-pound 60 Hz motor the size of a trash can. Boosting frequency shrinks electrical transformers in just the same way — that's why a 50 to 150 kHz AC subsystem gets buried smack in the middle of the Power-One (PWER) or SynQor brick on a Sun (SUNW) or Cisco (CSCO) motherboard *(See May 2000 DPR)*. Just raise the frequency, nothing more, and you can pull more power out of the wire, without using more wire. James Clerk Maxwell says so.

Gaining control over frequency is likewise the key to controlling power itself. The wider the range of frequencies you can shape, the more precisely you can shape the entire power profile. The underlying theorem was worked out in 1822 by the French mathematician Joseph Fourier – any curve, no matter how weirdly shaped, can be expressed as the superposition of a series of smooth sinusoidal curves of increasing frequency.

It isn't easy to control frequency, however. Radio receivers are highly tunable (10 kHz to 10 GHz) – but they only handle microwatts. Special-purpose, limited-range (or single-frequency) power tuners have been designed for radio and television broadcast stations, radar systems, and microwave ovens, for motherboard bricks, and for precision induction furnaces, for the systems used to "dry" etch silicon wafers, and for the variable-frequency-drive motors that have begun to be produced in significant numbers in the last decade or so. But the further you move up the power curve, the harder the tuning gets.

So for the heavy lifting, it was generally easier (until recently) to stick with the 60 Hz waves and control current levels (or, less efficiently, voltage levels) instead. That almost always meant using more metal — more turns (i.e. longer wires) in the transformer or motor, and fatter wires that could carry more current. The only other important alternative was to change the electrical properties of the materials themselves, by using exotic steels, rare-earth magnets, and (most recently) ceramic superconductors. Piling on wire – the "more motor" approach — has likewise been the main way to improve control. Use multiple tiers of wiring in the motor, or multiple motors.

But however cleverly engineered, these are all just different ways of submitting to the ghost of George Westinghouse. They accept the arbitrary 60 Hz clock speed as immutable, and proceed from there.



Maxwell's Chasm separates broadband power electricity from narrowband power in the click-click bang-bang world of shafts, gears, linkages, and pneumatic systems. To project power across the divide, you have to oscillate the electric current. In a radio, transformer, generator, or electric motor, it's the same basic principle every time: move power across the chasm by oscillating (i.e., alternating) the current. To transmit more power across the divide, using less wire, boost the AC frequency.

Power and Frequency

Though invented much earlier, the semiconductor powerchip came of age in the 1990s, a decade or so after the microprocessor smartchip. Many different powerchip architectures are now widely used, identified by an alphabet soup of acronyms: MOSFET, BJT, FRED, SCR, GCT, GTO, MCT, and IGCT. MOSFETs play a very important role in a wide range of low- to medium-power applications. IGBTs will occupy center stage in the high-power tunable Powercosm.

Intersil invented the IGBT in 1982 – just four years after International Rectifier had invented the MOSFET. The IGBT's architecture permits the handling of both high voltages (up to 4 kV in the latest generation of devices) and high currents (thousands of amps at 100 A/cm^2), which together mean high-power. A typical high-voltage MOS-

FET, by contrast, is limited to about 1000 Volts and 20 A/cm^2. All the while, the IGBT, like the MOSFET, is a *voltage*-controlled, not a *current*-controlled device. What that translates to, in practice, is a device that can be switched at very high speeds. Current-controlled devices, by contrast, dissipate too much power in each switching cycle to be pushed to very high speeds.

The IGBT is a perfect compliment to the smartchips needed for the intelligent control of broadband power

Until 1982, current-controlled devices were the only ones that could handle high-power. Variations of the basic silicon controlled rectifier (SCR) were used to control grid-level power flows, as well as very big industrial motors, mining trucks, and trains. Measuring up to six inches across, and a fat 1,500 microns thick (nearly triple that of conventional substrates), the single-gate SCR can handle enormous currents and voltages – if kept cool. The SCR remains, for now, the device of choice in ultra-high-power applications, above about 10,000 horsepower in motor control, or above 10,000 kW in grid applications. But it's much too slow, cumbersome, and electrically inefficient to serve as the ubiquitous building block for the tunable Powercosm.

