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Quantum Foundry

The foundries of the 21st century are growers of crystals used to make digital power and digital logic devices

A company whose technology we like a lot has seen fit to give itself a name—II-VI (IIVI)—that only inveterate techies can appreciate. Accordingly, we begin this month with a brief review of high school chemistry—there's simply no other way to make sense of where II-VI came from or what it does.

The elements used to build atomic-scale structures determine what those structures can do. Silicon structures channel and switch flows of electrons very well at the low powers of "logic," and quite adequately at modestly high powers too, though other materials—silicon carbide and gallium nitride, for example—perform much better at higher frequency and higher-power applications. Other exotic elements and compounds are far superior for other types of precision interactions of photons and electrons.

Recall that the Periodic Table arranges the 109-odd elements in a roughly rectangular chart, in which the columns group together elements with similar physical and chemical properties. The highly reactive halogens (fluorine, chlorine, bromine) land in column VII; the chemically inert gases (helium, neon, argon) fall in column VIII, and so forth. In column II, you find zinc, cadmium, and mercury (among others); in column VI, sulfur, selenium, and tellurium.

When the Russian Mendeleev first began mapping out the Periodic Table in 1869, he didn't know why it looked the way it does; he simply grasped that these groupings made sense. It wasn't until half a century later that atomic physicists realized that the Periodic Table tracks the shell-like arrangements of electrons that surround atomic nuclei, which determine the physical and chemical properties of the elements.

Much of engineering and industrial history can be mapped out as a march through the Periodic Table. When human craftsmen and engineers first progressed beyond stone and wood, it was because they had learned how to purify and build with copper, silver, gold, and iron. These and other metals and metallic compounds eventually made possible the heavy-lifting engines, generators, and electrical wires of the Industrial Revolution. Then, just half a century ago, engineers began building structures on silicon, which sits right below carbon in column IV. Amorphous silicon has been used in the manufacture of glass since antiquity, but now structures were being engineered with atomic-scale precision on silicon crystals. This single breakthrough made possible all digital logic.

Yet another family of new devices then emerged: crystalline layers of elements from columns III and V built side-by-side (gallium arsenide and indium phosphide) that can emit and detect photons from microwaves to millimeter waves and from infrared to visible optical wavelengths. With suitable tailoring and doping, made possible by the extremely complex and clever tools and recipes that are used to engineer quantum structures, the III-V structures are good at converting flows of electrons into flows of photons. They are thus used to build light-emitting and laser diodes, particularly in the visible (0.4—0.7 microns) and near-infrared (up to about 1.6 microns) bands. And then, even more recently, came the II-VI materials. They, it turns out, are particularly useful for channeling, focusing, and detecting photon fluxes—electromagnetic radiation—from roughly 1 to 20 microns, i.e., from the "near-infrared" to the "far-infrared" bands.

This pretty much completes the II-VI story for the chemist and physicist, but it's where confusion begins to set in for most investors. "Photons" and "lasers" mean telecom to many, bringing to mind markets that rose sky-high in the bubble years, and then fell as fast as they rose. "Optics" connotes lenses and mirrors made from glass—more telecom, many would suppose. They would suppose wrong. Roughly speaking, the infrared bands in which II-VI materials shine are the power bands. Near-infrared and visible-light lasers transmit data through fiber-optic glass; ultraviolet lasers are used in creating the masks that permit the etching of extremely fine structures on logic chips, or drilling microscopic "vias"; but the vast majority of industrial applications of photon power are in lower-frequency infrared—in the bands where coherent photon beams achieve power fluxes tens of thousands of times higher than are typical in telecom applications.

