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Powering RF Photons (II)

Within five years, the installed base for RF transmitters will increase ten-fold

We first wrote about radio-frequency (RF) powerchips in November 2000 (*Powering RF Photons*)—the high-powered silicon LDMOS chips that amplify "radio-frequency" (RF) currents to power levels of a hundred Watts or more. These high-frequency currents drive the antennas that punch out signals from a million base stations to reach a billion cell phones, along with millions of other wireless devices around the world. We now return to this subject to report on major advances in the power technologies responsible for the other half of the RF link—the powerchips that amplify the currents to dispatch the signals back to the base stations.

"Wireless" is certainly out of favor on Wall Street these days. No group of tech stocks was hammered much harder in 2001 and 2002 than those in the wireless telecom sector. It isn't hard to see why. Demand for new wireless services soared in the '90s, but by the end of the decade, too many service providers tried to grow too fast. Growth rates then settled down. Wireless networks, like others in the telecom sector, have high capital costs and relatively low marginal costs, so when industry capacity gets out ahead of demand, prices drop sharply, profit margins collapse, and companies with serious debt loads land in deep trouble. In some markets now, there's more capacity than demand.

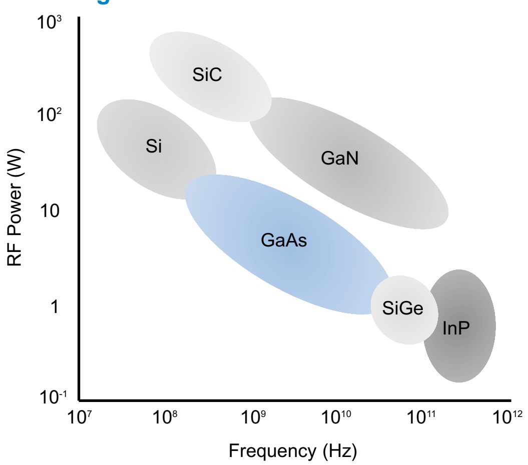
But this glut is a lot less serious than the one in long-distance fiber-optic markets, and will get worked off a lot faster. And the core technology that will propel the next wireless boom is just now coming of age. It's power technology—RF power. It cuts across lots of different platforms. And it's needed regardless of which company is providing the service, or whose nameplate is on the cell phone, wireless PDA, or wireless LAN, or which modulation scheme is being used to encode bits into the radio signal.

RF Micro Devices (RFMD) is the biggest pure-play supplier of RF powerchips. The company's stock price rose and fell with the bubble, but its technology has continued to improve rapidly through thick and thin. And its sales and revenues continue to rise too. The total number of chips and modules that it sold rose 60 percent in the last quarter of 2002 year-to-year, with revenues up 45 percent and a comparable increase in gross profit. RFMD is now the company best positioned to profit from the third great wave in RF power technology.

The Third Wave

Guglielmo Marconi built the first station, but Lee deForest provided the power that made the first wireless wave possible. Marconi's December 1902 transmission of the first commercial wireless signal (dispatched from Glace Bay in Nova Scotia to Cornwall, England) required a 160-foot-long building. Inside was a single massive spark transmitter, which consumed several hundred kilowatts of power, generated by a dedicated coal-fired generator. Within a decade, however, the RF amplifiers in Marconi's stations were all being built around the three-wire vacuum tubes invented by deForest in 1906. They were far more compact and efficient, and thus much cheaper than the alternatives they supplanted. Today's huge radio and television broadcasting industry was made possible by the invention of those tubes as were all the smaller mobile radios that emerged during that era.

Figure 1. RF Power from Semiconductors



The far more compact and affordable wireless devices that are ubiquitous today required a second major advance in power technology to complement advances in digital logic—RF semiconductor amplifiers made from gallium arsenide (GaAs).

As we've described before, it was in 1995 that TRW developed the first commercially viable communication chip using GaAs heterojunction bipolar transistor (HBT) technology (*The Power of Millimeter Waves*, November 2001). TRW's R&D had been done for the military, which is in perpetual pursuit of more power in a smaller package. Unacquainted as it was with civilian markets, TRW opted to commercialize the new technology through a 1991 start-up—RFMD—in which TRW took a major equity stake. TRW earned well over $500 million on that deal, on the sale of their position in the years following the 1997 IPO; for its part, RFMD emerged as the world's leading manufacturer of GaAs RF powerchips (most notably aluminum gallium arsenide—AlGaAs) for cell phones. Today, RFMD's chips power the antennas in everything from cell phones, to wireless LANs, to Bluetooth-enabled hardware, and global positioning systems (GPS).

