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The Power of Millimeter Waves

TRW's millimeter wave MMICs will serve as the ubiquitous, tireless, ever watchful eyes of freedom

Edison's bulb radiates power around 500,000 GHz, which is convenient, because that's in the frequency range our eyes can see. The downside: light doesn't penetrate clothes, walls, fog, smoke, foliage, and dirt. What we could use, in these troubled times, is light of a different kind, that can peer through all such clutter, into recesses that ordinary light is never able to reach.

We'd put the bulbs that can emit such light wherever civilian security matters—in airports, government buildings, near water reservoirs, around our backyards, inside our homes, and wherever we might wish to probe into cardboard boxes, or through walls. The military would attach them to spy planes, cruise missiles, artillery shells, and the foot soldier's equipment, to complement laser, infrared, and optical detectors. And we'd stick a few of them alongside the headlamps and tail lamps of every car, and electronically link them to the cruise control, the brakes, and maybe the airbags.

The "light" exists. It is projected out of wire filaments—antennas—about the same size as those found in an ordinary bulb. But what makes this kind of emitter shine isn't raw heat but rather current oscillating at frequencies of 30 to 300 GHz. Such a current can be produced by a solid-state single-chip amplifier, called a monolithic microwave integrated circuit (MMIC). The world's fastest integrated circuit is a MMIC. The high-speed MMIC chip is the key to wireless broadband telecom services. Add enough power on top of that—surmount the daunting challenge of building a high-power high-speed MMIC—and you can build an almost limitless range of new products to help us see.

See, just as Edison's bulb lets us see, but see many things, in many places, that cannot be reached by light or probed with optical instruments. See well enough to peer through walls, or inspect the contents of letters or boxes without opening them. See the way you'd really like to see, if you're fighting an enemy abroad, or watching for terrorists at home, or merely driving a truck or bus or car with its inevitable blind spots, or when the light is bad, or the air foggy.

The first century of electron technology began with the light bulb, and ended with the integrated circuit. Today, we manufacture both by the billions, and we put them everywhere. Milliwave MMICs come next. They fill an urgent need, and the technology has very recently reached the critical transition point where costs plummet as mass production ramps up. Milliwaves are headed into everything that moves, and into every place where we need to track things that move, and their contents, and the people that move them. The MMIC will emerge, alongside the microprocessor IC, as one of the two critical technologies that will rebalance the asymmetries of conflict in the high-tech versus low-tech clashes of the twenty-first century.

Much of the rest of TRW's (TRW) business is squarely centered in Powercosm technologies, such as automotive electronics and aerospace applications. But what really distinguishes that venerable company at this point in history is its mastery of the Indium Phosphide (InP) MMIC.

Milliwave Physics

The basic physical principles are straightforward enough. Electromagnetic radiation comes in an infinite range of frequencies, and different frequencies penetrate, are absorbed by, or reflect from, different materials. Light goes through clear glass, but not sheetrock. X-rays penetrate flesh, but not bones. Microwaves at a certain frequency are absorbed by water—that's how they reheat the pizza.

The higher the beam's frequency, the shorter the wavelength. Frequencies from 30 to 300 GHz translate into wavelengths of 10 to 1 millimeters. And as it happens, millimeter wavelengths define a very sweet spot in the business of seeing.

All other things being equal, shorter wavelengths pick up more detail. On that metric, then, X-rays are better than visible light, which is better than millimeter waves, and so forth. But X-rays pack a destructive punch, and take a lot of power to produce. Light gets absorbed by too many things we'd like to see through. Millimeter wavelength beams are fine enough to resolve millimeter-scale details. That makes them quite good enough for seeing most human-scale (and larger) things—everything from concealed weapons to the contents of tractor trailers on a highway.

A second key metric in the art of seeing is how well a wave penetrates fog, foliage, clothes, and other sources of clutter that don't matter, while reflecting off targets of interest, like concealed weapons, that do. Longer wavelengths pass through just about everything. That makes them useful for transmitting information over long distances, but almost useless for projecting power to generate an informative reflection. Absorption is a related issue. Visible light gets blocked by all sorts of opaque things. Microwaves get swallowed by the pizza. Waves in various millimeter bands are just about perfect: they can beam right through clutter—kilometers of messy air, for example—but they reflect off many things that we really do want to see, such as hard plastic and metal.