As we've discussed in previous issues, these infrared bands are where high-intensity beams of invisible photons are used to cut, drill, mill, weld, sinter, solder, cure epoxy, and treat materials in industrial settings—automobile and aircraft manufacturing, circuit-board fabs, textile mills—as well as in a wide range of medical applications (e.g., laser surgery), and an even wider range of military applications (e.g., to destroy an incoming artillery shell). Almost all of the heavy-duty industrial, medical, and military lasers in widespread current use operate in these bands—Nd:YAG lasers (1.06 microns), Yb:YAG (1.03), Tm:YAG (2.01), Ho:YAG (2.08), Er:YAG (2.94). These solid-crystal (yttrium-aluminum-garnet crystal—YAG) lasers pluck their active elements from the "rare-earth" row on the Periodic Table ("Lanthanides") that include neodymium (Nd), ytterbium (Yb), holmium (Ho), thulium (Tm), and erbium (Er). In addition, heavy photon work is done with, and still dominated by, the gas-based carbon-dioxide (CO_2) workhorse lasers (10.6 microns). Higher-frequency lasers are and will be used increasingly in heavy-duty industrial, medical, and military applications as well—but only when their power levels get pushed up; for now, the power bands and the lower infrared bands are basically one and the same.

Which brings us back to II-VI—the company, not the catacombs of the Periodic Table. Though II-VI started out working only with elements from those two columns, it has since broadened its scope to include a range of other crystals that are all but essential in the channeling, conditioning, and focusing of high-power photons: germanium (column IV), gallium arsenide (III-V), and a small cluster of other exotic elements and compounds plucked and formulated from the middle columns and the bottom row of the Periodic Table.

Incorrectly tagged (we suspect) as a "telecom" play, II-VI saw its stock price spike during the bubble—it was a "laser" company, after all, and that was enough for the herd. Much the same happened to Coherent (COHR) (*Photon Power*, June 2001), another (power) laser company, it too was easily misperceived as a manufacturer of telecom equipment, and its stock rose and fell accordingly. II-VI does indeed manufacture materials used for laser optics, but its products show up almost exclusively in power applications, from kilowatt-level infrared lasers, to microwatt-level infrared sensors. It fabricates ultra-pure polycrystalline layers for infrared imaging and laser power systems—polycrystalline coatings on lenses, mirrors, optics, and near-perfect crystal boules used to make infrared lenses, or laser "gain" materials (the "ruby" rods). It supplies components to OEMs of industrial, medical, and military lasers and IR systems. About half of the company's revenues come from power-laser optics; another 30 percent, roughly, go into the manufacture of gain materials that are used to amplify and purify high-power laser light.

II-VI is thus perfectly positioned to prosper from the seemingly disparate, but in fact closely related, rise of powerful diode lasers and low-cost infrared imaging chips. Corning (GLW) was in a comparable position around 1990 because it built the optical components (primarily fiber-optic glass) needed by telecom markets, which were poised for a decade of very rapid growth. The likes of JDS Uniphase (JDSU) and Alcatel (ALA) also had a great run during the same decade because they made (among other things) erbium-doped fiber amplifiers for telecom applications. II-VI fabricates the glass-like conduits required by photon-power markets and the components that go into erbium-, neodymium-, or ytterbium-doped crystals to produce photon amplifiers ("laser-gain" crystals) that emit beams up to five-thousand times more intense than JDSU's most powerful counterpart. The photon power markets are now on the verge, we believe, for a comparable decade (at least) of exceptional growth from today's already substantial $2-billion industry. (See Table 1.)

Only a handful of companies specialize in the lenses and coatings to transmit and shape photons in the ultra-high-power arena, and even fewer also fabricate the core, solid-state gain crystals that produce coherent laser light when pulsed with external beams of shorter-wavelength radiation. II-VI is one of them. It is, indeed, the world's pre-eminent pure-play grower of crystals used in the production of photon power. Over the course of twenty-five years of steady application, II-VI has built itself up as master in the art of growing power-photon crystals needed by the engineers and companies

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that build quantum-based power tools and machines that work materials with photons. It currently sells about $120 million worth of these components a year.

Infrared Optics

Mechanical power is transmitted via shafts and belts; electric power flows through copper, aluminum, and superconducting ceramic wires. Photon power requires conduits as well, to channel and focus it before it radiates out through the ether. Every kilowatt-class power laser is built around a constellation of lenses, mirrors, rods, and other “optical” components—built from the materials in which II-VI specializes.