The third wave is imminent now

For RF amplifiers up to about 1 Watt (i.e., all cell handsets), GaAs is now the dominant working material. But for higher-power amplifiers (100W and up in base stations), the technology of choice, developed in the 1990s, remains a very clever amplifier architecture built on to plain old silicon—the LDMOS chip we wrote about in November 2000. (The company that impressed us then was UltraRF, which was part of Spectrian; Cree (CREE) purchased the UltraRF business in 2001, and Spectrian—a cell-tower RF amplifier company—was itself bought by Remec (REMC) in mid 2002.) Motorola, the dominant LDMOS manufacturer, pushed performance up and cost down enough to permit huge numbers of silicon LDMOS amplifiers to be used in wireless base stations.

From the first to the second wave, from tubes to GaAs semiconductors, the number of RF transmitters rose over a hundred-fold. The third great wireless wave that's now forming will be propelled by a third, quantum improvement in power amplifiers centered on new families of semiconductors. RF powerchips will get another ten times smaller and cheaper, and their penetration into things all around us will, ultimately, increase one hundred-fold again.

The third wave is imminent now, as RF powerchip designers begin to take full advantage of extraordinary advances in materials engineering pioneered by the manufacturers of semiconductors for digital logic. These technologies offer material purities, and material handling methods and tools, that are ten to a hundred times more capable than those available even a decade ago. Powerchip designers now also have access to vastly improved packaging technologies and materials. And the packages are almost as important as the powerchips when you're dealing with RF currents, because at RF frequencies everything in sight, including the connections and packaging materials, behaves as an electrically active part of the circuit.

In higher-power amplifiers (100W and up), gallium nitride (GaN) is now clearly the new material to watch. GaN has been in development for more than a decade, with substantial support from DARPA, the Pentagon's high-tech research arm, but only in the last few years has GaN emerged as a serious commercial possibility. Advances in epitaxial

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growth now allow manufacturers to grow GaN layers on a variety of substrates—several companies are growing usable GaN layers on sapphire, silicon carbide (SiC), or even pure silicon substrates. These GaN-on-a-substrate wafers already permit dramatic improvements in power at high frequencies. Designers of high-power RF circuits have long dreamed of building systems around these new GaN components; soon they will.

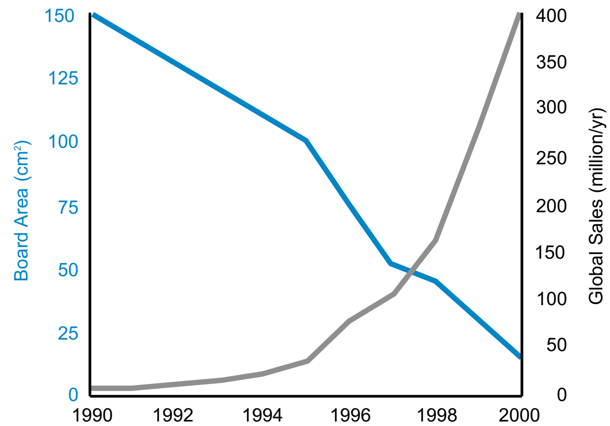
Each of the available GaN combinations has different strengths and weaknesses. GaN on sapphire is the poorest thermal conductor in the group, and it's available only in four-inch wafers. SiC is an excellent thermal conductor, but it's more expensive and still only available in smaller wafers. Silicon would be the lowest cost substrate, but its crystal structure doesn't match GaN's at all well, and that complicates things a lot.

For lower-power devices—in handsets and comparably sized devices—the big advances are coming from a different cluster of new material combinations and architectures—germanium layered on top of silicon (SiGe), for example, or indium phosphide (InP). IBM was the first to commercialize a SiGe process, in 1995; others have subsequently replicated it. The process combines the high-speed performance of germanium with the low-cost manufacturing processes of silicon wafers by layering the former on the latter. (SiGe devices can handle very high RF frequencies, but not much power.)

