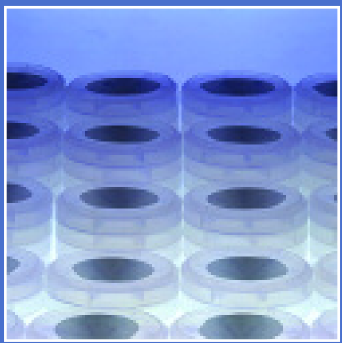
Venturing Through the Forbidden Band…

A GLANCE AT MDA'S INVESTMENT IN WIDE-BANDGAP TECHNOLOGY



Missile Defense Agency
Technology Applications Program

The Value of Technology

The Missile Defense Agencys mission is to develop and field an integrated Ballistic Missile Defense System capable of providing a layered defense for the United States and its deployed forces, friends and allies against ballistic missiles of all ranges in all phases of flight. MDA is responsible for research, development, testing, and evaluation. Using complementary interceptors, sensors, and battle management command and control systems, the planned missile defense system will be able to engage all classes and ranges of ballistic missile threats. Missile defense elements being developed and tested by MDA are primarily based on hit-to-kill technology. It has been described as hitting a bullet with a bullet——a capability that has been successfully demonstrated in test after test.

Much of this technology also can be used by other Federal agencies and Amercican businesses. MDAs Technology Applications program accelerates the maturation and commercialization of technologies funded for ballistic missile defense. The program accomplishes this mission by leveraging the expertise of technology professionals, business experts, and communicators.

The success of the mission is vital for:

- Developing superior technology for defending the United States and its allies;
- Promoting the economic growth of the Nation; and
- Enhancing the quality of life in the United States.

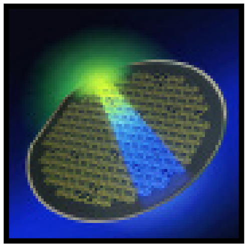
TA PROGRAM

This publication informs readers about significant Defense and commercial uses for wide-bandgap semiconductors and highlights many of the related projects funded by the Missile Defense Agency and it predecessors, the Ballistic Missile Defense Organization and the Strategic Defense Initiative Organization.

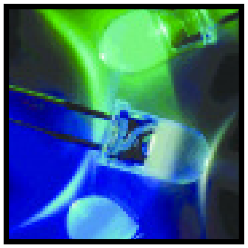
If you are interested in improvements for military radar systems, wireless communications, super-efficient lighting, electric-utility power transmission, or other power-electronics areas, you likely will find this publication to be of interest.

Table of Contents

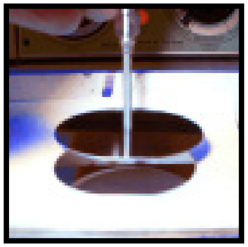
Page 16



Page 32

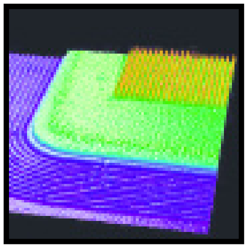


Page 26

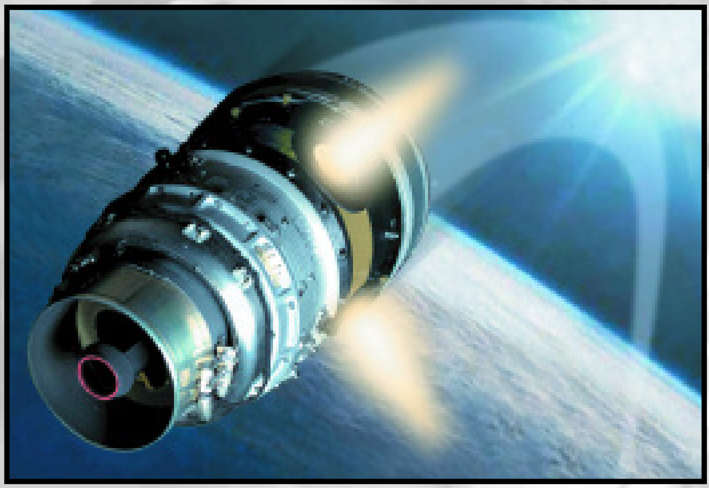


Page 12

Page 37



Page 24



Wide-bandgap semiconductors will touch nearly every aspect of our lives:

- Aircraft and space systems
- Electric power grids
- Industrial switching
- Military radar systems
- Wireless communications
- Commercial and residential lighting
- Chemical and biological-agent detection
- Data storage

Notes on Wide Bandgap

Venturing through the forbidden band . . .

Over the past three decades, industry and the U.S. Government have invested hundreds of millions of dollars in an emerging area called wide-bandgap materials. The technical significance of these materials is that they can be made into semiconductor devices capable of handling much higher voltages than silicon, while withstanding and operating at much higher temperatures. Such materials also have unique optoelectronic capabilities that allow them to emit blue and UV light. Thus, many aspects of our lives can be touched by transistors and diodes made from a new class of materials.

What makes a semiconductor “wide bandgap”? The answer remains at the atomic level of the material. A range of energies called “the forbidden band” separates the valence band and the conduction band of a solid-state material. The valence and conduction bands hold electrons; however, no electrons may reside in the forbidden band. When the forbidden band is wider, more energy is required to promote an electron from the valence band into the conduction band. If a material has no forbidden band (i.e., the conduction band is the valence band), it behaves as metal. If it has a very wide band, it is a good insulator. Semiconductors lie somewhere in the middle. When we speak of wide-bandgap materials, we are referring to gallium nitride (GaN), silicon carbide (SiC), and other compound semiconductors that have a relatively wide forbidden band (on the order of between 1.7 and 7 electron volts) compared with silicon and gallium arsenide.

More work is still needed for this technology to be available for many of the applications mentioned in this publication. Issues such as gate leakage and defect densities (which affect wafer size) need to be addressed. Large-scale manufacturing has not been fully implemented for applications, and researchers are still experimenting with techniques to bring this technology up to scale. Substrates made from materials such as SiC and GaN (which offer good lattice matches) that can be mass-produced are also needed. However, when these issues are fully addressed, wide-bandgap semiconductors will have a far-reaching impact on our natural resources, Defense capabilities, and the U.S. economy.

Solid-State Power Electronics

INDUSTRIAL PLANTS, AIRCRAFT, MILITARY SHIPS AND SUBMARINES, SPACE SYSTEMS, AND THE POWER INDUSTRY ALL CAN BENEFIT FROM WIDE-BANDGAP POWER ELECTRONICS.

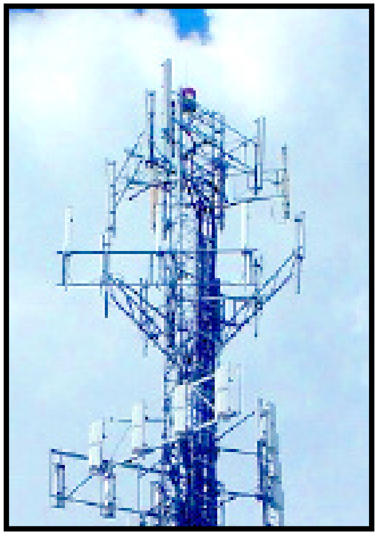
In 2001, the U.S. economy experienced an estimated $120-billion loss in productivity due to power-quality and reliability problems, which wide-bandgap technology may address.