How far you can shrink things is ultimately limited not by the chips that oscillate the currents, but by the antenna. Antenna size is inversely related to frequency—so higher frequency chips make possible smaller antennas. Millimeter-wave emitters require only centimeter-scale antennas, not much larger than the MMIC chips themselves. So an integrated emitter-detector—an integrated "lights-plus-camera" milliwave transceiver—can be built the size of a paperback book. Or a pack of cards. Or, before long, a matchbox.

We are already at the point where an entire milliwave radar system can be built from a handful of chips: The current amplifier itself, a microprocessor to control it, and a sensor and associated circuitry to pick up the reflected power and build an image. Arrays of MMICs can now be mounted on flat surfaces to create phased-array systems, which use light-speed tricks either to steer microwave beams electronically (no mechanically rotating antenna) or, conversely, to scan across space for inbound signals. Such tricks permit a low-power, but power-dense, focused beam to illuminate large areas. All-electronic scanning makes possible a speed and pattern of scanning impossible in mechanical systems.

Power MMICs

Millimeter-wave-emitting cavities were developed not long after their microwave counterparts that supplied radar during World War II. But it was only very recently that tube-based metal-cavity millimeter-wave technology collapsed into the solid-state world of semiconductors—the world of MMICs. And it was only in the last year or two that the development of Indium Phosphide MMICs pushed power levels up to the point where milliwaves can be used to paint a lot of space brightly enough for serious seeing.

The story of the milliwave MMIC revolution unfolds in two parts, bits first, then power. Low power is good enough for broadband wireless telecom—the business of signals. Here, each signal travels only one way, and is picked up at the far end by a highly sensitive receiver. It takes a lot more power, however, to see—to project milliwaves brightly enough to pick up stray reflections from unaccommodating targets.

The telecom side of the house pushes its way up to shorter wavelengths mainly to find more bandwidth—shorter wavelength means higher frequency, which means more bits. Cellular phones started at 800 MHz, and are now headed for 3 GHz. Wireless LANs migrated from 0.9 GHz to 5.8 GHz. The most recent push has been to stick digital video and other services into bands in the 24 - 31.3 GHz range. In 1998, the FCC auctioned off licenses to provide "local multipoint-distribution services" (LMDS) in these bands (buyers included companies like WNP Communications, NEXTBAND Communications, and WinStar), and followed with a 39 GHz auction (buyers included Hyperion and ART).

For see applications, by contrast, the first imperative is simply to punch enough raw power through to the target, so that enough will reflect back to the detector. For that, milliwaves of several frequencies turn out to be attractive, because they very effectively penetrate common clutter materials that just get in the way.

Military applications have led the way in the development of power-projecting see technologies. Microwave-frequency radar emerged to save London, and then the Atlantic convoys, in World War II. During the Cold War, the Pentagon pushed see technologies up the microwave ranges (1 to 30 GHz); fire-control radar, for example, typ-

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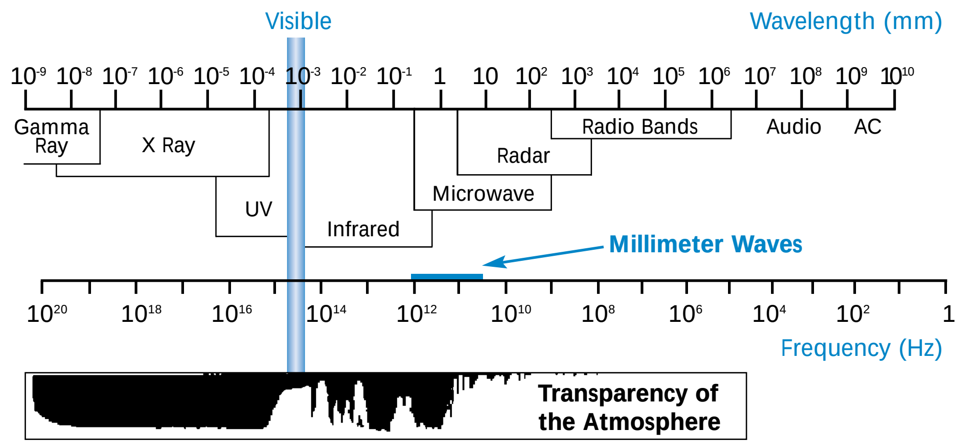
ically operates in the 8—18 GHz range. The military's consistent objective has been to push up power and frequency, so that the beam gets through to the target—and to push down cost, so that see technologies can be deployed wherever needed, which in the military is almost everywhere.