By combining the power handling capabilities of a bipolar transistor with the high-speed capabilities of the MOSFET, the IGBT marked a major milestone in the pursuit of the highly tunable power. MOSFETs could handle a wide range of frequencies, but only a limited range of power. The SCR could handle the power, but only a limited range of frequencies. The IGBT could handle both.

Also, IGBT designs have improved rapidly. Current-handling capabilities have increased fourfold since 1982 (now about 1,200 A). Voltage-handling capabilities have more than doubled in the 1990s, to about 4 kV. The time it takes to turn off an IGBT (i.e. to stop the current flow through it) has dropped from twenty-fold, to under 100 nanoseconds in Intersil's latest design. Switching capacitance – which determines how much power is dissipated each time the IGBT is switched — has plummeted. As a result, maximum switching frequencies speeds have risen rapidly. They started at 2 to 3 kHz in the early 1980s; IRF introduced its 150 kHz "WARP Speed" device in 1999; and Intersil raised the bar with the introduction of a 200 kHz family in early 2000.

The IGBT's ability to tune from tens-of-kilowatts to megawatts of power, from 0 to as high as 200 kHz, now places the IGBT smack in the middle of the important and ubiquitous sources of real world demand for highly-tunable power.

The MOSFET already delivers tunable power to low-power applications, those typically below 100 Watts, and rarely beyond 750 Watts (roughly 1 horsepower). At the opposite end of the power curve – in 4 MW electric locomotives, or 10 MW steel rollers, or local power grid substations — powerchip solutions are often custom-tailored for the narrow range of operation in which very large systems run most efficiently. The largest market is in the middle. In digital suites, smaller commercial buildings, and wireless transmitters, with loads in the 20-200 kW size range where many systems are now being deployed to deliver short-wire backup power to such locations – Capstone's microturbine (30 and 60 kW), Active Power's flywheel (250 kW), FuelCell Inc.'s molten carbonate fuel cell (250 to 1,000 kW), Power-One's silicon power plants (750 kW). The middle market is also filled with countless industrial engines, motors, robots, refinery pumps, welding systems, and lasers that operate in the 75 to 750 kW range. And in Detroit, where a car engine peaks at about 100 kW (130 hp). The MOSFET remains the powerchip of choice in the near-term applications for the automotive platform *(December 2000 DPR)*. But the IGBT will rule in the longer-term electrification of higher power components of the auto drive train – suspension, camshaft, valvetrain, and the wheels themselves.

IGBTs can now span just the right frequency range, too. As a rough rule of thumb, the powerchip must run at least an order of magnitude faster than the clock speed of the mechanical components it controls. Clock speeds in the mainstream of the mechanical world typically run from the 100 Hz to 1,000 Hz for shaft speeds of engines and turbines, to the tens of kHz for precision direct-drive motors and planar transformers. Even the slowest IGBTs can reach 10 kHz, and the fastest now readily push up to ten times that level.

Finally, the IGBT is a perfect complement to the smartchips needed for the intelligent control of broadband power. The IGBT's voltage-controlled gates draw very little current – typically only a few milliamps. IGBTs can thus be controlled directly from the low-power output of the smartchips, without any intermediate power amplifier. That greatly reduces size, complexity, and cost.

Intersil

The company was spawned in RCA's Solid State Division. Two of its original scientists, C. Frank Wheatley and Hans Becke, filed the first patent for the basic concept of the IGBT in 1980. The patent was issued on December 14, 1982. That same day, by coincidence, General Electric (GE) presented the first formal paper describing its own, independent development of an IGBT-architecture device. The lawyers might be fighting still, but for the fact that GE acquired RCA's semiconductor group a year later.