Wide-bandgap semiconductors are ideal candidates for serving as solid-state power electronics (e.g., switches and actuators), thus replacing electromechanical devices used today. They present advantages over other semiconductor materials such as silicon and gallium arsenide, which cannot withstand high voltages and heat as well. Industrial plants, aircraft, military ships, submarines, space systems, and the power industry could benefit from this technology.

One notable potential beneficiary, our Nation's power grid, illustrates the utility of wide-bandgap semiconductors for power electronics. According to a 2001 study conducted by the Electric Power Research Institute, the U.S. economy experienced an estimated $120-billion loss in productivity from problems associated with power quality and reliability. (Total retail sales of electricity are roughly $220 billion.) To address this problem, the electric-utility industry is investigating smart power-delivery systems. Such systems would employ microelectronics to increase the efficiency of electricity transmission and service by reducing, detecting, and addressing power disturbances, and maximizing the amount of current that can go over existing transmission lines. They include flexible alternating-current transmission systems, or FACTS, which use a series of microprocessors to control the flow of current.

FACTS have been used on a limited basis on the power grid, using silicon microprocessors; however, employing wide-bandgap materials, rather than silicon, could greatly simplify such systems while significantly improving their performance. For example, microprocessor devices made from silicon carbide could double the voltage per device, reducing the number of microprocessors needed in series in a "valve." They could increase operating frequency from about 500 hertz in today's material to about 20 kilohertz. Thus, utilities could save significant dollars in auxiliary controls and reduce the size, cooling requirements, and maintenance of systems.

Radio Frequency and Microwave Communications

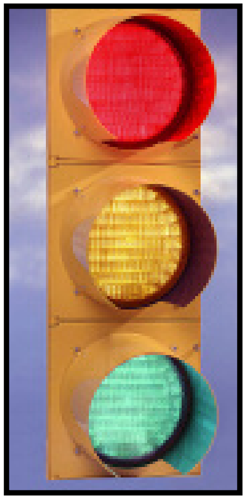


WIDE-BANDGAP TECHNOLOGY PRESENTS ADVANTAGES TO BOTH MILITARY RADAR AND COMMERCIAL WIRELESS COMMUNICATIONS.

Cooling requirements, size, weight, and maintenance are concerns for anyone developing communications electronics. Ballistic missile defense is no exception. Wide-bandgap semiconductor devices offer advantages in all these areas, potentially serving as better alternatives to MDA and other military systems. One competitor is the vacuum tube, an old technology that can withstand high power; however, it is bulky and needs frequent replacing. The other is gallium arsenide, a solid-state solution less capable of withstanding high voltages and heat. Devices made from wide-bandgap semiconductors theoretically will last significantly longer than vacuum tubes. Therefore, radar systems using such technology would be less expensive and easier to maintain while also being smaller and requiring less cooling. Wide-bandgap devices operate at higher powers than gallium arsenide and can withstand higher temperatures. A radar system using wide-bandgap materials, as opposed to gallium arsenide, can theoretically transmit more data at a greater distance or using fewer components. Either way, cooling requirements are greatly reduced, translating to significant savings in weight, size, and maintenance of the overall system. Defense can fully utilize such devices once technical hurdles are overcome, including one order of magnitude improvement in uniformity of epitaxial layers and better understanding of how material properties correspond to devices. The military is currently developing devices such as metal semiconducting field effect transistors (MESFETs) and monolithic microwave integrated circuits (MMICs) made from wide-bandgap materials.

The technology also presents similar advantages to the commercial sector, offering significant benefits for next-generation wireless communications systems. Wide-bandgap technology could transfer more information at higher efficiencies than silicon microelectronics currently being used at satellite or ground base stations. This capability translates to a better-quality signal for customers and allows a higher volume of calls or data to be handled on a given system. Such technology would be especially beneficial as cellular telephones perform more functions (e.g., multimedia capabilities), which require greater bandwidth.

Wide-bandgap technology could transfer more information at higher efficiencies, producing a better-quality signal for customers and higher volumes of calls or data.



High-Brightness Light-Emitting Diodes

WIDE-BANDGAP TECHNOLOGY IS ALREADY BEING USED FOR TRAFFIC SIGNALS, THE LIGHTS ON BROADWAY, AND AUTOMOBILES EVEN THE NATIONAL CHRISTMAS TREE.

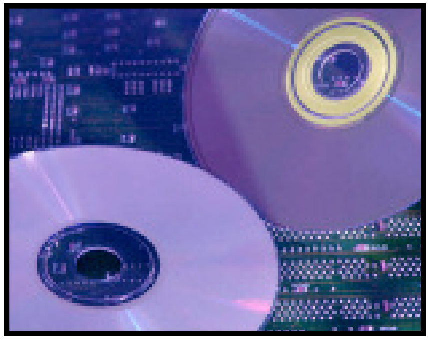
If every incandescent traffic light in the Nation were replaced with an LED signal, we would save 3.3 billion kWh of electricity and replace each light only once or twice in a decade.

The unique capability to emit light has already played a vital role in wide bandgap's commercialization, accounting for millions of dollars in sales; its impact will be even greater in the future. While industry could mass-produce red and yellow light-emitting diodes (LEDs), capabilities did not exist to make the cooler colors (which had shorter wavelengths). Wide-bandgap semiconductors enabled green and blue LEDs, completing the color spectrum and allowing for full-color displays, including the ticker tape in New York's Times Square, traffic lights throughout North America, and LEDs for backlighting and automotive panels.

While the energy, maintenance, and cost savings for traffic lights alone is intriguing, it does not hold a candle to the major impact that white LEDs, currently being developed for large-scale use, will have. As costs go down and technical issues are addressed, LEDs using wide-bandgap materials are expected to revolutionize the entire lighting industry, replacing existing incandescent and fluorescent lighting with a brighter and far more energy-efficient alternative. One study suggested that white LEDs, if fully implemented, would save up to $115 billion per year in electricity by 2015, reducing air pollution and other waste generated by power plants. While this industry is in its infancy, the first demonstrations of LED-based technology have recently occurred, first at an Austrian company, Barenbach Lighting Laboratory, in 2000. It was also demonstrated at an LED-based household lighting project implemented in remote communities of Nepal (142 households and two schools) in 2001. Interestingly, due to the LEDs' low electricity consumption, the devices superseded the kerosene wick lamps and burning sap-filled pine sticks used by the communities. Single white LEDs have already begun to be mass-produced for use such as night lights but are still years away from being fully commercialized.

Wide-bandgap semiconducting light-emitting devices can also be used for medical applications. For example, they could serve as a light source for photodynamic therapy in treating cancer patients. They could also be used as a light source in the treatment of seasonal affective disorder (SAD), which affects roughly 6 percent of the U.S. population in temperate zones. They also have been marketed as a long-lasting, low-glare, low-temperature replacement for halogen curing lights used for dental hardening.