Those materials are useful for these purposes only in perfect crystalline form—but the crystals are extraordinarily difficult to manufacture. Why use them, then? Because ordinary, amorphous (non-crystalline) glass, though transparent to visible light, absorbs infrared radiation, and anything that absorbs even the tiniest fraction of the power in a high-power laser beam is quickly degraded and destroyed. Power optics require materials that are highly transparent in power bands, not the visible bands, and that, in addition, have high thermal conductivities, so they can dissipate the tiny amount of radiation that they do nevertheless absorb, before the heat distorts optical qualities or melts down the hardware.

II-VI started out in 1971 as one of the very few companies able to manufacture high-purity cadmium-telluride (CdTe) crystals for infrared lenses and windows. CdTe is transparent to infrared radiation in the 1µm to 25µm bands (bands of great interest for military imaging systems). CdTe is also used as electro-optic material—it can be switched (“Q switching”) on and off to pulse a laser a beam.

As it improved its crystal-growing skills, and took advantage of the new tools being developed, II-VI progressed from one difficult infrared material to the next. CdTe is limited, however, by its relatively poor ability to conduct heat and thus dissipate the small amounts of power that it does absorb. It is thus suitable for use only in CO$_2$ lasers operating at powers below a few hundred Watts. Zinc selenide (ZnSe) is about three times better than CdTe on the thermal conductivity metric and has thus emerged as the preferred material for lenses, windows, output couplers, and beam expanders in higher-power applications. (Pure germanium is preferred for low-power applications—it is transparent to infrared and has a high index of refraction useful for camera-like optics.) Optical ZnSe is difficult to manufacture: the crystals must have very few internal defects, and sophisticated polishing technology is required to minimize damage from the polishing process. II-VI has emerged as the world’s largest producer of ZnSe for use in laser, imaging systems, and instruments. (Rohm & Haas (ROH), a $5.6 billion materials conglomerate, has a specialty products group that ranks second.) II-VI also manufactures optically similar zinc-sulfide (ZnS) crystals.

Table 1. Power Laser Markets ($ million/year)

Laser Type	Materials Processing	Medical	Commercial Printing	Pumps	Total
Solid-State Lamp-Pumped	410	321	0	—	731
CO_2	509	44	0	—	552
Gas/Excimer	221	115	0	—	336
Diode Lasers	12	48	4	99	163
Solid-State Diode-Pumped	52	52	6	—	110
Gas/Chemical	19	6	8	—	33
Total	1,223	585	18	99	1,925

Sales for 2001. Totals may not match due to rounding. Excludes low-power laser applications including $200M for instruments and R&D, as well as lasers for telecom ($3B), optical storage ($800M), barcode scanning, entertainment, and “other” ($50M)—virtually all of which are diode lasers.
Source: Laser Focus World 2002 Annual Review.

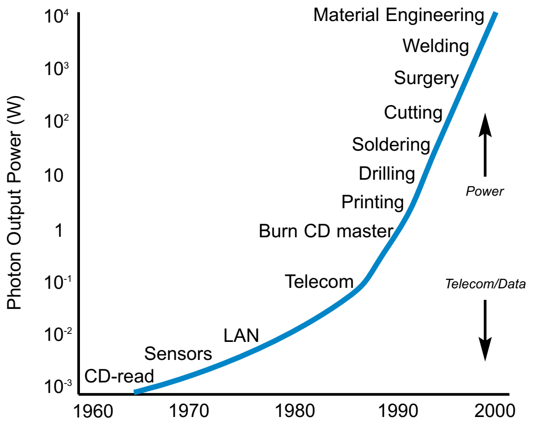
Go to www.DPRreferences.com for direct links to the indicated URLs and/or additional reference information.