It requires remarkable technology, however, to punch out a few Watts of electromagnetic power at 50 or 100 GHz. At these frequencies, there is no such thing as a passive electrical component. Everything from the interconnects to the very material used to form gates and junctions becomes "active." Maintaining electrical order requires a remarkable degree of design and precision.

In the 1990s, semiconductor circuits finally caught up with the frequencies and power levels that milliwave sight requires. A MMIC is a current amplifier built on a single chip (hence, "monolithic") that can push currents back and forth at extremely high frequencies. We looked at a similar technology—the LDMOS chip used for 1 to 2 GHz wireless power amplifiers—in a prior issue (*DPR November 2000*). Now we're up into the 10s and well into the 100s of GHz.

The gates on milliwave-frequency chips must be robust and electrically efficient, or they self-destruct. A flip-chip architecture is required to put all active components on the same side of the wafer with the active, hot side face down on a heat sink. To get to very high frequencies, the components must be very small. TRW is now etching 0.07 micron gates on its MMIC—enabled by the same deep UV lithography used to put gates of comparable size on the 2 GHz Pentium 4. But while Intel is happy to drive less power through each gate, just so long as the bits aren't lost altogether, TRW wants to drive more. That fact alone pushes things inexorably toward new materials—entirely new classes of semiconductors. TRW has turned to Indium Phosphide. With power densities up to 10 times higher than the now unseated state-of-the-art Gallium Arsenide, and running at frequencies nearly 10 times higher as well, TRW's InP devices now define an entirely new regime of quantum technology.

Electromagnetic Spectrum



Source: Manual of Remote Sensing

After September 11

Until 1995, all spectrum from 30 to 300 GHz was reserved for military and scientific (as opposed to "commercial") uses. Then, responding to a petition from General Motors in 1995, the Federal Communications Commission reallocated some of the millimeter bands for unlicensed commercial use. Two bands (46.7-46.9 and 76-77 GHz) were allocated specifically for vehicle radar systems, and a third band (59-64 GHz) for general unlicensed use. Final rules were adopted in 1998.

Other bands are currently allocated to quite broad categories of services that can readily be adjusted to accommodate security imperatives. The 92-95 GHz bands too, for example, are currently reserved for the federal government (not just the military), to be used for fixed services, earth to space satellite, mobile applications and radiolocation. But all frequencies, in any band, can be used under the FCC's "Part 15" rules, which covers short-range applications in which emissions are either contained and shielded, or otherwise kept at power levels sufficiently low to avoid concerns about interference. Most stationary screening systems can readily meet those limits. To cover more real estate, one simply deploys more low-power milliwave eyeballs.

Millimeter-wave technology companies boomed in Y2K, because milliwaves were the path to broadband wireless on earth, and from space. (They still are, NASDAQ woes notwithstanding.) Then, as milliwave MMICs pushed up in power and frequency, the possibility of new seeing applications began to attract more notice. Long before September 11, the technical literature was exploring the use of milliwaves for the detection of concealed non-metallic weapons at airports, border-crossing inspections, for security in prisons, and to the foiling of high-tech corporate theft and espionage. The one really huge opportunity, however, was thought to be Detroit, and the possibility of milliwave radar making it, eventually, into every car. But investors knew that nothing happens very fast in Detroit.

Then came September 11. America's challenge now is to deploy security systems good enough to intercept nineteen terrorists and as many knives—and countless other comparably tiny pockets of destructive malignancy—in the crowd of 280 million people, 130 million cars, 80 million trucks, 5,000 aircraft, and over 20 million parcels (plus 600 million letters) in transit across the country at any given moment. That will take some doing. Throw out, now, all pre-September 11 projections of where the milliwave market is headed, or how fast it will grow. Back then, there was talk of perhaps 5 million transceivers shipped by 2005. Our modest guess today: 50 million.

Before dismissing that as wildly excessive, check out just how much effort is now going into the monitoring of everything that moves in and out of, say, a single New York high-rise office, or a single airport. And then face this simple fact: security systems that rely on human eyes and hands are horrendously expensive, and frustratingly ineffectual. Most existing screening technologies are expensive too, and only slightly better. Much of our existing civilian security infrastructure is bluff and fake. We have settled for the appearance of security, instead of the reality.