Sensors and Data Storage



WIDE-BANDGAP MATERIALS CAN BE USED IN APPLICATIONS RANGING FROM BIOLOGICAL DETECTION TO DVD DATA STORAGE.

Ultraviolet (UV) Detection

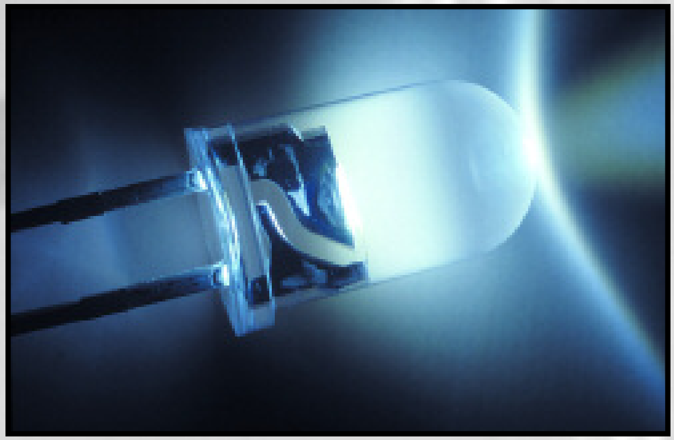
Wide-bandgap semiconductors can replace older methods of ultraviolet detection with a simpler and more efficient alternative. Being able to detect signals in the ultraviolet portion of the electromagnetic spectrum has significant value for a wide range of applications, including ballistic missile defense. For example, wide-bandgap-based detectors serve as "solar blind" detectors, by designing the detector, such that, it does not "see" solar wavelengths—a capability unobtainable with infrared detectors. They also enable submarines to communicate underwater in a stealthy manner and emergency responders in homeland defense to detect chemical and biological agents having strong signatures in the UV range.

In the commercial sector, UV detectors likewise have many applications. They can be used in the medical arena for sterilization and in heavy industry for engine monitoring and flame and heat sensors. UV detectors made from wide-bandgap materials present advantages over two traditional approaches for UV detection used today. One traditional approach is the photomultiplier tube—a large, fragile device requiring high voltages and frequent maintenance. These tubes are also sensitive to magnetic fields, which further limits their applications. The other approach is the silicon photodiode, which requires external filtering to block out the visible and IR light. Detectors using wide-bandgap devices do not share these problems associated with the more conventional approaches.

Data Storage

Finally, wide-bandgap semiconductors can be used to make ultraviolet, violet, and blue laser diodes—technologies hotly pursued by industry to meet the Blu-ray Disc standard for high-density DVDs. DVD systems now use red laser diodes for write and readout and have a capacity of only about 4.7 gigabytes; however, that is not enough storage capacity for the storage requirements of high-definition telivision (HDTV), which consumes almost 15 gigabytes for a one-hour show. However, according to the June 2003 issue of *Photonics Spectra*, violet laser diodes will be able to store up to 27 gigabytes of data on a single-sided DVD. Four years after the first blue laser diodes has been demonstrated, industry still plans to launch products in this area, with Sony and Nichia scheduled to release a violet laser diode for this application in the near future.

Violet laser diodes will be able to store up to 27 gigabytes of data on a single-sided DVD.

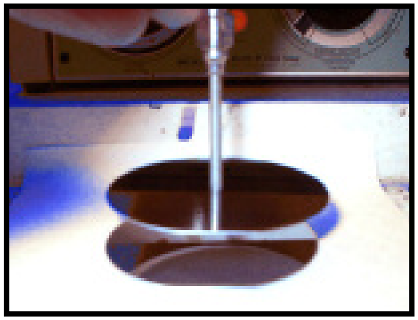


Wide-bandgap semiconductors are being or have been developed by the Missile Defense Agency using a wide range of materials:

- Silicon carbide
- Gallium nitride
- Zinc oxide
- Aluminum nitride
- Indium gallium nitride
- Aluminum indium gallium nitride

A Glance at MDA's Investment

The following pages highlight many of the stories describing MDA-funded research in the area of wide-bandgap semiconductors that is being commercialized. Through its science and technology programs, as well as the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, MDA has funded scores of efforts in this growing area since its inception as the Strategic Defense Initiative Organization. Some of this research has been at universities that are major players in this field, such as the University of South Carolina and North Carolina State University, where much of its progress began. Research at these universities has spawned new businesses, which have, in turn, received contracts through MDA's SBIR and STTR programs. Many small businesses receiving SBIR and STTR funding for wide-bandgap materials have capitalized on lucrative markets and, in two cases, have grown to become large public companies and major competitors in the global market.



Astralux, Inc.

- MATERIAL: Silicon carbide
- DEVICES: Hybrid wafers, heterojunction bipolar transistors
- PURSUED APPLICATIONS: RF electronics

Astralux estimates its hybrid SiC transistors will cost 70 to 80 percent less than those produced using substrates made completely of SiC.

Astralux received an MDA SBIR research contract in 2002 to address the high cost of silicon carbide (SiC) semi-insulating bulk material by developing high-quality, large-diameter, low-cost hybrid SiC wafers. To produce transistors for power and radio frequency (RF) electronics that can survive high temperatures, fabricators require high-quality semi-insulating SiC, having a much higher degree of orientation, and lower defect densities as compared with SiC substrates used for high-brightness lighting. Therefore, the processing requirements for semi-insulating SiC are much greater than those for SiC substrates for high-brightness lighting; the semi-insulating materials produced in lower quantities; it has limited availability through domestic suppliers; and it is extremely expensive. One wafer costs $3,000 to $4,000 as compared with a two-inch SiC substrate for high-brightness lighting, which is about one third of the cost and even less when mass-produced.

Researchers at Astralux are using bonding, ion implantation, and separation processes to reduce the amount of high-cost semi-insulating SiC needed for wafers. The company estimates that with its approach, SiC transistors will cost 70 to 80 percent less than those produced using substrates made completely of SiC semi-insulating material. The company approaches this problem by slicing off very thin membranes of the high-quality SiC wafers and bonding them to relatively inexpensive bulk carriers such as silicon. Transistors are then grown on the hybrid substrates.

This "slicing and bonding" process is not analogous to slicing a loaf of bread and making a sandwich, but rather uses a bonding process similar to the silicon-on-insulator process, which is well established in the commercial market. Wafer bonding is a process by which dissimilar materials are made to be extremely flat, cleaned, and pressed together. The materials are then held together through van der Waal attraction forces. If the materials are exceptionally clean and flat, chemical bonds will form even at room temperature; however, typically the chemical bond formation requires elevating the temperature and using an annealing step. Astralux does bonding and separation processes in-house, and subcontracts out the ion implantation work.

In another MDA SBIR project worth noting, several years ago Astralux developed the first transistor to operate above 500°C with a current gain over 100. At room temperature, this heterojunction bipolar transistor (HBT) had a current gain of over 10 million, and at 535°C, the highest temperature reached by Astralux's equipment; it had a gain of 100. The device was operated at a current density of 1,600 amperes per square centimeter and a power density of 30 kilowatts per square centimeter. Since this work was done, the SiC technology has achieved a breakdown voltage greater than 5 kilovolts and the HBT has operated at 2 kilo-amperes per square centimeter.