But even ZnSe isn’t good enough for some high-power applications—for example, in the final “output” window of compact, high-power (5 kilowatt) CO$_2$ lasers with special beam shapes. Diamond’s IR transparence combined with uniquely high thermal conductivity—it is one hundred times higher than ZnSe — utterly eliminates thermally induced coherence-degrading distortion in specialized beam shapes. DeBeers developed a leading position in a painfully slow but workable chemical vapor deposition technique to build pure, flat-plate diamond windows, and turned to II-VI to deposit a two-layer thorium-fluoride/ZnSe antireflective coating on the diamond window.

II-VI’s infrared optics are equally important in systems that detect power at a distance—here the challenge is to minimize losses in the optics so that a very weak signal can be detected. As we have discussed in previous issues (*Highly Ordered Power,* October 2001; *Infrared Imaging: Sense Out of Chaos,* January 2002), military demand for infrared optics is now growing exceptionally fast because these bands permit you to see a great deal more than is revealed in the visible bands alone. These bands are particularly useful for fire control, missile guidance, and navigation systems in ground vehicles and aircraft.

In both the projection and the detection of infrared power, much of what II-VI has to offer takes the form of specialized coatings. Every lens, mirror, polarizer, beam-splitter, and laser-gain crystal in a high-power laser requires a coating of some sort to protect the surface from both mechanical and chemical degradation, as well as to change or improve the optical properties of the interface. The coatings have to be exceptionally uniform and trans-

Figure 1. Semiconductor Lasers



Source: Laser Institute of America.

parent, or the imperfections will dissipate enough energy to ruin optical performance, or melt everything in sight. Military applications, in particular, require remarkably robust coatings to protect the ultra-high-precision optics from the harsh surroundings of the battlefield.

The solution is to apply coatings of suitable chemical composition in near-perfect polycrystalline forms. II-VI is a world-leading source of thin, polycrystalline coatings for photon-power applications. The company operates a Large Optics Coating Facility—one of the very few able to provide high-performance coatings to withstand extremely high-laser energies. Coating is an extremely delicate art—even in the best of circumstances, yields can sometimes fall as low as 50 percent. II-VI has achieved important cost reductions through its ability to achieve high yields (up to 90 percent) and by transferring much manufacturing to China and Singapore while maintaining both quality and yields.

II-VI optics are thus (to borrow the ubiquitous Intel adage) "inside" every OEM's high-power CO_2 laser in the world, occupying a comfortable de facto technology monopoly in the rarified world of power optics.

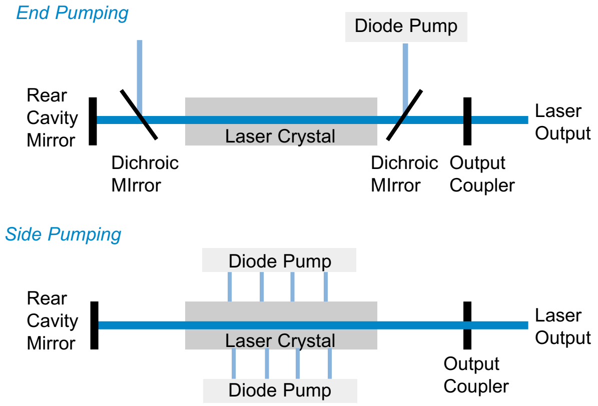
Laser-Gain Materials

Until quite recently, all high-power lasers were gas-cavity lasers. The only way to produce a powerful laser beam was to pump a large gas cavity with an electric field. Solid-state lasers, pumped with flash lamps, were terribly inefficient—well under 1 percent of the electrical power coming in at the front end emerged as photon power at the back. As a result, the high-power laser world is still dominated by electric-discharge CO_2 lasers.

High-power semiconductor diode lasers have recently been developed that have begun to change this picture significantly. (See Figure 1.) Manufactured into tiny "bars," these solid-state lasers offer very compact sources of up to 100 Watts of laser light. Stacked bars of diode lasers can achieve practical power levels of 4 kilowatts—an enormous amount of power, when concentrated in a beam of coherent photons. Diode-laser tools are already beginning to transform industrial material processing. (Our V.C. partners recently acquired a stake in one leader in this new realm, the privately held Nuvonyx, which provides kilowatt-level pure semiconductor lasers for companies like Caterpillar, and which recently won a contract to help develop directed-energy weapons for the Air Force.)