With the advances in materials, technologies, and tools, complete RF power systems have collapsed into single modules, and even on to single chips, eliminating hundreds of discrete components. RF power amplifiers that once occupied 300 mm^2 of board space disappear into a single 9-mm^2 package. So the curtain is now coming down on RF transmitters assembled on a board from discrete devices. Across the whole range of powers used in wireless communication, RF amplifiers are collapsing into a small set of fully integrated, sealed packages, and before long the entire cell phone's RF stages will be in a single package as well. Only industrial and other similar, ultra-high-power applications will continue to depend on discretes.

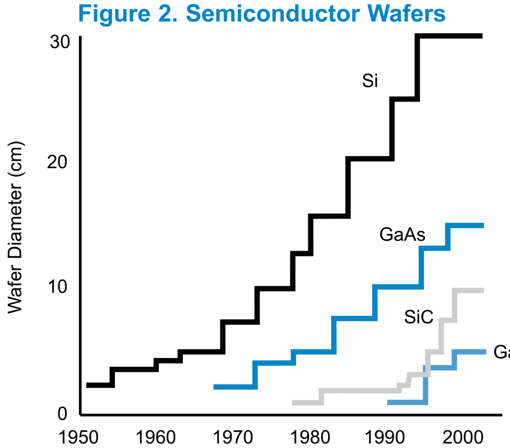
Thus, from terminal to base station, the performance of wireless amplifiers will improve by at least a factor of ten in the coming decade. Improvements that large presage the beginning of the third great wave of wireless expansion—every bit as big as the one made possible by deForest's tube, and then again by TRW's GaAs.

Figure 3. Cell Phones: The Collapsing Motherboard



Source: Kada, Morihiro and Lee Smith,"Advancements in Stacked Chip Scale Packaging," Pan Pacific Microelectronics Symposium Conference (January 2000).

Figure 2. Semiconductor Wafers



Source: "Wide Bandgap Semiconductors," *Proceedings of the IEEE* (June 2002); Weeks, Warren and Ricardo Borges, "Silicon Substrates Provide a Disruptive Technology for GaN," *Compound Semiconductor*, November 2001.

RF Micro Devices

William Pratt had been a general manager of high-speed analog-to-digital converter devices at Analog Devices (ADI) (*A Sense of Power*, August 2001). In the late 1980s, after a decade of stunning growth in the analog-to-digital business, he began looking for the next big, high-growth opportunity. A tiny group of customers was paying hundreds of dollars apiece for RF semiconductors, mainly for use in specialized military applications. Pratt concluded that such devices could be made for dollars or pennies and that at that price they would spur enormous growth in civilian telecom markets.

As Pratt himself is the first to admit, he began his search for better RF technology in the material he was most familiar with—silicon. Analog Devices wasn't too excited about RF markets, however, so in 1991, the company let Pratt and two of his ADI colleagues—Powell Seymour and Jerry Neal—move their ideas and the IP they had accumulated, into an independent design shop—RF Micro Devices. All three men remain with the company today; Pratt is still chairman and CTO.

The three engineers soon grasped the emerging promise of GaAs. They began designing RF GaAs chips, using Gigabit Logic as their foundry. But Gigabit went under, and the new company had to go begging to the two leading GaAs-capable RF chip fabs in existence at the time, both of them defense contractors—Rockwell and TRW. Rockwell had its hands full with military commitments and wouldn't help, but TRW decided it would. In short order, RFMD's commercial markets were growing so rapidly that TRW licensed its GaAs technology to the new company and took an equity stake in it as well. RFMD built its first fab in North Carolina in 1998 and just brought another one on-line in 2002. (Ironically, Rockwell spun out its own communications business in 1999, as Conexant (CNXT); last June, Conexant spun out its GaAs chip foundry to form Skyworks (SWKS), which is now RFMD's main competitor.)

RFMD's hardware provides the electrical punch that propels the radio signal

Today RFMD has some 1,600 employees, and its fabs are running flat out. It is the leading worldwide provider of RF power amplifiers for wireless handsets. Found inside all the major platforms, RFMD's hardware provides the electrical punch that propels the radio signal through the antenna cupped in your hand to the antenna at the top of a base station a mile or more away. The company's handset amplifiers are built around AlGaAs HBTs. The company continuously evaluates new architectures and materials for these amplifiers, including the recent introduction of indium gallium phosphide (InGaP) HBTs (although RFMD claims the now venerable AlGaAs remains superior for most applications). RFMD's newest fab was built to handle the new 6" GaAs wafers; 4" was the biggest available until wafer suppliers achieved 6" boules, which happened just about the time when the tech bubble began its collapse. In the second quarter of this year, RFMD has scheduled the temporary shutdown needed to switch the line over to the cost-reducing bigger wafers. RF GaAs chips cost \$1.30 per square millimeter when RFMD was formed; that figure stands at about 10 cents today, and is still falling.