Where they are today

Researchers at Astralux fabricate 2-inch wafers and are currently developing 3-inch prototypes. They are also experimenting with other mechanical wafers that can be processed at higher temperatures than silicon. The company has received notice of allowance on a bonding-related patent and plans to scale up its process to sell this as a product.

Astralux is a six-employee company with 3,100 square feet, several CVD reactors, and an optical characterization lab that allows the company to perform cathodoluminescence, photoluminescence, and electroluminescence. The company can perform full optical and electrical characterization of wide-bandgap devices. Its business strategy is to license out technology, and to this end, the company recently executed its first deal, which led to the formation of a spinoff company, PowerSicel. Astralux has licensed a bipolar junction transistor related to the HBT work and has ongoing development projects with PowerSicel. Astralux also has partnerships with EMCORE Corporation, Colorado State University, UCLA, and the Naval Research Laboratory.

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Suggested Reading

High-Temperature Transistor
Web: www.mdatechnology.net/techsearch.asp?articleid=321#listing

New Transistor Beats the Heat
BMDO Update, Summer 1999

Astralux has partnerships with EMCORE Corporation, Colorado State University, UCLA, and the Naval Research Laboratory.

ATMI, Inc.

- MATERIAL: Gallium nitride
- DEVICES: Substrates and epitaxy for devices
- PURSUED APPLICATIONS: Radar, data storage, UV sensors and emitters

ATMI is using a technique called hydride vapor phase epitaxy to grow gallium-nitride boules at rates greater than 100 microns per hour.

ATMI, Inc. (Danbury, CT) is manufacturing and selling gallium nitride (GaN) substrates and epitaxy to consumer and defense electronics manufacturers. In 1994, BMDO awarded the company a few SBIR contracts related to this work. As part of these contracts, ATMI has explored the use of these substrates for transistors used in radar. The company has also explored the benefits of these substrates for the laser-diode and ultraviolet (UV) light-emitting diode (LED) industries.

The company is using a technique called hydride vapor-phase epitaxy (HVPE) to grow GaN boules at a growth rate greater than 100 microns per hour. Inside a hot-walled HPVE reactor, the GaN boules are originally grown on sapphire, which is then separated from the GaN. Once grown, the GaN boules are fabricated into wafers using conventional techniques. A chemical-mechanical polish process is used to remove any damage created during fabrication. The process may be used to produce material of improving quality by using the best GaN wafer to use as a seed to grow the next GaN boule. Two-inch-diameter wafers are fabricated and are processed into devices by ATMI's customers.

GaN lends itself to more effective electronic devices as well. High thermal conductivity, wide-bandgap energy, and high breakdown field and electron mobility allow GaN to be effective for use in high-power, high-frequency applications. Low-defect-density GaN substrates extend GaN's intrinsic materials advantages to many technologies including blue laser diodes, radar and UV LEDs. Using the same material in the substrate as in the epitaxial layer creates a smaller dislocation density, which improves device performance and yield.

Where they are today

Originally called Advanced Technology Materials, Inc., ATMI was founded in 1986 by four entrepreneurs. The company's focus is on creating new materials using chemical vapor deposition technology. ATMI has developed new semiconductor materials; packaging, delivery, and abatement systems; and solid-state sensors.

The company is publicly traded on the NASDAQ, with more than $223.8 million in sales and 1,000 employees, and has sales representatives in the United States, Europe, Japan, and Korea. It received a significant amount of funding for ballistic missile defense applications starting in 1987, just a year after it was founded, and graduated from the SBIR program in 1998 after growing its employees-base above 500. GaN substates are being developed through its division called ATMI GaN.

ATMI began selling 2-inch GaN substrates and expitaxy for blue laser diodes, light-emitting diodes, and high-performance electronics in May 2003 to major consumer electronics companies. The new free-standing GaN substrate products have a uniform dislocation density of 10^6 per square centimeter in contrast to other GaN wafer products that have a low dislocation density only in select regions, which restricts device size and placement.

The company also has a contract with the Defense Advanced Research Projects Agency's Wide Bandgap Semiconductor Technology Initiative to develop its substrates further for use in radar applications. The company has more than 20 patents issued on this technology.

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Other MDA-related stories about ATMI's work

GaN Microelectronics
Web: www.mdatechnology.net/techsearch.asp?articleid=559#listing

Bulk Gallium Nitride Substrates Now Available
MDA Update, Winter 2002/2003

Note:

ATM's GaN Division was acquired by Cree, Inc., at the time this report was produced.

Cermet, Inc.

- MATERIAL: Zinc oxide
- DEVICES: Substrates for gallium nitride
- PURSUED APPLICATIONS: Data storage, high-brightness lighting

Cermet is using zinc-oxide material as a substrate to address costly problems associated with lattice mismatch while also providing a speedy approach to substrate fabrication for wide-bandgap materials.

The promise of gallium-nitride (GaN) devices is dependent on the type of substrate used in device production. With MDA (formerly BMDO) SBIR and STTR funding, Cermet, Inc. (Atlanta, GA), has developed a patented process and equipment for fabricating zinc-oxide (ZnO) crystals, which may be fabricated into 50-millimeter-diameter substrates for use in blue lasers and high-brightness light-emitting diodes..

In a competing approach, GaN is grown on sapphire substrates. This method is problematic because sapphire substrates have a lattice mismatch with the GaN layers of about 16 percent, which stresses and damages the immediate surface layers of GaN. Technicians are therefore forced to place two or three sacrificial layers of GaN on the substrate, resulting in an additional cost of $700 to $1,000 per layer.

An alternative is zinc oxide, which only has a 2-percent lattice mismatch with GaN—not enough to seriously affect the operational integrity of the wafer. ZnO crystals, however, until now, have been extremely costly to produce because they degrade when heated at atmospheric pressure. Cermet's approach can produce high-quality zinc-oxide crystals at a much lower cost than current vapor growth processes and, thus, may be the enabling technology for the blue laser's large-scale entry into the commercial marketplace.

Cermet uses a patented pressurized melt-growth (modified Bridgman growth) process, which employs a high-pressure chamber, radio frequency (RF) heating, ZnO powder, and a cold crucible. The pre-crystalline material, ZnO powder, is placed in the cold crucible, where RF energy is used as the heat source, producing a molten phase. This entire melting-and-containment process is carried out in a controlled gas atmosphere of less than 100 atmospheres, so that volatile materials are not produced and compounds do not decompose into atomic species. The patented process produces 1- and 2-inch-diameter by 11-inch high crystal cylinders in less than 24 hours. Once the orientation is verified, the cylinders are sliced and polished, ready for sale.

Cermet's process has been proven at temperatures exceeding 3,600°C and melt environments in excess of 100 atmospheres. It is especially useful for crystallized materials with melting points above 1,450°C, volatile components in the structure, and thermodynamic instabilities at or near the materials melting point at atmospheric pressure.