Diode lasers are now rapidly replacing conventional flash lamps used to "pump" the pure rods and slabs of laser-gain crystals. (See Figure 2.) The pumping process can change the frequency of the light emitted. Even more importantly for many applications, a pumped laser's output beam is much brighter and more coherent—i.e., higher quality—an essential factor where exceptionally uniform beam quality is needed, as it is for drilling very fine holes, and in a number of welding and medical applications. Thus diode-laser pumps make possible very high-power lasers operating in various wavelengths (much broader than possible with the diodes alone), and higher beam quality (the diode's beam quality is inherently limited by junction geometry) without a gas cavity at any stage in the process—yielding devices that are much more compact and reliable, and much cheaper. The efficiency of the best diode-pumped laser can rise as high as 20 percent.

Figure 2. Diode-Pumped Solid-State Laser



In 1996, with its acquisition of VLOC, II-VI seized the opportunity to extend its crystal foundry skills into the manufacture of crystalline laser-gain materials. VLOC's own expertise in the manufacture of laser-gain crystals had emerged earlier from Bell Labs. II-VI's VLOC division is now one of the world's two leading suppliers of the entire array of doped laser-gain crystals—alongside Poly-Scientific, a division of Northrop Grumman (NOC). Together, these two have over half the world market. (Poly-Scientific is now up for sale: it could emerge as a stand-alone company, or it could land with a component/systems company like L-3 (LLL) (*The Electric Battlefield,* December 2002), or an integrated laser manufacturer like Coherent, or it might even conceivably be bought by II-VI.)

A wide range of laser "colors" (wavelengths) and features is achieved by doping ultra-pure YAG (and other) crystals with selected elements (e.g., Nd, Ho, Er, Tm, Yb) that emit light when pulsed with an external source of photons. A strong, transparent, thermally conductive crystal serves as the scaffolding for the key elements that, when combined with the right optics and geometries, can be pumped up to emit coherent streams of photons. The challenge for the quantum-structural engineer, here, is to build the optimal mechanical, thermal, optical, and quantum properties into the largest possible crystal boule (larger boules yield more and ultimately cheaper gain rods and slabs)—much as sister industries manufacture silicon and gallium crystal boules, which are then sliced into wafers.

The neodymium-doped yttrium aluminum garnet (Nd:YAG) is the most widely used high-power laser-gain material because large crystals are more readily grown. In addition to Nd:YAG, II-VI manufactures neodymium-doped vanadate (Nd:YVO_4) which is among the highest gain combinations, though it can only be grown as a smaller crystal. Among other combinations, VLOC also grows large-diameter neodymium-doped yttrium-lithium-fluoride (Nd:YLF) crystals, and chromium-doped aluminum oxide (Cr:Al_2O_3, i.e., ruby), as well as various chromium-doped colquiriite crystals, most notably lithium-strontium-aluminum-fluoride (Cr:LiSAF). VLOC developed the latter under contract with NASA's Langley Research Center to pursue the new class of compact, efficient ultra-short pulsed lasers.

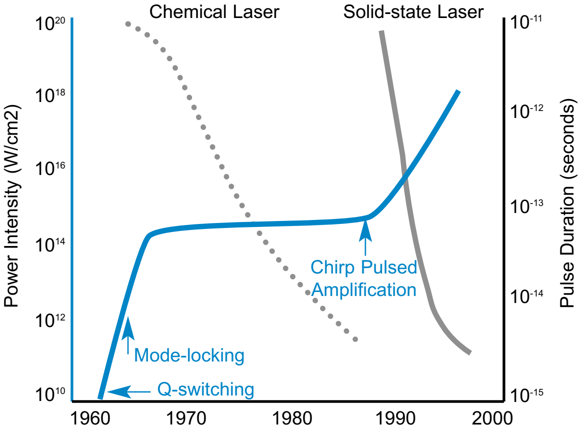
By pulsing a laser—in effect briefly bottling photons to be abruptly released in short pulses—the compression increases power levels dramatically. Pushed to the extreme, and coupled with additional sophisticated pulse-compression optics in a technique known as chirped-pulse amplification, we now have a revolutionary class of femtosecond lasers that produce photon pulses at stunning power levels that last only thousandths of trillionths of seconds. (See Figure 3.)