RFMD has moved well beyond the amplifiers, too—the company is now progressively taking over other real estate inside handsets, as the logic components get smaller and smaller. It has expanded into the manufacture of other high-speed signal processing and conditioning hardware in the radio section of the handset, including mixers, gain blocks, and driver amplifiers. RFMD's objective is to become the complete supplier of RF power-electronic components in these devices—everything required to transmit and receive the signal itself, before or after the logic sections of the device do the coding and decoding.

Late last year, RFMD introduced the Polaris "Total Radio" transceiver—the company's first step toward, ultimately, packing an entire cell phone's RF sections in a fully sealed and integrated package. Five years ago, RFMD had no packaging engineers; today, 100 of the company's 500 engineers do nothing else. RFMD's highly integrated RF modules, which accounted for 10 percent of the company's revenues in 2001, produced over 40 percent last year. Having earlier put the entire RF high-power (output) amplifier into a single package, the next challenge (still on the drawing boards) is to combine the power amplifier, RF filters, and RF transmit/receive switch into a single package.

Standing alone, RFMD's established technological and market leadership, and the inevitability of continued growth in handset sales, would certainly be enough to promise the company a respectable future. Handset sales are expected to grow at 13 percent per year for the next five years. Analysts predict that dropping prices will nearly offset this growth so far as the major handset vendors are concerned—but the provision of the power components for those same handsets is on a different, and much more favorable, trajectory. The \$1.2 billion market for handset power amplifiers is projected to grow at 8 percent per year for the next four years. And the \$2.8 billion global market for all the other active (silicon) RF components in handsets will grow as well, albeit somewhat more slowly.

While the cell phone will remain the anchor tenant of RFMD's business for some years to come, the company is now mapping out plans to grow even

Table 1. RF Power and Wireless Networks*

		Bluetooth	802.11b	802.11a/g	Cellular Handsets (CDMA, TDMA, GSM, etc.)	Cellular Base Station
Data Rate	Mbs	0.7	5-6	20-25	0.01-0.1	Same
Range	Feet	30	100	100	3,000-10,000	Same
RF Power	Watts	0.001-0.003	0.05-0.1	0.08-0.2	0.5-3	100-2,000
Spectrum	GHz	2.4	2.4	5	0.85, 0.9, 1.8, 1.9	Same
RF Chip Costs	$	3-5	10-20	20-40	6-10	5,000-30,000
Chip Type	Semiconductors	Si	Si, SiGe	Si, SiGe, GaAs	GaAs	Si, GaAs, (GaN)

* Typical

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faster by providing RF power elsewhere. The basic cell phone market provides the volumes and supports the R&D; all the new wireless markets will provide growth and margin. RF powerchips are now headed on to PC motherboards (140 million units sold per year worldwide), into televisions (120 million), video game consoles (40 million), and PDAs (15 million). RFMD has the technology and IP to become a one-stop provider of RF power circuitry to all of these markets.

The cell phone itself certainly offers the first huge platform (400 million units per year) on which to deploy several other complementary RF wireless technologies, including Bluetooth, Wi-Fi, and GPS chip sets. Only about 5 percent of cell phones have Bluetooth today; almost all are expected to incorporate it by 2007. Bluetooth is the emerging new standard for short-distance (<30 feet) wireless connections between and among handheld, small desktop, and portable devices. Some 35 million Bluetooth chipsets were shipped in 2002; a billion will be shipped in 2006. Cambridge Silicon Radio (Europe) and Silicon Wave (San Diego) are two successful start-ups that have focused on this particular market and have seized market share; Infineon (IFX) (which bought Ericsson's microelectronics unit), Texas Instruments (TXN), and Philips (PHG) are in the market too. But, the company that has emerged to dominate power electronics in the enormous handheld market has inherent advantages in this RF sector as well. Bluetooth is still a nascent market, growing rapidly, and the suppliers that will end up dominating it have yet to be determined. Look for rapid technical advances from RFMD, complemented by a series of acquisitions of some of the innovative newcomers in the field.