As milliwave MMICs pushed up in power and frequency, the possibility of new seeing applications began to attract more notice

We won't any more. Enterprises, landlords, and governments will spend what it takes to prevent even a tiny echo of September 11 on their own premises. Investment in milliwave technologies will surge for the simple reason that milliwave eyeballs see so much more than optical ones. They're a lot more sensitive and informative than ordinary visual searches, and far faster and cheaper than any more intrusive human-centered screening system. And while milliwaves can readily see through lots of things that are opaque to other bands, they reflect off quite a number of other materials, not just metals but also plastic and human flesh, that the security conscious do want to see. They're much safer than X-rays for searching humans—at low power levels they don't penetrate skin, and they don't ionize molecules.

Suitably configured milliwave systems can form clear three-dimensional images of people and objects of almost any description concealed behind walls, in packages, or under clothing. Funded by the FAA in the mid-1990s, Pacific Northwest Labs developed and delivered a fully functional 3-D millimeter wave imager that sees hidden objects of all kinds right through clothes. Delicate privacy issues derailed enthusiasm for the project. But we are less delicate now. And image analysis software has advanced so far that machines themselves can do much of the threshold screening, which helps abate at least some concerns about bored security agents ogling the scaffolds and fasteners of travelers' lingerie.

With suitable frequency selection and tuning, milliwave systems can be especially sensitive to even the slightest levels of motion, human or other—quite sensitive enough, for example, to pick up, from a good distance away, the rhythmic chest movement created by breathing, or by the beating of a human heart. Millivision, a private company, has developed a milliwave "flashlight" that detects respiration at a distance—a concept originally pursued to locate wounded soldiers but equally useful in searching for civilians in collapsed buildings.

Numerous automotive applications have already emerged. Milliwave radar can detect blind spots, assist with lane changes and parking, alert the driver to collision threats, and pre-activate airbags moments before a crash. The 77 GHz active cruise control system in the Mercedes-Benz S-class, for example, slows the vehicle down when it pulls too close to one in front. Stop-and-go cruise control takes things the obvious next step for city driving. Some of these systems are already widely deployed in buses and trucks; they will likely become mandatory for all new commercial vehicles before long. They are being deployed to make sure snowplows plow snow, not parked cars or fire hydrants. Comparable systems play a key role in fully autonomous landing systems for aircraft.

Delco, Eaton-Vorad, Hitachi, NEC, Fujitsu, and Infineon have all developed units. Toyota, Jaguar, Nissan, Mercedes, Lexus, and others have been putting them in luxury-model vehicles sold in other countries for several years, and now being introduced to U.S. markets. The ideas behind most of these products have been around for decades; the products are coming to market now because rugged, both reliable MMICs and microprocessors have very recently become available at low cost and in high volumes. The systems operating at 60 and 77 GHz are already acceptably compact for tucking behind automotive grills. Under current FCC regulations, government applications can move up into the 94 GHz band (and beyond), where devices get smaller still.

Milliwave sensors can add sight to factories, chemical plants, urban areas, and the great outdoors, just as they do to airports and highways. Milliwave radar is ideal for measuring liquid levels in tanks, in chemical, pharmaceutical and power plants, oil refineries, and countless other industrial settings. The sensors operate without moving parts or mechanical contact, a significant advantage in hostile environments. They can detect voids and deterioration in concrete, pavements, bridges, and railroad beds. They can map oil spills, buried hazardous wastes, underground containers, pipes, tunnels, buried mines, ice thickness, and archaeological sites. Space-based systems play major roles in remote sensing of weather and earth resources.

As MMIC building blocks grow smaller and cheaper, the capabilities of the modules they make possible rise almost indefinitely. Compound systems—arrays of tightly coordinated transmitters and receivers—evolve like the compound eye of a housefly. The Mercedes system switches rapidly among three beams to provide scanning and breadth of view without any moving parts. More advanced phased-array systems are now rapidly emerging. Milliwave sensors and optical-band sensors-on-a-chip are being combined into integrated modules to synthesize composite radar-video images.

The rise of milliwave technology was inevitable before September 11, as MMICs matured and followed the now familiar trajectory of semiconductor devices, growing smaller, faster, cheaper, by multiples of two or more every few years. But September 11 changed things fundamentally. Before, the rise of the milliwave MMIC was technically and commercially inevitable when costs dropped enough, and performance rose enough, to motivate tire-kicking consumers, work-a-day factory managers, and highway engineers. The new inevitability is driven by the specter of the collapsing skyscraper.