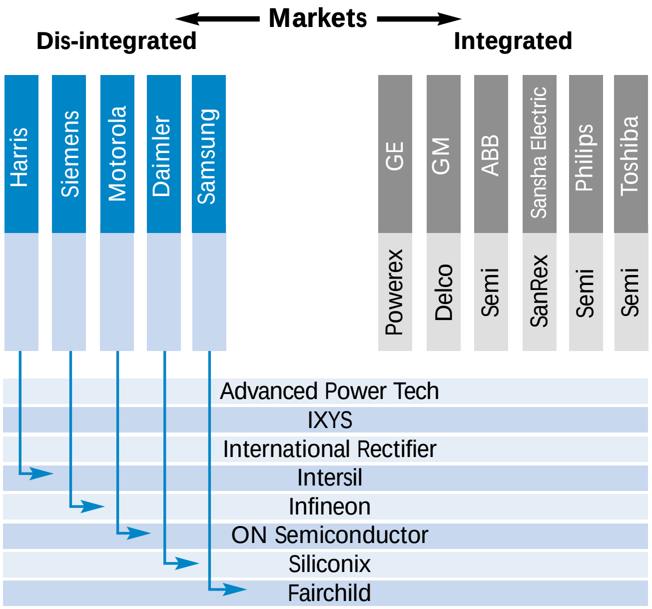
When GE set about divesting all non-core activities in 1988, Intersil went to Harris Corporation, the big electrical defense contractor. Harris, in turn, acceded to a management buyout in 1999, capitalized by Citicorp's (C) venture group. A smaller piece of the operation, centered on very-high-power MCT powerchips, became the still-private Silicon Power Corporation *(See April 2000 DPR)*. Intersil went public in February 2000. Citicorp still owns 63 percent.

Intersil clearly ranks as one of the leading manufacturers of highly tunable, high-power powerchips. The company currently owns some four-dozen IGBT patents, and plows 12 percent of sales back in to R&D. About one-third of Intersil's $600 million business is in power, and much of that in powerchips, IGBTs in particular. Over 40 percent of the company's revenues come from silicon chips (of one kind or another) used in industrial and automotive applications. Intersil operates three silicon manufacturing lines; their powerchip operation in Mountaintop, PA can produce 800,000 wafers per month (two other lines in Ohio and Florida produce ICs and analog chips). Intersil also manufactures wireless LAN chipsets (used by 45 telecom providers, and currently the company's fastest growing segment), subscriber-line circuits used to interface individual phone lines with central-office phone switches, and the analog ICs used on motherboards to manage power for one-third of all Pentiums, and half of all Athlons.

The company began developing powerchips for Detroit (and its foreign competitors) twenty-five years ago. Its mid-speed IGBTs are now widely used in car ignition and fuel injection systems; its MOSFETs, in antilock brakes. Intersil has sold 60 million IGBTs for ignition systems alone. Clocking in around 50 kHz, even these lower-speed IGBTs are quite fast enough to be used in a broad range of industrial motor drives – and are indeed so used by GE, Rockwell (ROK), Baldor (BEZ), Danfoss (SHS), Ametek (AME) and other major motor manufacturers. Intersil is working closely with motor control designers at Bosch and Siemens (SIE). The world's fastest electric drag racer (200+ mph, made by EVCL) uses Intersil IGBTs in its drive train. Roughly 40 of Intersil's IGBTs are sold to the motor/industrial market; the rest go to the rapidly growing market for power conversion systems used in the telecom/datacom market *(see May 2000 DPR)*.

In its many years developing IGBT technology for automotive ignitions, Intersil has found ways to overcome one of the IGBT's core weaknesses, its inherent vulnerability to voltage surges. As a result, Intersil's IGBTs are now robust enough for widespread use in fan motors – a huge market in itself – and a wide range of other motors, arc welders, and UPS's. (Severe voltage transients occur in the Telecosm as often as elsewhere; they arise whenever large racks of smartchips shift abruptly from idle into high gear; such changes create harmonics, and thus voltage surges in the labyrinthine wiring upstream.) IBM has developed new high-speed cooling fans for mainframes using Intersil IGBTs. Other Intersil customers include Power-One, Emerson Electric (EMR), Lucent's (LU) power group (now part of TYCO (TYC)), Invensys, Delta (DAL), Marconi (MONI), Magnetek (MAG), and Lambda. In July last year, Artesyn (ATSN) introduced a new line of ultra high-9s power systems for the expanding RAID market, built around the latest Intersil IGBTs.

