BMDO Update

Linking American Businesses to Ballistic Missile Defense Technology

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Future So Blue

Materials research brings commercial blue laser diodes closer to market

Three years ago, blue laser diodes were being touted as the next big thing, a holy grail within reach. We seemed just months away from a revolution that would quadruple the amount of information we could store on an optical disc, improve the accuracy of medical devices and the quality of desktop printers, and make possible reliable optical communication with submerged submarines. Analysts even predicted the blue laser diode market would reach $2 billion by 2006. But in 2000, the market is still in its infancy and cannot grow until there are laser diodes to meet demand.

BMDO also has a keen interest in blue laser diodes. Blue light has a shorter wavelength that allows it to carry much more information than red or infrared (IR) light. This could significantly enhance BMDO networking, data storage, and optical communications capabilities, which would in turn improve missile defense systems. For example, an optical disc based on a blue laser diode could store 15 gigabytes of sensor data, compared with today's IR-based systems, which are limited to just 0.65 gigabytes.

Despite the great demand and potential of blue laser diodes for commercial and military uses, manufacturers have been slow to bring the devices to market. Now, a year after the first commercial blue/violet laser diode was introduced, it is still alone on the market. The gap—which sometimes resembles a chasm—between the potential of blue laser diodes and the capabilities of today's technology, remains. Once we overcome the difficulties associated with making and manipulating the materials needed for blue light, the benefits will extend beyond the commercial blue laser diode market. That is why BMDO helps fund materials research at a number of companies whose various technologies are leading the way to blue laser diodes.

The Trouble With Blue

The basic design for a laser diode was established with red and IR devices in the 1960s, but the materials needed to create blue light have complicated the production of blue laser diodes. A laser diode is essentially a light-emitting diode (LED) with an optical cavity in which light is reflected back and forth and amplified until lasing is stimulated. The color of the light produced depends on the energy bandgap of the semiconductor that constitutes the device. Gallium nitride (GaN) has the ideal bandgap to produce short wavelengths of about 450 nanometers (nm), but it has proven very difficult to work with. GaN usually separates into its constituent elements when heated, so researchers had to develop

Base player. *Cree's blue laser diodes will consist of GaN active regions on a SiC substrate (pictured above). BMDO funded Cree's early research in SiC for use in electronic devices.*

a reliable process for keeping the elements together during heating and crystallization. The crystal must then have few defects, or a low defect density. Still, to get the semiconductor to produce light, it must be

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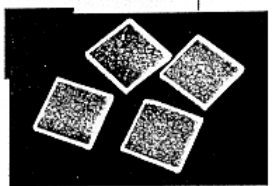
doped to create a p-n junction. It was not until the 1990s that GaN was successfully p-doped.



Blue beginnings. *Cermet has begun selling 1-cm^2 samples (pictured above) of its ZnO substrate wafers. It is working with another company to develop the substrates into blue laser diodes.*

One additional obstacle remained—and still remains—in the path to a blue laser diode: GaN cannot be grown without another material serving as a substrate.

Sapphire and silicon carbide (SiC) are currently the substrates most often used, but each has its own shortcomings. Sapphire is inexpensive and readily available, but it is neither a close lattice nor thermal match with GaN. The stresses created by these mismatches cause fractures that can render the GaN active regions useless. Sapphire's inability to conduct electricity means that an electrical contact cannot be placed on the device bottom, unless the expensive step of etching through the sapphire is added. SiC is a closer match to the lattice and thermal properties of GaN, but still not perfect, and it is very expensive to produce. The ideal blue laser diode would be made entirely of GaN, but that still requires an initial substrate on which to grow the device layers.

BMDO-funded materials research is shaping the future of blue laser diodes.

Overcoming Today's Obstacles

BMDO has been funding, at several companies, materials research that will have a direct impact on the future of blue laser diodes. Researchers at Northwestern University have come up with a novel way to decrease the defect densities that result from the mismatch of sapphire and GaN. Cree, Inc., is working to overcome the mismatch problems associated with SiC. Cermet, Inc., on the other hand, has moved on to a different substrate entirely, creating wafers of zinc oxide (ZnO).

Northwestern University's Center for Quantum Devices

The Center for Quantum Devices (CQD) at Northwestern University (Evanston, IL) has taken a significant step in overcoming the limitations imposed by a sapphire substrate. Researchers at Northwestern have designed a very simple structure that uses a gallium indium nitride (GaInN)/GaN multi-quantum well, rather than aluminum gallium nitride (AlGaN) layers. AlGaN is often used because it has a higher bandgap and a lower refractive index than GaN and GaInN, which leads to better electrical and optical confinement. However, the addition of AlGaN layers also results in defects at interfaces with GaN and GaInN; and the AlGaN layers cause higher series resistance, which in turn leads to device heating. The team recently demonstrated a laser diode that operated in continuous-wave mode at room temperature, with a wavelength of 405 nm. The laser diode lifetime was over 160 hours, still not the 10,000 hours required for a commercial device, but an important milestone, nonetheless. Northwestern received funding through BMDO's Innovative Science and Technology program for development of high-quality group III-nitride films for ultraviolet photodetectors and other devices. The next step will be to increase the lifetime of the blue laser diodes. Northwestern's CQD will be collaborating with MP Technologies, LLC, to further develop and commercialize the nitride technology.