TRW

It has $17 billion in sales and 120,000 employees across the globe. One quarter of its revenues come from direct and indirect sales to the government, primarily the Defense Department and NASA. Only weeks ago, the prominence of those two particular customers on TRW's balance sheet would have repelled many investors. It won't now. For our part, we've been following the Pentagon-to-Powercosm technology pipeline from our very first issue. As we've noted all along, it takes power to win wars of any kind—not just lots of power, but fast, focused, high-quality, high-density power—the side with the most and the best generally wins. The technologies that can deliver that kind of power are very much the same technologies that can light up a warehouse filled with silicon, or light up the industrial and commercial landscape with microwaves, milliwaves, and laser beams.

A century old this year, the modern TRW evolved out of companies that manufactured such things as fasteners, engine valves, carburetors, and magnetos. It delivered Pioneer 1 in 1958, the first industry-built satellite, and it has built some 200 spacecraft since. Among them, Pioneer 10 which flew by Jupiter, the instrument package on the Mars Viking lander, the Chandra X-Ray telescope, and the Defense Department's new Milstar satellite (launched last February), the first such satellite to operate entirely in millimeter wave bands.

TRW technologies also help provide some of the huge amounts of old-fashioned power—chemical combustion—that it takes to get a craft into space: TRW builds rockets, too, including the new boosters for the Air Force Minuteman III ICBMs. But most of TRW's aerospace revenues are centered on the power and sensor technologies that take over after that, which is to say, on technologies of the Powercosm. These are the technologies that produce and shape the electrons and photons that control, communicate, and sense. And the technologies that are now beginning to be used as well, to project power at the speed of light to destroy hostile targets. TRW is also a very significant player in the development of high-energy laser systems, along with other space and defense communication systems, and earth observation platforms.

Moving down in altitude a bit, TRW manufactures a wide range of systems for aviation customers, including both Boeing and Airbus: engine and flight controls, power generation and management. TRW provided the Bristol Britannia in 1951 with the first control-by-wire technology for commercial aircraft; and in 1986 TRW supplied the first fly-by-wire system for a civil aircraft, the Airbus A320. TRW technology powers or controls avionics systems, airborne reconnaissance systems, unmanned aerial vehicles, air-traffic control systems, and a variety of public safety and transportation, counter-terrorism, security, and criminal justice platforms and technologies.

It is against this backdrop that one can make sense of the business that now generates some 60 percent of TRW's revenues—the automotive business. Here, as in air and space, TRW's main focus is not on steel or combustion, but on semiconductors and electricity. About half of the company's automotive revenues come from products closely related to the same technologies that were developed first for space and aircraft platforms. They are moving into cars now because digital power technologies have just reached the inflection point on the price-performance curve, where they can be mass-produced for mass market applications. Almost all the major car manufacturers are TRW customers.

TRW has been supplying key products at every key stage of the march to the "Silicon Car," which we first examined last December. The company developed the first electronic brake assist in 1996 for the 2000 Mercedes, and electrically powered hydraulic steering for the 1998 Opel Astra. (TRW built a 94 GHz automobile radar in 1993—too expensive then, and before the necessary algorithms and low-cost CPUs were available.) Today, TRW manufactures a wide range of systems for sensing and controlling steering, traction, vehicle stability, braking, and cruise speed, as well as sensors for detecting occupant positions in the car (important for passive restraint systems), crashes and rollovers, and tire pressure. Other TRW products go into seat belts, access and security electronics, vehicle communications systems, and power management. TRW is the world's leading supplier of occupant-restraint systems and a pioneer in the development and integration of air bag, seat belt, steering wheel, and crash sensor technologies. Its proprietary crash discrimination algorithms are tailored to vehicle type, size, and the point on the chassis where the sensor is located.

Another 15 percent of TRW's revenues come from military and civil communications systems. In the commercial sector, TRW has relied primarily on partnerships and alliances to move its technologies into civilian telecom markets. Partners have included such companies as Nokia (next-generation wireless base station amplifiers), Hitachi (InP-based 3G handset amplifiers), and RF Micro Devices (RFMD) (commercialize GaAs MMICs for cellular base station amplifiers). In March 2000, TRW merged its Milliwave subsidiary into Endwave (ENWV), which supplies high-speed RF equipment to Nokia, Hughes Electronics, and Nortel, among others.