For longer-range wireless and higher bandwidth than Bluetooth, there are the new 802.11 Wi-Fi standards. These are driving a rapidly emerging market for RF components in PDAs, networked PCs, cable television modems, video cameras, and an ever expanding array of peripherals. Almost half of new notebooks already incorporate 802.11b wireless radios (where the "b" standard designates the 2.4 GHz band), and sales of Wi-Fi chipsets are projected to grow five-fold by 2007. Wi-Fi chipsets enable effortless connection to broadband access points—digital subscriber lines or cable modems in homes, or Ethernet networks in corporations—at distances of up to 100 feet, and at (practical) speeds of up to 6 Mbps.

Intersil (ISIL) and Lucent spin-out Agere (AGR.A) currently make most of the chips in the (first) 802.11b market; other manufacturers include Texas Instruments and Philips Electronics. But, using its handset-derived expertise, RFMD already lays claim to the highest performance (range) and lowest cost 802.11b chipset. RFMD's cost-cutting expertise developed in years of supplying the aggressively price-sensitive handset business will doubtless become an increasingly important differentiator, as will its demonstrated capacity to develop components that bridge platforms and markets. To build its 802.11 expertise, RFMD last year acquired WLAN-chip maker Resonext for $133 million in stock.

Bluetooth is still a nascent market

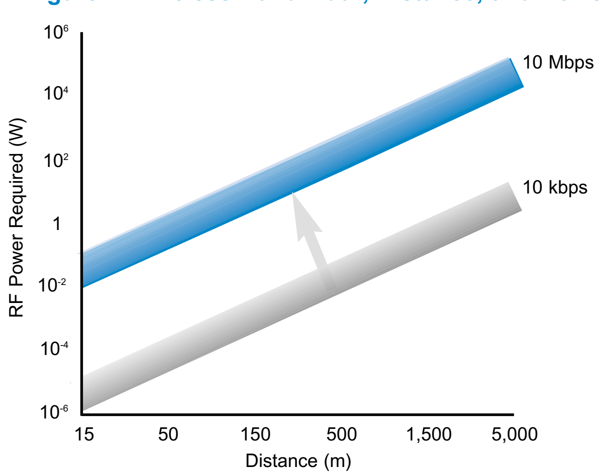
Then there is the emerging 802.11a standard, an even newer RF market, in which final standards have yet to be set. Operating in the 5 GHz band, 802.11a can (in principle) attain speeds of up to at least 25 Mbps; to get there requires about 30 percent more power and even greater RF design sophistication. It was only in the last week of

January 2003 that the commercial RF community and the Pentagon came to terms on critical issues relating to interference in this very attractive high-bandwidth spectrum. But with 802.11b already gaining a firm foothold, it is much more likely that a dual-band 802.11 architecture will be the design of choice (over a pure "a" chip), the so-called 802.11g standard able to communicate in either "a" or "b." RFMD's engineering skills are a perfect match for the demanding design integration this requires. RFMD is, as well, perfectly positioned to provide the chips that integrate Wi-Fi into handsets; cellular providers are likely to end up deploying Wi-Fi pico-cells to expand network capacity in congested areas.

At the other end of the RF power spectrum lies the base station

RFMD is aggressively pushing its products into other rapidly growing wireless markets as well—satellite radio and GPS, among others. GPS markets present a particularly intriguing, high-growth opportunity. GPS devices are proliferating rapidly, as they shrink down in size and cost, and find their way into car dashboards, boats, and a rapidly growing number of laptop-sized, palm-sized, wrist-wearable, or smaller devices. RFMD purchased IBM's GPS development organization in 2002—a very logical acquisition, if only because GPS capabilities are now migrating on to cell phone motherboards. The next-generation GPS satellites, now being launched, broadcast signals that are powerful enough to be picked up inside buildings—which will make them all the more attractive options in handsets. And the proliferation of GPS devices will propel further growth in wireless communications. Once a GPS unit determines where it is, the next step, more often than not, is to convey that information to another machine somewhere else.

Figure 4. Wireless Bandwidth, Distance, and Power



Source: *Energy Efficient Technologies for the Dismounted Soldier*, National Academy Press, 1997.