Cr:LiSAF gain crystals are a key component of the femtosecond lasers now transitioning from research to commercial applications. (The 1999 Nobel Prize in Chemistry went to Ahmed Zewail for his use of femtosecond lasers to probe chemical reactions as they occur in real time.) The first femtosecond lasers were as big as walk-in closets—they relied on a Ti:sapphire gain crystal pumped by a large blue-green gas laser. With Cr:LiSAF, pumping comes from diode lasers instead, and the whole package shrinks to shoebox size. VLOC produces both these laser-gain crystals and the special pulse-compression optics.

Femtosecond lasers can do extraordinary things. (See for example, "Extreme Light," Morou and Umstadter, *Scientific American*, May 2002.) The fantastically powerful pulses trigger photon-atom interactions that just don't occur under any other circumstances. Ordinary lasers produce heat which vaporizes material; femtosecond lasers produce cascades of energetic free electrons that repel each other, dragging positively charged atoms in their wake—the light literally annihilates the basic structure of the matter. All this happens so fast that the process removes material well before it is transformed into chaotic heat that can propagate thermally or as a shock wave to damage the immediate surroundings. Femtosecond lasers could be used as extremely precise drills, for anything from steel to high explosives to the enamel on teeth. Practical applications today are limited (they still have slow overall material removal rates), but will expand rapidly now as the technology matures, and with advances in the 670 nm pumping diode lasers (a band of little interest to telecom laser makers who focus on fiber-compatible wavelengths).

Coming as well (possibly sooner) to the industrial landscape are power blue and ultraviolet lasers. A 100-Watt UV laser can do the work of a 1000-Watt infrared laser. However, even a few watts of UV is an achievement and, until recently, UV lasers were enormous gas-based systems that barely hit 0.05 percent efficiency. All-solid-state, table-top UV lasers are a hundred times more efficient using laser diodes pumping Nd:YLF combined with crystal frequency triplers. Laser systems leader, Spectra Physics (a VLOC customer) makes an 8 W UV (355 nm) solid-state laser, and is on track to 20 W. Practical high-power UV lasers are eagerly sought in medical, drilling, and scribing applications, just for

Figure 3. Femtosecond Lasers



Source: NAS: National Research Council.

starters. Scientists at VLOC await the advent of blue and UV diode lasers that will eliminate the power-robbing (25 percent efficient) frequency tripler, and propel a new era in photon power. They're not here yet, but high-power blue/UV gallium-nitride diode lasers are clearly coming, and when they arrive, they will drive additional demand for VLOC crystals.

Detection and Imaging

II-VI materials have also been ordained (by the whimsical laws of quantum physics) to serve as excellent detectors of the highest-energy photons, those in the X-ray and gamma-ray bands. Though transparent in the infrared bands, CdTe blocks—and behaves as a photoelectric detector of X-ray wavelengths in the 0.1 to 0.001 nm bands. So do several other combinations of zinc, cadmium, mercury (column II elements), and selenium or sulfur (column VI elements). In our December 2001 *DPR* (*X-Ray Vision*), we wrote about X-ray-based baggage inspection systems, noting that one leading manufacturer of these systems (Analogic (ALOG)) uses, as an integral part of its scanning engine design, a selenium (column VI) solid-state X-ray detector. But we noted at the time that while the selenium detector was a whole lot better than gas-tube scintillators, because it produces a direct electrical output, it still cannot operate with the type of resolution (and energy differentiation) that other photon detectors can achieve in the lower-frequency bands.