Milliwave technology finds applications across all of these sectors, from aerospace to cars to communications.

TRW has longstanding connections with all these highest-growth sectors for power milliwave applications. And the company is the clear leader in high-power solid-state milliwave technology. That puts TRW in a very favorable position. As the company itself has certainly recognized. For a voice of authority from the company, see Al Lawrence, "Millimeter-wave ICs Open up New Spectrum" (*Compound Semiconductor Magazine,* (May 2001) (http://www.compoundsemiconductor.net/archives/7-4final/csmaytrw.htm).

The Eyes of Freedom

Under contract with DARPA, the lead federal sponsor of high-technology military R&D, TRW was one of the first companies to build MMICs of any kind. And TRW was the first to meet what was, at the time, thought by many to be the "impossible" challenge of building a commercial MMIC on Gallium Arsenide (GaAs). TRW's GaAs Heterojunction Bipolar Transistor (HBT) MMIC has since emerged as the leading technology for a wide range of commercial telecom applications. TRW licensed the technology to RF Micro Devices (and still owns 10 percent of that company); RF Micro now supplies nearly 20 percent of the worldwide GaAs MMIC output for wireless applications.

Higher-power, higher-frequency applications require a new semiconductor

But GaAs has now been pushed about as far as it can be. Higher-power, higher-frequency applications require a new semiconductor. For the next decade at least, that material is almost certainly Indium Phosphide. For very high-speed operations, the ultimate limits are the inherent electron speed in the semiconductor material, and its thermal properties—each cycle dissipates heat, and too much heat melts the chip. InP has a triple advantage over GaAs: it is 50 percent more power-efficient, its thermal conductivity is 50 percent better, and InP gates have double the electron mobility (speed). All together, this makes it possible to push operational speeds at least four times higher, and peak performances as much as 10 times higher—InP chips are now approaching speeds of 1 Terahertz. InP devices can operate at much higher current densities than GaAs devices, which means smaller chips at higher power, which lowers bottom-line cost even while InP wafers remain more expensive to manufacture. InP chips also exhibit exceptional linearity. Their inherent noise levels are several orders of magnitude lower than GaAs at room temperature, and close to zero when InP is cryogenically cooled.

Until very recently, however, the cost, yield, and reliability of the raw InP wafer manufacturing process was too poor to bother with. Processing the wafers was equally troublesome, especially because deadly phosgene gas had to be used to supply the phosphorous. The InP substrates themselves are more fragile and brittle than even the already delicate GaAs. The industry lacked InP processing experience—the delicate skills required to cut and polish wafers, then dope them and form precise quantum junctions in a high-yield chip-fab production line.

Much of the expertise that TRW developed in manufacturing GaAs devices is now being transferred directly to its InP production lines. A key challenge was in moving from an arsenic to a phosphorous process—the latter requires higher temperatures and pressures, and is horrendously poisonous when delivered as phosgene gas. TRW developed, mastered, and wrapped in a picket-fence of patents, a process for sublimating the phosphorous atoms directly from a benign solid. The new process is also much cheaper and purer. TRW also mastered the use of molecular beam epitaxy to lay down pure epitaxial layers and precisely engineered quantum junctions. To help overcome another core challenge—etching 0.07 microns lines into MMICs—TRW purchased Cutting Edge Optronics Inc., a manufacturer of extreme ultraviolet solid-state lasers.

When TRW's InP commercial foundry started operation in January 2000, the company cautiously promised commercial devices in 18 to 24 months. Volume production in fact began last Spring, ahead of schedule. After beginning with 3-inch InP wafers last year, TRW now has the world's first production facility for 4-inch wafers, on a production line designed to move easily to 6-inch wafers when demand so justifies. The devices TRW is now rolling off its InP fab have already proved to be as reliable as the mature GaAs predecessors.

Large scale production is no longer limited by the supplies of the basic InP raw material—high purity, high uniformity substrates are commercially available from the likes of American Xtal Technology (AXT), Sumitomo Electric, and several small private players, such as EpiWorks, MTI, and Atramet, a divison of French Groupe Arnaude. But in the manufacturing of InP heterojunction MMICs, TRW faces little serious competition. The competition's production MMIC lines are still based on GaAs, and only a small list of companies have pre-commercial (or limited specialty) InP MMIC capabilities: Fujitsu, Litton (now part of Northrup Grumman), Hughes Microelectronics (a private JV of Boeing, GM, and Raytheon), Sanders (BAE), and Vitesse. TRW has the world's only InP MMIC commercial fab line.