Where they are today

Founded in 1991, Cermet is a materials research and development company housed in approximately 11,000 square feet of laboratory and office space. This facility contains Cermet's bulk crystal foundry, nitride- and oxide-epitaxy foundry, a prototype-device fabrication facility and a material- and electrical-characterization facility. Cermet produces and sells 1- and 2-inch ZnO bulk wafers. The process is scalable, and Cermet is looking at expanding to 4-inch wafers.

In March of 1999, the *Red Herring* selected Cermet as one of 44 of the hottest high-technology companies in the Southeast. Cermet is also a member of the Yamacraw Organization, an economic development initiative to make Georgia a world leader in the design of broadband communications systems, devices, and chips.

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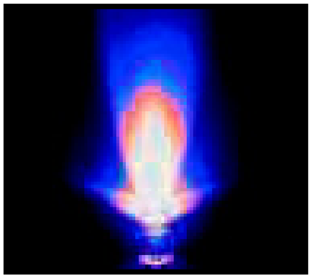
Other MDA-related stories about Cermet's work

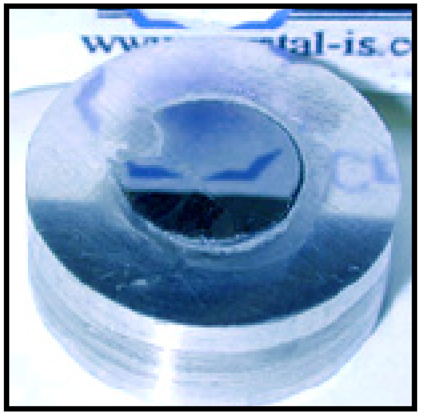
A Bulk Crystal Growing Process for Wide Bandgap Substrate Materials
Web: www.mdatechnology.net/techsearch.asp?articleid=441#listing

Future So Blue
BMDO Update, Spring 2000

Window of Opportunity Crystal Clear for Blue Lasers
BMDO Update, Summer 1999

Cermet produces and sells limited quantities of bulk zinc oxide wafers.





Crystal IS, Inc.

- MATERIAL: Aluminum nitride
- DEVICES: Substrates
- PURSUED APPLICATIONS: General

Crystal IS corporate officials indicate the company has developed some of the largest aluminum-nitride single crystals.

Crystal IS, Inc. (Watervliet, NY), has used funding from the MDA SBIR program, as well as other DOD sources, including the Defense Advanced Research Projects Agency, and the Office of Naval Research, to develop a competitively priced single-crystal aluminum-nitride (AlN) substrate that is isostructural with III-nitride epilayers. It possesses higher thermal conductivity, low thermal-expansion mismatch, as well as relatively low lattice mismatch with gallium nitride (GaN). In the absence of economical GaN substrates, diode producers are using sapphire and silicon-carbide (SiC) substrates. SiC offers higher thermal conductivity than sapphire, but both substances have relatively large thermal-expansion coefficient mismatch with GaN, creating cracking problems during the growth of the epitaxial layers.

The AlN substrate's low lattice and expansion coefficient mismatch with GaN virtually eliminates cracking during the temperature shift from epitaxial growth to room temperature. The high thermal conductivity measured at 340 watts per meter-Kelvin (W/m-K) and high electrical resistivity makes AlN ideal for high-power applications such as the U.S. Navy's Advanced Multifunction Radio Frequency System program to develop an integrated radio frequency (RF) system. Additionally, AlN is the perfect substrate for high aluminum-fraction III-N device layers, which poses benefits for higher-power RF devices and ultra-high-efficiency ultraviolet (UV) and deep-UV devices. The latter may have important biological molecule-sensing applications.

According to Crystal IS, it has developed AlN substrates that are larger in diameter than any other AlN single crystal in the world. The company uses proprietary sublimation growth technology, which includes innovative crucible technology that can withstand hundreds of hours of continuous crystal growth. It can produce crystals that have much lower defect densities, and are grown with excellent crystal growth rates exceeding all previous nitride semiconductor records (close to 1millimeter [mm] per hour).

Where they are today

The company recently announced the demonstration of 25-mm-diameter substrates as well as the availability of limited quantities of ultra-low dislocation density A-plane, M-plane, and C-plane A1N substrates. The company can offer "virtually any" customer-specified crystallographic orientation while maintaining dislocation densities of less than 1,000 square centimeters. According to the company, other approaches produce much higher dislocation densities and are limited in terms of available crystallographic orientation. The company currently offers 12-mm-diameter substrates, and plans to offer 50-mm-diameter substrates in limited quantities in 2004.

AlN substrates could be used in GaN semiconductor devices for wide-bandgap semiconductor applications, such as high-power switches for electricity grids, satellite communications, light-emitting diodes, or higher-capacity CD-ROMs and DVD players using blue lasers.

Crystal IS was incorporated and founded in New York State, in March of 1997. Currently, the company is part of the small business incubator on the Rensselaer Polytechnic Institute (RPI) campus and has teamed to conduct joint development with several universities and companies, such as the University of South Carolina, Sensor Electronic Technology, Inc., Kansas State University, and Lumileds. It has also worked with U.S. Government agencies including the Air Force Research Laboratory, the Naval Research Laboratory, and Sandia National Laboratories. The company's current focus is to increase the quality and the diameter of its AlN crystals. The company has received favorable U.S. Patent and Trademark Office actions on several pending patents. Substrates greater than 25 mm in diameter have been produced.

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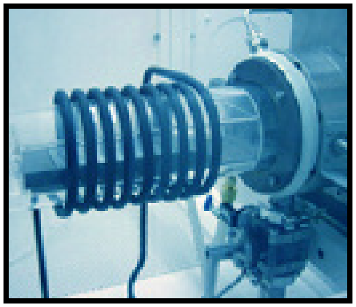
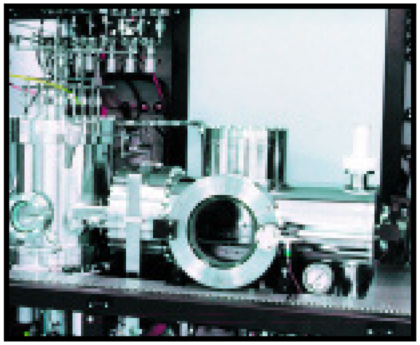
Suggested Reading

Development of Single-Crystal AlN Substrates
Web: www.mdatechnology.net/techsearch.asp?articleid=503#listing

Alternate Substrate Developed for GaN Electronics
BMDO Update, Spring 2001

The company has teaming relationships with several companies and universities, including the University of South Carolina.





EMCORE Corporation
GELcore, LLC

- MATERIAL: Indium gallium nitride
- DEVICES: Light-emitting diodes
- PURSUED APPLICATION: High-brightness lighting

Early funding of the TurboDisc® reactor has led to a wide range of LED products on the market today.

During the late 1980s, the former Strategic Defense Initiative Organization (now MDA) funded EMCORE (Sommerset, NJ) through the SBIR program to develop a process for making compound semiconductors using atomic layer epitaxy in a rotating-disk reactor. Metal-organic chemical vapor deposition (MOCVD) was a principal deposition technology process during the formative period of compound semiconductor materials, but realistically, it was viable only on a laboratory scale. EMCORE's TurboDisc® opened the door to controlled, high-quality material growth to support full-scale commercial production. Using TurboDisc, EMCORE has produced many wide-bandgap semiconductor materials, including materials based on gallium nitride (GaN).