II-VI's eV Products division is the world's leading manufacturer of cadmium-zinc-telluride (CZT) radiation detectors. These allow true X-ray photon imaging—they convert X-ray photons directly into electric currents that are proportional to incoming wavelength (and thus energy). Drawing on its core crystal manufacturing skills, stepping the crystal purity up a notch, and adjusting the ratios of Cd, Zn, and Te from those used for IR optics, eV Products now builds the first true, room-temperature, "multi-color" X-ray detector arrays.

Table 2. Companies: Infrared Optics and Power Lasers

Company	Website	Comments
Casix (subs. JDSU)	www.casix.com	Laser optics, gain crystals
Coherent (COHR)	www.coherentinc.com	Laser optics, gain crystals (primarily laser diodes)
ELCAN (subs. Raytheon) (RTN)	www.elcan.com	Imaging optics/coatings
Ophir Optronics (OPIR.TA)	www.ophiropt.com	Imaging optics/coatings, laser optics
Poly-Scientific (subs. Northrop Grumman) (NOC)	www.polysci.com	Imaging optics/coatings, laser optics, gain crystals
Rohm and Haas Company (ROH)	www.rohmhaas.com	Imaging materials only
Saint-Gobain (SGOB.PA)	www.saint-gobain.com	Imaging optics/coatings, laser optics, gain crystals
Sumitomo (SOHVF.PK)	www.shi.co.jp/laser/e_frame.htm	Imaging optics/coatings, laser optics, gain crystals
Umicore Germanium Optics (ACUM.BE)	www.optics.umicore.com	Imaging optics/coatings, laser optics

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In addition to its multi-spectral capabilities, II-VI's CZT detectors provide an order-of-magnitude better capture of incoming X-ray photons, and commensurately greater sensitivity. II-VI also designs its own integrated silicon circuitry for the X-ray-spectrum, and has designed a uniquely effective (patented) process for bonding the "read-out" logic chip directly to the pixel elements of its X-ray detector. The result is a true, smart, semiconductor X-ray detector that can distinguish different X-ray frequencies at stunningly high resolution.

These devices have capabilities that will have a huge impact on security, industrial, and eventually medical applications. II-VI already sells its solid-state radiation detectors and components to companies engaged in the manufacture of medical diagnostic, medical imaging, industrial gauging/inspection, and security and monitoring equipment. These same II-VI materials are also excellent gamma ray detectors—gamma rays are simply short-wavelength X-rays, and the term is typically used in reference to radiation produced by naturally radioactive materials, rather than by X-ray machines. II-VI's expertise in this field defines another area for rapid growth, in light of the growing concerns about the potential role of radioactive contamination as a weapon of terrorism. eV recently teamed up with the Los Alamos National Laboratory to develop a battery-powered hand-held radiation detector (with a Palm Pilot-based control system) capable of monitoring radioactive materials and conducting spectral analyses on the fly to determine what materials are present. The instrument is suitable for use at cargo transfer points, border crossings, and transportation hubs.

While still a relatively small part of II-VI—the eV subsidiary generates under 10 percent of the company's revenues—there is virtually unlimited growth potential for the X-ray photon detection business.

Quantum Foundries

II-VI's dominance in high-power IR optics is well established; the company is one of the two leaders in the manufacture of laser-gain crystals, alongside only a half-dozen or so other significant players. (See Table 2.) In a move towards yet another class of power crystals, II-VI recently acquired the silicon carbide (SiC) group from Northrop Grumman (from Northrop's May 2001 Litton acquisition). As we have discussed before

(*Analog Power*, April 2001; *Quantum Power,* May 2001), SiC is another extremely difficult crystal to grow, but it is uniquely useful for fabricating blue and green light-emitting and laser diodes and other high-power electrical devices. II-VI has not announced products or a schedule, but we fully expect to see it emerge as a commercially viable player in this very important market that is currently served by only a few capable suppliers.