Powerchips: Captive and Free



The powerchip will impel a convulsive restructuring of atom movers, just as the smartchip restructured the bit movers. The powerchip operations of the old engine and electric companies are being spun out, and replaced by independent outsiders. A roll-up of powerchip companies is then likely, with a handful of Intel- and AMD-like giants emerging at the end of the process.

As noted, the IGBT is, in effect, a marriage of low-power, high-speed MOSFET with low-speed, high-power bipolar transistor. Its top speed is determined by the speed the device can be turned on, and then off – two separate problems. Turn-on speed is dominated by the structure of the chip's top surface, where a high-speed MOSFET-like design is used. Turn-off performance depends mainly on what happens lower down, inside the silicon. And wherever they're made, design changes made to boost overall speed cannot unduly boost the device's on-resistance. Designing fast, high-power IGBTs thus presents a series of very delicate trade-offs.

Intersil has mastered the art. In early 2000 the company introduced a second generation of high-speed IGBTs with a gate charge 60 percent lower than its predecessor. Lower gate charge raises efficiency, which in turn raises the top speed at which an IGBT can be switched. The critical turn-off time on the Intersil IGBTs is under 100 ns – at least 50 percent faster than anything else currently in the market. Intersil now sells a 200 kHz IGBT, the fastest in the industry; IRF, the former leader, peaks at 150 kHz. (Expect IRF to respond in short order, however.)

In the standard IGBT architecture, multiple MOSFET-type cells are etched on to the top surface of the chip. Instead, Intersil uses a patented stripe geometry, based on the company's patented UltraFET MOSFETs (a similar concept to that used by UltraRF (SPCT) for its LDMOS radio frequency chips *(November 2000 DPR)*). By substituting stripes for a large number of individual, rectangular cells, Intersil lowers the number of corners on the powerchip surface – the corners, it turns out, are another place where the tail currents tend to either linger, or start flowing prematurely. This architecture also allows more precise, and shallower doping of the top structure of the device. That lowers on-state resistance in the top part of the IGBT, which then allows Intersil to increase turn-off speed by doping the silicon lower down in the chip in a way that somewhat raises on-state resistance.

Intersil's patented Stealth Diode performs dramatically better than most; good enough to eliminate the need for additional components normally required to filter out EMI

Stripes, and the precise, shallow surface doping are more difficult to manufacture, however. Intersil appears to be the only IGBT manufacturer that is currently etching its powerchips with the more sophisticated and expensive multi-mask process that has for some time been the standard in smartchip fabs. A single mask can't be positioned finely enough to align small features very accurately across an entire surface of a large five-inch to eight-inch silicon wafer. The solution is a "stepper" process by which the mask is aligned multiple times, stepping across the wafer's surface. Superior manufacturing processes that lower defect density will likely be the key to pushing up IGBT performance from here on out.

With long experience serving one very demanding (automotive) end of the IGBT market, Intersil excels at this kind of painstaking, sweat-the-details engineering. Two years ago Intersil's Mountaintop facility was the world's first fab to use eight-inch wafers for MOSFETs and six-inch wafers for IGBTs. With powerchips, as with smartchips, larger-diameter wafers push down device costs by yielding more devices per wafer. Intersil's Mountaintop fab achieves a remarkable 98 percent yield. The newer equipment can also handle thinner wafers (10 mil instead of 14 mil) which make possible the manufacture of IGBTs with lower thermal resistance, and thus higher power performance, at lower cost.

Intersil has also largely overcome a final, refractory problem in the pursuit of higher switching speed – the high-frequency electrical noise that is inevitably generated whenever a current is switched rapidly in any real world circuit. However fast (i.e. digital) the IGBT itself may be, the control circuits and wires connected to it still have their own inherent inductance and capacitance, and the switching thus inevitably sets up secondary harmonics in the system. The problem is called conducted "electromagnetic interference" (EMI). Diodes in the control circuit are a primary source of EMI; Intersil's patented Stealth Diode performs dramatically better than most; good enough to eliminate the need for additional components normally required to filter out EMI.