From the get-go, TRW's InP MMICs established new device performance records. As of last November, TRW's 215 GHz InP Low Noise Amplifier held the record for the highest frequency integrated circuit ever publicly reported. TRW recently used InP to manufacture the world's fastest all-digital (CPU-type) integrated circuit, too—a static frequency divider operating at 80.1 GHz. TRW chips can deliver up to 1 Watt at 60 GHz, and a half-watt at 95 GHz. InP MMICs at 10 Watts are now achievable; arrays will push power to triple digits, and beyond.

Last May, TRW formed a new subsidiary, Velocium, to market its InP and high-speed GaAs devices. Dwight Streit, Velocium's articulate President is a physicist and 15-year TRW veteran—and he's "nearly as eager" to talk about InP as about his own children. As Streit sees it, InP MMICs are at the same point in their development as GaAs devices were in 1994, but poised to improve much faster going forward, because of all the experience acquired in the last GaAs round. The InP MMIC that cost $1,000 five years ago, runs about $70 today, Streit notes. The cost of GaAs MMICs dropped from "impossible" two decades ago to about a buck a piece today.

Velocium's initial focus for InP MMICs is on telecom applications, where they've already set new speed records in a number of key areas. The GaAs chips TRW/Velocium currently produces for telecom applications run at 100 GHz; the next-generation InP products will hit 300 GHz. InP capabilities are all but essential for the economic deployment of broadband services on mobile platforms. It takes highly linear performance together with high frequencies to deliver bandwidth—but high frequencies burn power, and heat tends to destroy linearity. GaAs took over the wireless market because it could support much higher power density, and thus much more compact amplifiers, than the silicon chips used before. The InP wireless power amplifiers that TRW will be manufacturing in volume in 2002 represent an equivalent leap beyond GaAs.

InP devices offer comparable advantages in fiber-optic hardware, which depends on extremely fast digital logic circuits to get the bits out of the electric wires and into flashing beams of light. InP devices can support 40 Gbps fiber applications, and show strong potential for 80 Gbps operation. It is also quite straightforward to grow Indium Gallium Arsenide (InGaAs) PIN photodetectors on the same InP substrate—thus, miniature, inexpensive, fully integrated photoreceivers can be built, for certain wavelengths of light, on a single monolithic chip.

But at least equally important, in our view, is the much less widely recognized opportunity to deploy InP MMICs in higher-power, high-frequency applications, where milliwaves shine not to signal but to see. Last June, TRW announced its development, under contract to the Navy's Office of Naval Research, of the world's fastest direct digital frequency synthesizer—a 7 GHz, 3,000-gate InP-based digital MMIC. Think of it as a variable frequency combination of both radar and telecom capabilities in the same device—an eyeball plus a wireless optic nerve, all on a single chip. Detroit is moving in the same direction, at least as to the first two functions, <u>see</u> and signal. A single milliwave projector will not only see the nearby car, it will also talk to it. The inevitable end point: "Cooperative adaptive cruise control," in which the sensors in cars spontaneously form their own "local area" networks to coordinate movement with each other, and eventually with an intelligent roadway, too.

By packing more power and higher frequencies onto less chip, InP devices shrink not only the current amplifier itself but also the antenna. TRW is already supplying the automotive sector with high-frequency MMICs. And InP milliwave technologies that, in effect, secure cars from the peril of other cars on the highway, can, by similar means, secure buildings, stadiums, and transportation networks of every description from the peril of other dangerous things headed their way. Next time around, a great number of people charged with public or private safety will be determined to <u>see</u> the cardboard cutters (or whatever comes next) before such instruments of mayhem make it through the airport, into the cargo hold, down to the edge of the water reservoir, or into the government office. TRW InP milliwave modules will do a lot of that <u>seeing</u>.

Seeing farther and better, in more frequency bands, and from more vantage points, has become a top priority of national security. America is now mobilizing its most advanced technology to track down mass murderers before they murder again. As milliwave sensors multiply, they will propel a new surge in purchases of smartchip hardware and associated software: image analyzers, target-recognition databases, smartchips—the whole panoply of digital systems that can transform data into information, and information into action. An industry eternally in search of the next "killer app" has very likely found one in killers themselves.