The TurboDisc system is vacuum-loadlocked and uses a high-speed, rotating substrate holder. To produce an epitaxial layer, feed gases are introduced into the reaction chamber where high temperatures dissociate the gases into constituent elements. These newly liberated reactants combine at the substrate wafer surface where the proprietary TurboDisc geometry ensures uniform temperature and reactant gradients to form the compound layers.

Using TurboDisc, EMCORE has produced GaN films with thickness uniformities as tight as 2 percent on a multiwafer production scale. Additionally, EMCORE demonstrated reproducible n- and p-type doping in the GaN, and has grown high-quality aluminum gallium nitride (AlGaN) and indium gallium nitride (InGaN). Numerous other group III-V compounds have been developed as well as silicon carbides and complex oxides.

In 1999, EMCORE and GE Lighting formed a strategic partnership called GELcore (Valley View, OH) to use the same semiconductor technology to develop and sell high-brightness light-emitting diodes (LEDs) and LED systems. Their current stable of products include LED traffic signals and the GE Tetra™ brand of channel-lighting, cove-lighting and border-tube products. Tetra products use ultrabright LEDs made from aluminum-indium-gallium-phosphide (AlInGaP) and indium-gallium-nitride (InGaN) materials, like those made using the TurboDisc MOCVD reactor.

Where they are today

Since MDA's first funding four years after the company's inception, EMCORE grew significantly, issuing a public offering in March 1997 under the ticker symbol EMKR (NASDAQ). It sold hundreds of millions of dollars in materials and TurboDisc Systems and established many partnerships beyond General Electric, to include companies such as General Motors and Agilent. EMCORE's TurboDisc business was sold in November 2003 to Veeco Instruments, Inc. The sale of EMCORE's MOCVD division will allow the company to focus on its communications product lines, including fiber-optic, wireless, CATV, and satellite products, and the joint venture with GE, which concentrates on high-brightness LEDs and LED systems.

GELcore, LLC, is a 200-employee company that develops innovative LED systems and advanced LED technologies for general illumination. Its product line includes discrete LEDs for automotive use and LED systems for traffic signals, indoor/outdoor signage, and specialty lighting applications. The company has corporate headquarters in Valley View, OH, with additional manufacturing R&D and field offices across the globe. One of its worldwide customers for traffic lights is the state of California, which has historically faced electricity-capacity and transportation issues.

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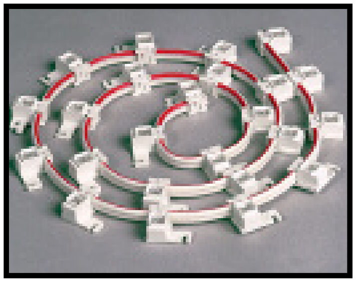
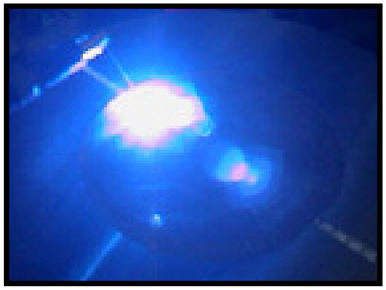
Suggested Reading

TurboDisc® Metal-Organic Chemical Vapor Deposition
Web: www.mdatechnology.net/techsearch.asp?articleid=366#listing

White LEDs Illuminate a New Lighting Path
BMDO Update, Winter 2000

GELcore's product line includes discrete LEDs for automotive use and LED systems for traffic signals, indoor/outdoor signage, and specialty lighting applications.





Kyma Technologies, Inc.

- MATERIAL: Gallium nitride
- DEVICES: Substrates
- PURSUED APPLICATIONS: High-brightness lighting, data storage

Kyma is producing gallium-nitride substrates using a fast-growing vapor-phase process based on technology licensed from North Carolina State University.

Through the SBIR program, BMDO (MDA's predecessor) funded Kyma Technologies, Inc. (Raleigh, NC), to develop gallium nitride (GaN) substrates for X-band radar. According to Kyma, the process technology has a growth rate up to 10 times faster than any other commercialized deposition process for nitride-based materials and can be scaled up to the larger 4-inch-diameter wafer size. The process provides a very high material quality at one-tenth the cost of other manufacturing processes. In addition, Kyma's process can grow multiple wafers simultaneously out of large crystals. Moving to wafers larger than 2 inches will create lower cost opportunities through process scaling.

To fabricate its GaN wafers, Kyma is using a fast-growth vapor-phase process. The technology combines a chemical vapor-phase process to grow the bulk GaN material and a physical vapor-phase process, licensed from North Carolina State University (NCSU), to provide a starting template that ensures excellent uniformity and very high crystal quality.

GaN substrates are matched in lattice constant and thermal expansion properties for epitaxial growth of doped GaN layers needed for fabrication of GaN-based devices. This eliminates stress and defects induced by growing GaN epilayers on non-nitride substrates such as sapphire or silicon carbide, which increase device fabrication complexity and cost and compromise device performance. Kyma's high-purity GaN substrates allow GaN-based device manufacturers to eliminate processing steps and improve device quality compared with those grown on other substrates.

Kyma, as a start-up company, received some of its first funding in wide-bandgap semiconductors from BMDO beginning in 1999 through an STTR contract for aluminum nitride, under the name Carolina Sputter Solutions. The company subsequently changed its name and received several Phase I SBIR contracts and two Phase II contracts for prototype development, all related to GaN.

Where they are today

Kyma Technology is a 16-employee small, privately held business. In June 2003, it attracted $4 million in venture funding, led by Digital Power Capital and Siemens Venture Capital, which will add six new staff members and increase its production capabilities by early 2004.

Kyma plans to produce 4-inch GaN wafers by the end of 2004. These wafers are needed for next-generation optoelectronic and microelectronic technology applications. The company's customers are in the optoelectronics industry, which is currently capable of using only 2-inch GaN wafers. The most prominent application of Kyma's GaN wafers is for optical data storage, where the short wavelengths of the laser diodes provide higher performance.

Kyma is currently partnered with RF Micro Devices on an MDA SBIR Phase I, and the company is also working with several universities, including North Carolina State University, on SBIR projects.

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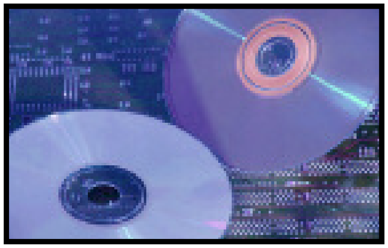
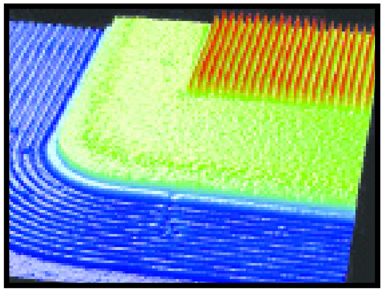
Suggested Reading

Four-Inch GaN Wafers to Debut in 2004
MDA Update, Winter 2003/2004

Kyma recently received $4 million in venture funding and plans to produce 4-inch gallium nitride wafers by the end of 2004.