By pushing IGBTs up the speed curve, Intersil gains two key competitive advantages. Sufficiently fast IGBTs can use the same control/drive circuits already developed and optimized for MOSFETs. This is important, because real world deployment of digital-electrical drives depends so heavily on the smartchip systems behind them. And as they get faster, IGBTs become increasingly competitive with MOSFETs themselves. Until very recently, the only way to handle higher powers at high speeds was to use an array of MOSFETs in parallel. If they run fast enough, IGBTs can handle the same power with one-quarter (or less) the powerchip silicon area, and at substantially lower total cost (and at higher 9s, since fewer components, all things being equal, are more reliable). The total number of components used in a high-power digital drive typically drops four-fold when state-of-the-art IGBTs replace MOSFETs; efficiency rises substantially, so the units run a lot cooler. All of which translates into smaller footprint, better performance, more reliable operation, and lower overall cost.

Dis-Integrating the Competition

Four of Intersil's main competitors already appear on our panel; several other larger competitors don't, and won't, at least not under their current integrated nameplates.

Until quite recently, higher power, higher frequency powerchips were developed under the wings of giant companies established in other, vertically related lines of business. They were giant electric or motor companies, by and large: GM (through Delco Semiconductor), ABB (ABB Semiconductors), Sansha Electric (SanRex); Toshiba (Toshiba Semiconductor); Fuji (FELTF) (Fuji Electric), Samsung (Samsung Semiconductor); Philips (Philips Semiconductor). General Electric and Westinghouse formed Powerex in 1986; Mitsubishi then replaced Westinghouse in the venture, and Powerex now serves as a Mitsubishi captive outlet for power silicon. Such ventures evolved organically, inside the businesses that foresaw possible uses in the (relatively) narrow range of applications that defined their already established businesses.

When it comes to powerchips, however, we don't believe that such corporate structures will last. They certainly didn't for smartchips. Many of the key building blocks of modern computing were likewise developed by the integrated giants of a prior age. The Bell System invented the transistor, because it needed a better technology for its telephone switches; IBM (IBM) pushed forward the technologies of solid-state memory and disk drives, because it needed them for its "business machines." The technologies emerged from under the wings of their leading-edge users. But as Andy Grove described in *Only the Paranoid Survive* (1996), the integrated circuit ended up transforming not just particular products, but the entire structure of the industries that built them. Sperry Rand, Burroughs, Wang, DEC and even AT&T's (T) manufacturing arm Western Electric, gave way to a new generation of horizontally stratified suppliers of chips (Intel (INTC)) and software (Microsoft(MSFT), Oracle ORCL)), and system integrators (Compaq (CPQ), Dell (DELL)). IBM itself was forced into a wrenching reorganization that unleashed IBM's components manufacturer to compete directly against other divisions within the company.

We believe that the coming of age of the integrated power circuit – the powerchip – will impel an equally convulsive restructuring of atom-moving industries. However technically excellent their operations, the powerchip businesses spawned by the old engine and electric motor companies will be spun out, or they will be overtaken by independent outsiders. When a radically new technology comes along that is deeply disruptive across a broad range of old industries, it inevitably emerges as a new industry in its own right. It does not remain a captive of the old guard.

The highly-tunable, high-power powerchip is just such a technology. What is rapidly emerging now is the integrated, general purpose, power processor. It will indeed transform the design and manufacture of both combustion engines and electric motors, and the old guard was quite right to take the lead in developing the technology. But powerchips are destined to find their way into just about everything that moves, from weightless bits at one end to hundred ton high-speed trains at the other, with furnaces, arc welders, passenger cars, and 3G wireless base stations in between. Very powerful economies of scope and scale will operate in the powerchip's design and manufacture. Developers will have to collaborate closely with a broad range of suppliers on one side, and of customers on the other – just as Intel does. DaimlerChrysler (DCX) isn't going to rely on GM for its mission-critical powerchips, nor is Siemens going to rely on GE, or even Powerex. They will rely instead on companies with an Intel-like focus on the powerchip itself.