RFMD is building into a single package the digital signal processor, low noise amplifier, RF integrated circuit, and GPS engine modules, which combine the components of GPS chip sets with the components necessary to interface with the end-user device. It will take time and significant price reductions, but an almost complete fusion of GPS and wireless communication technology is inevitable. Like cell phones, GPS devices are sensitive wireless receivers—they require power circuitry to amplify the very weak inbound signals. Both halves will require power and a high degree of integration to drive down costs; both will, in all likelihood, be provided by RFMD hardware. To ensure access to SiGe technology for GPS, RFMD bought a 10 percent stake in Jazz Semiconductor—the silicon fab spin-out from Conexant. (Competitor Skyworks is also co-invested in Jazz). In addition, RFMD maintains foundry services for silicon and SiGe in IBM's fab and in Taiwan Semiconductor Manufacturing Company (TSM).

At the other end of the RF power spectrum lies the base station and its high-power RF chips. (One finds higher-power RF semiconductors only in military radar, TV broadcast, and industrial processing.) Although there are a thousand times more wireless handsets than there are base stations, the higher power and more expensive base station powerchips generate comparable amounts of revenues. Every base station contains up to a dozen RF power amplifiers and dozens of RF chips on the receive and transmit units. While RFMD has only a modest position in today's base station market (about 10 percent of revenues—from low-power pre-amplifiers, filters, and similar RF components), the company is positioning itself to become a major provider of high-power amplifier components too.

RFMD plans to enter this market by leapfrogging to the gallium nitride (GaN) RF power transistors that will inevitably displace the current generation of silicon-based LDMOS devices. The company's first step in this direction came with a 2001 acquisition of RF Nitro for its GaN (on sapphire and SiC) capabilities, as well as high-performance InGaP HBT and GaAs pHEMT devices. (RF Nitro's IP came out of defense contract work at Cornell University.) RFMD is letting customers sample early GaN-based devices now as it continues to develop the technology and establish reliability; commercial production is likely to begin in 2004. After that will come ultra-high-power RF chips built on pure, bulk GaN wafers. Here RFMD has a stake in Kyma Technologies, an early-stage GaN wafer developer. (So do we, through our VC partners.)

Ubiquitous RF "Light Bulbs"

Sales of RF powerchips ultimately depend on only one thing: how many devices are built with the capability to project or receive RF photons through the airwaves. And photon fluxes are going to continue to rise rapidly: that is about as certain a bet as there is to be found in the tech sector today.

After a decade of continuous growth (50 percent or so annually), 2001 marked a first year of slip back in the largest equipment sector: mobile phone shipments dropped by 5 percent. Last year's sales were essentially flat. But there are still lots of people to sell handsets to, as the economy and populations grow, and as prices continue to drop. A number of European and Asian countries have subscriber penetration rates of 70 to over 100 percent—but many other countries land much lower, the United States (45 percent) and Japan (50 percent) among them, and the global average is still only 15 percent. Analysts who forecast shipments are all projecting relentless growth for years to come.

About half of all sales now are replacements. Even for handsets, which are now so familiar, there is still strong demand for smaller, lighter units with new features—voice-actuation, multi-mode and multi-band capabilities, integrated functions like FM radio or MP3 players, integrated cell phone/PDAs, color displays, color video capabilities, embedded digital cameras, Internet Web access, Bluetooth capabilities, and more.

And from the phone on out, wireless links will continue to multiply rapidly. Communication between things—across a desktop, throughout the passenger cabin and drive train of a car, across the factory floor, Internet café, college campus, hotel lobby, passenger terminal in an airport, and so forth—is convenient and useful. Permeating space with RF photons, in other words, is as valuable as permeating it with light. And the core power components of the RF "light bulbs" are the same, whatever the technical standard they use to "illuminate" or "read"—cellular, PCS, Wi-Fi, Bluetooth, UltraWideband, you name it. Over the next five years, some $30 billion of new wireless networking devices will be sold, all of this new output on top of the handset market.