When murderers are on the loose, civilized societies fortify and arm themselves, and above all, they stand guard, they wait, and they watch. Much of America's watching will necessarily be electronic. TRW's InP MMICs will serve as the ubiquitous, tireless, ever watchful eyes of freedom.

Peter Huber and Mark Mills
October 24, 2001

Lehman Brothers gets it

Read their excellent September 7, 2001 report *Power Semiconductors*. "Power semiconductors exist in virtually every end market" (p. 1); analog powerchips "interface with real-world inputs" (p. 6); "proliferation of power features in automobiles" (p. 10); "power grid...archaic infrastructure" (p. 10); "power semis for digital cellular" (p. 12); "RF discretes could be significant" (p. 13); "motion control power chips" (p. 20). Lehman therefore "initiates coverage" of International Rectifier (IRF) and Fairchild (FCS). They accurately capture the powerchip's role in the Powercosm and provide Wall Street type market analysis. We look forward to a follow-up report from our friends on Wall Street to expand coverage to the Pentagon/Powercosm synergies–an area we have emphasized from the outset, and that suddenly became so much more important four days after the Lehman report was published. (www.lehman.com)

The Power Panel

Ascendant Technology	Company (Symbol)	Reference Date	Reference Price	10/24/01 Price	52wk Range	Market Cap
Project, Sense, and Control	TRW Inc. (TRW)	10/24/01	33.21	33.21	27.43 - 45.45	4.2b
	Raytheon Co. (RTN)	9/16/01***	24.85	32.00	23.95 - 37.44	11.5b
	Rockwell Automation (ROK)	8/29/01	16.22	14.75	11.78 - 49.45	2.7b
	Analog Devices (ADI)	7/27/01	47.00	38.71	29.00 - 83.56	14.0b
	Coherent (COHR)	5/31/01	35.50	30.09	25.00 - 53.75	854.1m
Electron Storage & Ride-Through	C&D Technologies (CHP)	6/29/01	31.00	21.96	16.35 - 60.88	574.8m
	Maxwell Technologies (MXWL)	2/23/01	16.72	8.10	5.81 - 22.56	82.4m
	Beacon Power (BCON)	11/16/00	6.00*	1.74	0.89 - 10.75	74.4m
	Proton Energy Systems (PRTN)	9/29/00	17.00*	6.19	4.00 - 29.00	205.4m
	Active Power (ACPW)	8/8/00	17.00*	5.37	3.56 - 49.81	214.4m
Powerchips	Cree Inc. (CREE)	4/30/01	21.53	17.10	12.21 - 64.13	1.2b
	Microsemi (MSCC)	3/30/01	14.00	37.09	9.47 - 39.17	1.0b
	Fairchild Semiconductor (FCS)	1/22/01	17.69	22.48	11.19 - 25.35	2.2b
	Infineon (IFX)	11/27/00	43.75	16.50	10.71 - 47.31	10.3b
	Advanced Power (APTI)	8/7/00	15.00	9.35	6.50 - 36.50	81.4m
	IXYS (SYXI)	3/31/00	6.78	6.67	4.27 - 29.75	178.3m
	International Rectifier (IRF)	3/31/00	38.13	35.15	24.05 - 69.50	2.2b
Network Transmission	ABB (ABB)	9/29/00	24.24**	8.58	6.10 - 18.95	10.2b
	American Superconductor (AMSC)	9/30/99	15.38	12.94	8.35 - 55.94	263.7m
Power: Heavy-Iron-Lite	General Electric (GE)	9/29/00	57.81	37.08	28.50 - 56.19	368.4b
	Catalytica Energy Systems (CESI)	9/29/00	12.38	7.29	5.40 - 24.00	125.5m
Distributed Power Generation	FuelCell Energy (FCEL)	8/25/00	24.94	14.95	10.48 - 46.72	582.9m
	Capstone Turbine Corp. (CPST)	6/29/00	16.00*	3.68	3.20 - 63.00	282.8m
Silicon Power Plants	Emerson (EMR)	5/31/00	59.00	50.27	44.04 - 79.75	21.5b
	Power-One (PWER)	(see below)				
Motherboard Power	Power-One (PWER)	4/28/00	22.75	8.18	5.32 - 88.94	644.8m

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 October 2001 issue closed on September 16, 2001 and was posted at 8 a.m. on September 17, 2001. Due to the markets' close in the week after September 11, our reference price reflects Raytheon's closing price on September 10, 2001.*