This is why we expect the powerchip industry will undergo a radical restructuring in the next few years. Others will follow the road that Intersil has already traveled, from small division within a huge diversified parent (like GE or Harris) to dis-integrated powerchip specialist. A roll-up of powerchip companies is then likely, along with a handful of Intel- and AMD-like giants emerging at the end of the process.

The first stage of that process is already well under way. Samsung spun off its powerchip business (focused on the lower-power end) to Fairchild Semiconductor (FCS) in April 1999. Motorola (MOT) spun its powerchips off with the ON Semiconductor (ONNN) IPO in 1999. Daimler-Benz (DMJ) sold its 80.4 percent interest in Siliconix (SILI) to Vishay Intertechnology (VSH) in March 1998. (SILI likewise focuses on the lower end of the power curve.) STMicroelectronics (mainly a smartchip company along with some lower-power powerchips) emerged in 1987 from the combination of the semiconductor portions of the French and Italian state defense and telephone corporations respectively (20 percent remains owned by the two state entities).

And the most promising high-power IGBT manufacturers are already established as independent entities. International Rectifier is one of them, but its sales are stronger in lower-power MOSFET technologies. For a time, IRF overtook Intersil with higher-power and higher-speed IGBTs; but Intersil has since caught up again and recently raised the performance bar. Then there's IXYS (in which, portentiously, ABB has a minority stake) with its aggressive technical and business performance. Another is Advanced Power with a strong high-power focus, which went public last September. Infineon is a fourth – spun out from Siemens, the giant German electric company, in 1999, just three years after Siemens itself had acquired powerchip powerhouse Eupec. (Eupec is now wholly owned by Infineon.)

As recently as a few years ago, the leading providers of mission-critical, high-9s power were the manufacturers of telecom equipment – and understandably so, because the leading consumers of that kind of power were telecom-service providers. Today, however, high-9s power is needed throughout the digital economy – and its supply is centered in new families of providers of general-purpose powerchips (IXYS, IRF, Infineon, APTI, Intersil), bricks (Power-One, SynQor), silicon powerplants (Power-One, Emerson), flywheels (Active Power, Beacon (BCON)), turbines, (Capstone, GE), and fuel cells (FuelCell Energy), and so forth. High-9s electrical power used to be a niche market, a specialty input required by only a small cluster of specialized services. It is now fast emerging as a general purpose fuel, essential to General Electric, Siemens, Rockwell, Baldor Electric, Lucent, Alcatel (ALA), Nortel (NT), BMW, DaimlerChrysler, and countless other manufacturers, who are now incorporating tunable broadband, power into everything that moves.

High-speed, high-power IGBTs are the key building blocks of the tunable Powercosm. They make power supplies, transformers, motors, and engines smaller, faster, more precise, more controllable, and cheaper. Intersil's IGBTs rank among the best.

Peter Huber and Mark Mills
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The Power Panel