Table 2. Major RF Players

Company	Comments
Hitachi (HIT) www.hitachi.com	RF part of semiconductor division
Infineon (IFX) www.infineon.com	2002 acquisition of Ericsson Microelectronics
Intersil (ISIL) www.intersil.com	Wireless one-third revenues
Mitsubishi Electric (MIELY.PK) www.mitsubhishielectric.com	RF part of semiconductor division
Northrop Grumman (NOC) www.northgrum.com	Now includes TRW GaAs fab
Philips (PHG) www.semiconductors.philips.com	RF part of semiconductor division
Raytheon (RTN) www.raytheonrf.com	RF part of $400M "commercial electronics"
*Skyworks (SWKS) www.skyworksinc.com	2002 Conexant spin-out ($450M revenues)
Texas Instruments (TXN) www.ti.com	RF under 5% semiconductor revenues
*TriQuint (TQNT) www.triquint.com	$330M (acquired Agere Systems opto-electronics operations, January 2003)

* Pure-play RF company

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Somewhat further down the line, automobiles will become yet another huge growth market for wireless networks, used for vehicle diagnostics and communication between on-board components. Bluetooth and Wi-Fi will permit seamless integration of phones, PDAs, and back-seat entertainment systems. Saab is the first to ship this year a Bluetooth-equipped car. And some 20 percent of new cars will incorporate heavy-duty wireless networks within five years to support communication among components under the hood. Factories are headed toward the same end point—an environment suffused with radio waves that enable complete communication among every person and device that moves or thinks. (*Networking the Digital Factory*, September 2001; *Digital Movers*, February 2002).

It took almost a century for wireline phone companies to reach a billion subscribers worldwide. It took less than twenty years for wireless carriers to reach the same mark, building, in the process, the planet's largest RF network. Within five more years, the installed base for RF transmitters will increase ten-fold again. RFMD will provide a substantial share of the semiconductor components that will provide the essential power.

Peter Huber, Mark Mills, February 7, 2003

The Power Panel

For an explanation of the ascendant digital power technology for each of these companies, see the indicated issue of the DPR.