Across the board, photon-power technologies are now undergoing the kinds of breathtaking performance improvements that define highly disruptive industries and presage very rapid growth across a wide variety of formerly discrete markets. The power densities of high-power laser systems—the amount of raw power per pound or per unit volume of box—are rising by orders of magnitude every few years, as solid-state lasers displace gas lasers, and as quantum-crystal materials boost performance. The CO_2 gas lasers themselves are improving rapidly too, as powerchips shrink critical power supplies, and magnetic technologies eliminate bearings from high-velocity gas pumps.

The core components of infrared detectors are improving equally fast—growing cheaper and shrinking rapidly in size. Room-temperature detectors (*Infrared Imaging: Sense Out of Chaos*, January 2002) are rapidly expanding the markets and applications for infrared imaging, and military and security demands are rising rapidly in the post-9/11 environment.

In the three decades since 1971, II-VI has developed its business through steady, painstaking advances in its crystal-growing know-how. It has taken full advantage of technical improvements, and falling prices, in the markets for crystal-growth tools—crystal-growth ovens and machines for chemical and physical vapor deposition. Like so many other companies in the digital-power sector, II-VI is thus riding on the coattails of manufacturing technologies developed for the digital logic and telecom industries. This is a great trailing edge to be riding, particularly now: tools and processes that were once unimaginably expensive are now relatively cheap, and all the more so, when demand from the logic and telecom sectors is severely depressed.

II-VI uses chemical vapor deposition (CVD) tools to grow zinc-selenide crystals, physical vapor deposition (PVD) to lay down polycrystalline thorium-fluoride antireflective coatings, Czochralski crystal-growth ovens (the same devices used in silicon manufacturing) to grow the YAG, YLF, and similar family of laser-gain crystals, and High Pressure Bridgman crystal-growth processes to manufacture ZnTe and CdZnTe semiconductor detectors. II-VI's VLOC was growing 50-mm diameter YAG boules in 1996; it is now routinely growing 75-mm boules and is aiming for 100 mm within a few years. This sharply increases the number of rods that can be cut from a boule, and concomitantly lowers costs. II-VI has made similar improvements in infrared optic lenses. A decade ago, a 1.5-inch ZnSe lens cost $600; today it runs about $150.

Even if nothing else were changing, such improvements would ensure that photon projection and detection systems would be making rapid inroads in medical and industrial markets, and in military markets where the adoption process is now being greatly accelerated by the Pentagon's near-universal commitment to an altogether new generation of much smarter, faster, more compact weapons hardware. Some quite small lines of business for II-VI now present possibilities for stunning growth. The worldwide market for all solid-state radiation detectors is currently about $250 million, with the CZT market accounting for about $50 million. But with the now acute concerns about airline security, parcel shipments, and radiological weapons, these markets alone could well double and redouble over the next few years.

II-VI was never a telecom company, even if its stock did rise sharply during the bubble. The bubble burst, but II-VI's revenues were set back only slightly (8 percent) during the same period because of the widespread reductions in industrial capital spending. While other fads have come and gone, II-VI has demonstrated a decades-long commitment to mastering the growth of crystals that emerge from the obscure, power-centered recesses of the Periodic Table.

II-VI is, fundamentally, a crystal-growing company—a quantum-crystal foundry. The specific materials it works with set it sharply apart from others in the new class of quantum foundries—e.g., Wacker for silicon crystals, Cree (CREE) for silicon carbide, and AXT (AXTI) and IQE (IQE.L) for gallium arsenide and indium phosphide. All of these enterprises produce materials of purity and crystalline perfection that are simply never found in nature and that could not exist but for the new class of ultra-high-precision thermal tools—modern-day forges—that have been invented only in the last few decades: CVD, PVD, molecular beam epitaxy, and so forth.

The new industrial economy is emerging from the quantum materials provided by these quantum foundries. The handful of companies that master the exotic tools at the heart of these new foundries are destined to grow in the twenty-first century in much the same way as US Steel and Alcoa grew at the start of the twentieth. They supply the key raw materials required to supply digital logic and digital power. A very small group of companies is emerging to dominate certain choice segments of real estate in the Periodic Table. II-VI ranks prominently among them.

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)
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.