Cree, Inc.

Cree, Inc. (Durham, NC), as producer of most of the world's SiC, has learning curve and economy of scale advantages over its competition. For example, Cree was the first U.S. company to announce demonstration of continuous-wave operation of a SiC and nitride-based blue laser diode. The company believes the unique characteristics of SiC, including its ability to function well at high power and high temperature, make it more suitable than other substrates for blue laser diodes. The natural cleave planes within SiC crystals make possible smooth mirror surfaces, without excess polishing. SiC's conductivity allows for a vertical chip structure that keeps chips small and reduces manufacturing costs. In 1999, Cree teamed with Microvision, Inc., to develop blue and green laser diodes for scanned beam display systems. Cree received BMDO funding through several SBIR contracts to develop SiC for electronic devices, including blue laser diodes.

Cermet, Inc.

Cermet, Inc. (Atlanta, GA), offers an alternative substrate to sapphire and SiC: ZnO. Like SiC, ZnO has about a two percent lattice mismatch with GaN, which means fewer defects (compared with sapphire) in the GaN active regions. ZnO is conductive, which allows contacts to be placed on both the top and bottom of a device. Like GaN, long before ZnO reaches its melting point, the elements separate. Cermet developed a new processing system to keep ZnO together throughout the

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melting and crystallizing process. They have recently begun selling 1-square-centimeter (cm^2) wafers of their ZnO, and are working with another company to develop the substrates into blue laser diodes. Additionally, Cermet is turning its attention to producing aluminum nitride (AlN) substrates. The company demonstrated the feasibility of the new process for making ZnO crystals with funding from a BMDO SBIR contract. Through a BMDO STTR contract, Cermet and partner Georgia Tech Research Corporation demonstrated production of AlN crystals. The company's next milestone will be to create one-inch, and eventually two-inch, wafers.

Tomorrow's Challenges

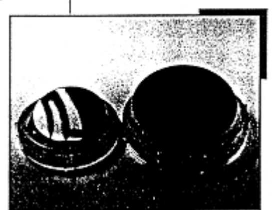
Still other research firms, including Technologies and Devices International, Inc., and Crystal Photonics, Inc., are looking ahead to the next generation of blue laser diodes, which will likely be mass-produced and based on substrates of GaN. The material continues to be a reluctant participant in the process, however, because of its inherent characteristics. But with the help of BMDO SBIR contracts, researchers at these two companies are developing the technologies for creating viable GaN substrates.

Technologies and Devices International, Inc.

Technologies and Devices International, Inc. (TDI; Gaithersburg, MD), is investigating hydride vapor phase epitaxy (HVPE) for production of multilayer GaN device structures and substrates. HVPE is a more cost-effective deposition process than metal organic chemical vapor deposition (MOCVD), which is commonly used in GaN growth. If TDI can produce wafers of GaN, homoepitaxial growth of device layers will be possible. Homoepitaxial growth, as opposed to heteroepitaxial growth, means layers are grown on a substrate of the same material. Homoepitaxial growth results in significantly lower defect densities and enhanced device quality. The company has thus far demonstrated it can produce epitaxial wafers of GaN and AlN, as well as a range of alloys of the two materials, through HVPE. For its BMDO SBIR contract, the company plans to produce a 2-cm wafer, and hopes eventually to produce 2-inch wafers.

Crystal Photonics, Inc.

Crystal Photonics, Inc. (Sanford, FL), has a novel idea for growing single-crystal substrates of GaN. The company is building a hybrid MOCVD/halide vapor phase epitaxy (HVPE) reactor that will grow large, single crystal thick films of GaN on lithium gallium oxide ($LiGaO_2$). GaN and $LiGaO_2$ are very closely lattice-matched, but not entirely chemically compatible. To protect the $LiGaO_2$ surface, a thin layer of single crystal GaN film is first grown on a $LiGaO_2$ wafer by MOCVD epitaxy, followed by the fast but corrosive HVPE process. The homoepitaxial growth of GaN on GaN limits the defect density and also retains single crystal rather than mosaic structure (which is produced when GaN is grown on sapphire or SiC with their greater lattice mismatches). The micro-boundaries found throughout a mosaic layer of GaN are the primary sources of defects. When the GaN thick-film growth is completed and cooled, it easily separates from the $LiGaO_2$ substrate because the bond between the $LiGaO_2$ and GaN is weak. The company hopes the BMDO SBIR research will produce a flat GaN single-crystal substrate that can be used for mass production of blue laser diodes similar to today's production procedures for red laser diodes using gallium arsenide (GaAs) single-crystal substrates.



The journey begins. *Using hydride vapor phase epitaxy, TDI is looking to create multilayer GaN wafers for blue laser diodes. The company already has taken its first step toward this goal—producing GaN and AlN epitaxial wafers, as pictured above.*

Despite the many difficulties that have delayed the production of commercial blue laser diodes, the potential payoff keeps these BMDO-funded companies striving toward their goal—a future in which blue laser light will light our homes, deliver our electronic messages, store and read our data, and treat our illnesses. And BMDO will have played a significant role in helping these companies get there.

—Jennifer Huergo

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