Ascendant Technology	Company (Symbol)	Reference Date	Reference Price	12/29/00 Price	52wk Range	Market Cap	Customers
Powerchips: Insulated gate bipolar transistors (IGBTs)	Intersil (ISIL)	12/29/00	22 15/16	22 15/16	15 15/16 - 85 1/4	2.3b	GE, Emerson Electric, Rockwell, Siemens, Bosch, PowerOne, Artesyn, Invensys, IBM, Delta, Marconi
IGBTs	IXYS (SYXI)	3/31/00	6 25/32	14 5/8	2 15/16 - 45 3/8	387m	Rockwell, ABB, Emerson, Still GmbH Eurotherm Ltd. (UK), Alpha Technology
	International Rectifier (IRF)	3/31/00	38 1/8	30	23 1/2 - 67 7/16	1.9b	Nokia, Lucent, Ericcson, APC, Emerson, Intel, AMD, Ford, Siemens
	Advanced Power (APTI)	8/7/00	15	12 5/8	11 1/4 - 49 5/8	106m	Alcatel, Ericsson, ITI, Power-One, Advanced Energy Industries, Emerson
Power MOSFETs	Infineon (IFX)	11/27/00	43 3/4	36	34 3/4 - 88 1/4	22.1b	Siemens, Visteon, Bosch, Mansmann-Sachs, Hella, Delphi
	International Rectifier (IRF)	*(see above)*					DaimlerChrysler, Bosch, Bose, Delphi, Ford, TRW
Ghz Power RF Powerchips: LDMOS	UltraRF (SPCT)†	10/31/00	11 3/4	16 1/4	11 1/8 - 31 3/4	179m	Nokia, Samsung, Lucent LGC, Alcatel, Nortel
Network Transmission and UPS: High-temperature superconductor	ABB***	9/29/00	96 61/64	106 5/8	N/A	N/A	National Grid (UK), Microsoft, Commonwealth Edison, American Electric Power
	American Superconductor (AMSC)	9/30/99	15 3/8	28 9/16	19 5/8 - 75 1/8	577m	ABB, Edison (Italy), ST Microelectronics, Pirelli Cables, Detroit Edison, Electricite de France
Power: Heavy-Iron-Lite	General Electric (GE)	9/29/00	57 13/16	47 15/16	41 5/8 - 60 1/2	475b	Reliant Energy, Enron, Calpine, Trans Alta, Abener Energia, S.A.
	Catalytica Energy Systems (CESI)	9/29/00	12 3/8	17	9 1/8 - 19	362m	GE, Kawasaki Turbines, Enron, Rolls Royce, Solar Turbines
Electron Storage & Ride-Through Flywheels	Active Power (ACPW)	8/8/00	17**	21 15/16	12 3/4 - 79 3/4	851m	Enron, Broadwing, Micron Technologies, PSI Net, Corncast Cable, ABC
	Beacon Power (BCON)	11/16/00	6**	10	6 1/8 - 10 1/8	386m	Century Communications, Verizon, SDG&E, TLER Associates, Cox Cable
Hydrogen Generation	Proton Energy Systems (PRTN)	9/29/00	17**	10 1/2	5 1/4 - 36	347m	Matheson Gas, NASA
Distributed Power Generation Microturbines	Capstone Turbine Corp. (CPST)	6/29/00	16**	28	17 3/4 - 98 1/2	2.1b	Chevron, Williams ECU, Tokyo Gas, Reliant Energy
Fuel Cells	FuelCell Energy (FCEL)	8/25/00	49 7/8	68 9/16	10 5/8 - 108 3/4	1.1b	Santa Clara, RWE and Ruhrgas (Germany), General Dynamics, LADWP
Micropower Nano-fuel cells	Manhattan Scientifics (MHTX)	8/25/00	2 3/4	2 1/2	1 7/32 - 5 1/16	N/A	Incubator (no customers)
Silicon Power Plants In-the-room DC and AC Power Plants	Emerson (EMR)	5/31/00	59	78 13/16	40 1/2 - 79 3/4	33.8b	Citicorp, Verizon, Nokia, Motorola, Cisco, Exodus, Qwest, Level 3, Lucent
	Power-One	*(see below)*					
Motherboard Power Bricks, High-end DC/DC converters	Power-One (PWER)	4/28/00	22 3/4	39 5/16	10 5/8 - 89 13/16	3.1b	Cisco, Nortel, Teradyne, Lucent, Ericsson

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 of the month prior to Digital Power Report 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.

** Catalytica (CTAL) spun off its Combustion Systems unit on December 13, 2000 into a new company called Catalytica Energy Systems Inc (CESI). According to the corporate release, each CTAL stockholder of record at the close of business on December 15, 2000, will receive $10.41 in cash per share owned, and 0.16547 of a share of CESI. We have revised all price information as well as the reference date to reflect this change.*

*** Offering price at the time of IPO.*

**** ABB's plans to list its stock on the NYSE have been "delayed due to the volatility of the U.S. equity markets." ABB plans to provide further information on this issue in February.*

† Cree Inc. (CREE) closed its acquisition of UltraRF from Spectrian for 1,815,402 shares of Cree common stock, additional Cree shares worth $30 million in cash, and a two-year agreement to supply Spectrian with chips. The acquisition was finalized after the official close of this month's Power Panel.