FEATURED COMPANY	DPR ISSUE	OTHER PLAYERS IN THE ANALYZED SPACE*
II-VI (IIVI) www.iivi.com	1/03	Poly-Scientific (subs. Raytheon (RTN)); Umicore (Umicore Group, Belgium (ACUM.BE)
Advanced Power (APTI) www.advancedpower.com	12/00	Hitachi America (subs. HIT); Mitsubishi Semiconductor (subs. MIELY.PK); ON Semiconductor (ONNN); Philips Semiconductors (subs. PHG); Siliconix (SILI); STMicroelectronics (STM); Toshiba (TOSBF.PK)
American Superconductor (AMSC) www.amsuper.com	10/00	ABB (ABB); Intermagnetics General (IMGC); Waukesha Electric/SPX (subs. SPW)
Amkor Technology (AMKR) www.amkor.com	4/02	ChipPAC (CHPC); DPAC Technologies (DPAC)
Analog Devices (ADI) www.analog.com	8/01	Linear Technology (LLTC); Maxim Integrated (MXIM); STMicroelectronics (STM)
Analogic (ALOG) www.analogic.com	12/01	American Science & Engineering (ASE); Heimann Systems/Rheinmetall Group (subs. RNMBF.PK); InVision Technologies (INVN); L3 (LLL); Rapiscan/OSI Systems (subs. OSIS)
C&D Technologies (CHP) www.cdtechno.com	7/02	East Penn (pvt.); Enersys (pvt.); Exide (EXTDQ.OB)
Coherent (COHR) www.coherentinc.com	6/01	OSRAM Opto Semiconductors/subs. Osram (Siemens, SI, sole shareholder); Rofin-Sinar (RSTI)
Cree Inc. (CREE) www.cree.com	5/01	AXT (AXTI); Nichia Corporation (pvt.); Toyoda Gosei Optoelectronics Products/Toyoda Gosei (div. 7282.BE)
Danaher Corp. (DHR) www.danaher.com	2/02	Emerson Electric (EMR); GE-Fanuc (JV GE (GE) and Fanuc Ltd. (FANUF.PK)); Mitsubishi Electric Automation/Mitsubishi Electric (div. MIELY.PK); Siemens (SI)
Emerson (EMR) www.gotoemerson.com	6/00	American Power Conversion (APCC); Marconi (MONI.L); Toshiba (TOSBF.PK)
Fairchild Semiconductor (FCS) www.fairchildsemi.com	1/01	(See Advanced Power entry.)
FLIR Systems (FLIR) www.flir.com	1/02	DRS Technologies (DRS); Raytheon Commercial Infrared/Raytheon (subs. RTN); Wescam (WSC, Canada)
Harris Corp. (HRS) www.broadcast.harris.com	9/02	AI Acrodyne (ACRO); EMCEE Broadcast Products (ECIN); Itelco (pvt.); Thales (THS.L)
Infineon (IFX) www.infineon.com	12/00	(See Advanced Power entry.)
International Rectifier (IRF) www.irf.com	4/00	(See Advanced Power entry.)
Itron (ITRI) www.itron.com	10/02	ABB (ABB); Invensys (ISYS.L); Rockwell Automation (ROK); Schlumberger Sema/Schlumberger Ltd. (SLB); Siemens (SI)
IXYS (SYXI) www.ixys.com	4/00	(See Advanced Power entry.)
Kemet Corp. (KEM) www.kemet.com	5/02	AVX Corporation/Kyocera Group (AVX); EPCOS (EPC); NEC Corporation (NIPNY); TDK Corporation (TDK); Vishay (VSH)
L-3 Communications (LLL) www.l-3com.com	12/02	DRS Technologies (DRS), Integrated Defense Technologies (IDE), and United Technologies (UTX)
Magnetek Inc. (MAG) www.magnetek.com	8/02	Ascom Energy Systems/Ascom (subs. ASCN, Switzerland); Astec/Emerson Electric (subs. EMR); Delta Electronics (2308, Taiwan); Tyco (TYC)
Maxwell Technologies (MXWL) www.maxwell.com	3/01	Cooper Electronic Technologies/Cooper Industries (div. CBE); NESS Capacitor/NESS Corp. (pvt.)
Microsemi (MSCC) www.microsemi.com	4/01	Semtech Corporation (SMTC); Zarlink Semiconductor (ZL)
Oceaneering Int'l. (OII) www.oceaneering.com	6/02	Alstom Schilling Robotics/ALSTOM (subs. ALS, France); Perry Slingsby Systems/Technip-Coflexip (subs. TKP); Stolt Offshore (SOSA); Subsea 7 (JV Halliburton (HAL) and DSND (DSNRF.PK))
Power-One (PWER) www.power-one.com	5/00	Artesyn Technologies (ATSN); Celestica (CLS); Lambda Electronics/Invensys (subs. ISYS.L); Tyco Electronics Power Systems/Tyco Electronics (div. TYC); Vicor (VICR)
Raytheon Co. (RTN) www.raytheon.com	10/01	BAE Systems (BA.L); Integrated Defense Technologies (IDE); Lockheed Martin (LMT); Northrop Grumman (NOC)
RF Micro Devices (RFMD) www.rfmd.com	2/03	Hitachi (HIT); Skyworks (SWKS); TriQuint (TQNT)
Rockwell Automation (ROK) www.rockwellautomation.com	9/01	Honeywell (HON); Invensys (ISYS.L); Mitsubishi Electric Automation/Mitsubishi Electric (div. MIELY.PK); Parker Hannifin (PH); Siemens (SI)
TRW Inc. (TRW)*** www.trw.com	1/01	Conexant (CNXT); Fujitsu (6702, Taiwan), Information & Electronic Warfare Systems/BAE Systems (div. BA.L); Northrop Grumman (NOC); RF Micro Devices (RFMD); Vitesse Semiconductor (VTSS)
Veeco Instruments (VECO)** www.veeco.com	7/02	Aixtron (AIX, Germany); Emcore (EMKR); FEI Company (FEIC); Riber (RIBE.LN); Thermo VG Semicon/Thermo Electron (subs. TMO)
Vishay Intertechnology (VSH) www.vishay.com	11/02	(See Advanced Power and Kemet entries.)
Wilson Greatbatch Technologies (GB) www.greatbatch.com	3/02	Eagle-Picher Industries (EGLP.PK); Ultralife Batteries (ULBI)

* Listed alphabetically; not a list of all public companies with similar or competing products; typically does not include private companies.
** Veeco and FEI Company announced a merger agreement on July 12, 2002; FEI will become a wholly owned subsidiary of Veeco.
*** Northrop Grumman and TRW announced a definitive merger agreement on July 1, 2002, in which NOC will acquire TRW.

Note: This table lists technologies in the Digital Power Paradigm and representative companies in the ascendant technologies. By no means are the technologies exclusive to these companies, nor does this represent a recomended portfolio. 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 interest in the companies.