Mississippi State University SemiSouth Laboratories, Inc.

- MATERIAL: Silicon carbide
- DEVICES: MESFETs, VJFETs, and other RF and power electronics devices.
- PURSUED APPLICATIONS: Power and RF electronics

Mississippi State University has spun off a small business to commercialize its silicon carbide transistors.

With significant MDA science and technology funding, engineers at Mississippi State University (MSU: Mississippi State, MS) are conducting research and building a facility to prototype silicon carbide (SiC) rectifiers and power transistors in relatively large quantities. The university has spun off a small business, SemiSouth Laboratories, Inc. (Starkville, MS), to commercialize this technology and further develop it with MDA SBIR funding.

Using an epitaxy process based on low-pressure chemical vapor deposition (LPCVD), the university researchers are fabricating multiple transistors with varying properties, layer by layer, on a single wafer up to 3 inches in diameter. The wafers are fabricated so that, once diced, a strip of transistors are combined on one device/chip. In addition, a recently allowed patent resulting from MDA work could lead to the elimination of packaging steps such as wire bonding, as in a multichip module, or combining several individual integrated-circuit (IC) devices. Having all circuits vertically integrated on one wafer/chip significantly improves the efficiency and reliability of the power electronics, while decreasing size, production time, and cost of the electronics package.

MSU has made significant progress in this area, producing metal semiconductor field-effect transistors (MESFETs), vertical-junction field-effect transistors (VJFETs), Schottky rectifiers, and other types of power electronics. As part of its efforts, MSU has also developed and demonstrated an epitaxy process that addresses issues concerning the extreme hardness of SiC.

Where they are today

MSU researchers and SemiSouth are working closely to bring this technology to commercial and military markets and have several government research projects under way in addition to those from MDA. The university, in conjunction with Mississippi state government and venture capital investors, is building a research park that houses a 5,000-square-foot cleanroom inside the new Ralph E. Powe Center for Innovative Technology.

The Class 1,000 cleanroom holds MDA-funded processing equipment. In addition, Lam Research, IBM, and Northrop Grumman donated major tools to the cleanroom. SemiSouth will lease these facilities to scale up the SiC technology to production levels and has participated with the university researchers on several projects. There is considerable spillover between projects, to which MDA has contributed significantly. For example, Lockheed Martin, General Electric, and MSU have teamed with SemiSouth under a Phase III SBIR project with SemiSouth to develop SiC MESFETs for a U.S. Marine Corps long-range radar upgrade. As part of this project, the Marines are providing SemiSouth with a commercial SiC epi reactor, which may be housed in the incubator's new cleanroom.

SemiSouth spun off from MSU in 2001 and is planning to lease the incubator facilities to scale up the SiC technology to production levels and has participated with university researchers on several projects. The company is primarily pursuing power-electronics applications, such as switches for electric utility transmission and actuators for industrial controls. SiC power rectifiers are expected to be available through Semisouth by early 2004. The company currently has 14 employees.

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Suggested Reading

SiC to Cut Transistor Bulk, Cost
MDA Update, Fall 2000

SemiSouth plans to release silicon-carbide rectifiers and switches in 2004.

North Carolina State University
Cree, Inc.

- MATERIAL: Silicon carbide
- DEVICES: Solid-state lighting, MMIC wafers
- PURSUED APPLICATIONS: High-brightness lighting, RF communications

Start-up funding from the Strategic Defense Initiative as well as other sources were the beginnings of this large public company.

In its early years, the Strategic Defense Initiative Organization (SDIO) invested in research at North Carolina State University (NCSU: Raleigh, NC) through its Innovative Science and Technology (IS&T) Directorate. IS&T invested in wide-bandgap materials to address a handful of missile defense challenges, such as solid-state radar systems with amplifiers having longer life, small electronic switches that could withstand higher power surges. NCSU's share of investment was under a group led by Dr. Robert Davis to fabricate and control the growth of nitride-based materials and address defect densities common to fabrication of these materials.

NCSU also had other related research contracts from the U.S. Department of Defense, and much of the research on the different contracts spilled over into each of the projects. During the time of the SDIO investment, the research team performed parallel efforts in silicon carbide (SiC). As part of this research, four of the university's graduate students became involved in groundbreaking progress in SiC for optoelectronic and microelectronic applications. The students subsequently left the university, licensed 10 related patents, and started their own company, Cree Research, Inc. (Durham, NC). They received start-up funding from SDIO's SBIR and IS&T programs, as well as a round of venture capital. With the SBIR program alone, SDIO funded more than $4 million, about $2.5 million of which was during Cree's first year.

At the time of Cree's formation, blue light-emitting diodes (LEDs) were in their infancy. While the world could mass-produce red and yellow LEDs, industry could not mass-produce the "cooler" colors of shorter wavelengths. Cree began to pursue the blue LED market to grow the company and technology, knowing that the use of its technology in high-power switching and radio frequency and microwave communications would take more time to gain acceptance.

Where they are today

Cree has grown significantly since its early years of R&D, transitioning from technology developer to product supplier, although the firm is continuing a considerable amount of research and development. By 1993, the then-60-employee company filed for an initial public offering, raising $11 million. In February 2003, Cree had more than 1,000 employees, a $1-billion market capitalization and $187.8 million in sales to companies such as Osram, which supplies LEDs for dashboard lights, market tickers, and large video screens such as the one in New York's Times Square.

In addition, DOD's investment has not been without benefit to its mission. For example, in 2002, Cree received a $26-million multi-Service DOD contract to scale up a manufacturing process for SiC microwave monolithic integrated circuits (MMICs), used in military radar and communications systems. The new contracts for MMICs bring the DOD closer to capitalizing on its initial investment. Jointly funded by the Navy, MDA, and DOD's Title III program through the Air Force Research Laboratory, Cree builds on past improvements in producibility of SiC substrates, epitaxy of SiC wafers, and cleanroom processing for high-power MMIC amplifiers.

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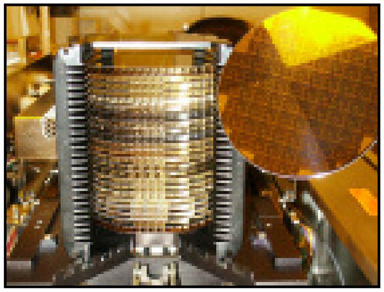
Suggested Reading

From Innovative Research to Missile Defense
MDA Update, Spring 2003

Future So Blue
BMDO Update, Spring 2000

All that Glitters is not Diamond
BMDO Update, Spring 1998

Cree's product is part of New York Times Square video screens, brightening the lights on Broadway.



North Carolina State University
Nitronex, Corp.

- MATERIAL: Gallium nitride
- DEVICES: Blue laser diodes
- PURSUED APPLICATION: Data storage

Nitronex has licensed technology from North Carolina State University to commercialize the Pendeo™ process to fabricate gallium-nitride diodes.

During the 1990s, SDIO and BMDO funded significant work at North Carolina State University (NCSU) for a lateral epitaxy overgrowth process for gallium-nitride (GaN) materials with low defect densities. This research, under the direction of Dr. Robert Davis, led to pendeoepitaxy process—"pendeo" being the Latin word for "hang" or "be suspended."

Pendeoepitaxy is a radical new method of lateral overgrowth using metal-organic epitaxial chemical-vapor deposition (MOCVD), which has been shown to reduce defect densities by four orders of magnitude. In addition, it provides an optimal process route for integrating GaN with silicon on a fundamental atomic level. This integration allows for the device level combination of complementary metal-oxide semiconductor (CMOS) devices on silicon with power field effect transistors on GaN. Other groups were likewise involved in the development of pendeoepitaxy at NCSU, including the Naval Research Laboratory and the Defense Advanced Research Projects Agency.

In 1999, NCSU licensed eight patents, six of which were to university researchers who started a small business called Nitronex, Inc. (Raleigh, NC). Nitronex has subsequently received a handful of Phase I SBIRs and STTRs with NCSU from BMDO and the MDA, as well as other agencies to further develop the process for GaN and aluminum gallium nitride (AlGaN) and apply it to various substrates, including silicon. Some of this research for BMDO was for detection in the ultraviolet region of the electromagnetic spectrum. Some of this research was for high-electron-mobility transistors (HEMTs) that might potentially be used for radio frequency communications. The company has trademarked the pendeoprocess under the name PENDEO™.

Nitronex has sublicensed a field-of-use patent to an overseas manufacturer for blue laser diodes. The scope of the license is for GaN on sapphire for next-generation devices of data storage, (e.g., for DVD players). The limited scope of the sublicense has allowed Nitronex to retain use of the PENDEO process for GaN-based materials on other substrates, including silicon. The company sees opportunity to later grow GaN on silicon for laser diodes using the PENDEO process as an inexpensive alternative compared with using other substrates. The use of silicon has allowed the company to scale wafers all the way up to 4 inches and enables the possibility to scale to 8 inches.

Where they are today

Nitronex currently employs approximately 60 people and has a 7,500-square-foot facility, which houses the engineering team and Class 1,000 cleanroom. Its core business is to grow GaN and AlGaN on 4-inch silicon substrates to make HEMTs for wireless base stations using a more conventional (non-pendeo) process. The company has received roughly $45 million in venture capital for this application. It has used these funds to build 4-inch GaN crystal growth equipment and a 4-inch GaN-based processing line, as well as an RF-test, assembly, and packaging suite. This allows for a three-week-cycle time from bare-silicon wafer to fully packaged and tested GaN RF transistors. Nitronex takes advantage of its silicon platform by using standard laterally diffused metal-oxide semiconductor (LDMOS) packaging, as well as silicon wafer processing and die-attach processes. The company is also in the early stages of leveraging its technology developed for the commercial wireless industry for use in military wireless communication and data-link applications.

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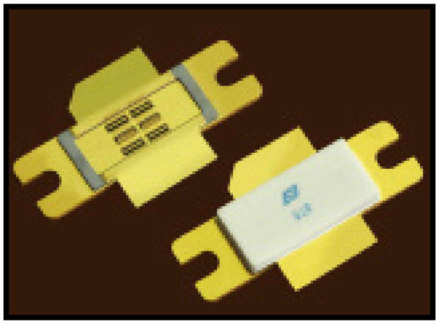
Other MDA-related stories about Nitronex's work

From Innovative Research to Missile Defense
MDA Update, Spring 2003

Future so Blue
BMDO Update, Spring 2000

All that Glitters is not Diamond
BMDO Update, Spring 1998

Nitronex has sublicensed for blue laser diodes the PENDEO process, which soon may be used for next-generation DVD data storage.



RF Micro Devices
Cornell University

- MATERIAL: Gallium nitride on silicon carbide
- DEVICES: HEMTs
- PURSUED APPLICATION: Microwave communications

RF Micro Devices is using Cornell's flow-modulation epitaxy process to fabricate high-power transistors.

The Strategic Defense Initiative Organization (a predecessor of MDA) funded a modified version of organometallic vapor-phase epitaxy (OMVPE) called flow modulation epitaxy (FME) at Cornell University (Ithaca, NY). Under the supervision of Dr. James Shealy, this research created a short-period superlattice involving an arsenide-to-phosphide transition. FME, which requires modified use of an OMVPE apparatus, enables the creation of smooth interfaces between heterogeneous crystalline lattices. It involves the use of non-steady-state reactant fluxes, but it is scaled up to function as an OMVPE method for large-scale production of such heterostructures. A company called RF Nitro exclusively licensed the FME process from Cornell University. RF Micro Devices (RFMD) subsequently purchased RF Nitro in 2001 so that the large publicly traded company could develop gallium-nitride (GaN) power amplifiers for the wireless infrastructure market.

RFMD is now using the FME process to fabricate GaN high-electron mobility transistor (HEMT) circuits on sapphire and silicon-carbide (SiC) substrates. Synthesis of GaN and related alloys is accomplished using the FME techniques in a cold-wall OMVPE reactor. A single-step, high-temperature process is used to initiate the crystal growth leading to GaN epitaxial films. The high-throughput reaction cell is capable of producing uniform epitaxial layers on eight 4-inch-diameter substrates. GaN devices have at least 10 times the power density of conventional gallium-arsenide and silicon devices.

Where they are today

RFMD is currently selling GaN-on-sapphire and GaN-on-SiC epitaxial wafers. The company will soon start qualification testing of its GaN devices and expects to be selling sample transistors by the end of the year. It is developing GaN HEMTs for power amplifiers in cellular phone base stations. RFMD's pilot production facility in Charlotte can handle 5,000 4-inch wafers per year. The number of GaN devices produced per year will depend on the application and layout of each transistor. Commercially, the company's next step will be to move GaN HEMT technology up the frequency ladder to devices for X-band and K-band.

RFMD is working with GaN on SiC for devices as well. It currently has the capability to fabricate GaN HEMTs on 2- through 4-inch SiC wafers. Devices fabricated on SiC substrates take advantage of the high thermal conductivity of the substrate for high-voltage, high-power military applications.

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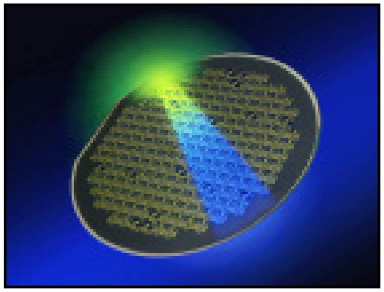
Suggested Reading

Flow Modulation Epitaxy
Web: www.mdatechnology.net/techsearch.asp?articleid=269#listing

Gallium Nitride: The Material Behind Improved Electronics
MDA Update, Fall 2002

RFMD is selling GaN on sapphire and GaN-on-SiC epitaxial wafers.



Santa Barbara Technology Center

- MATERIAL: Indium gallium nitride
- DEVICES: Light-emitting diodes
- PURSUED APPLICATION: High-brightness lighting

The SBTC develops new LED device technology, as part of Cree, Inc.

Santa Barbara Technology Center (SBTC), a subsidiary of Cree, Inc., is an example of how wide-bandgap technology funded for the ballistic missile defense system evolves over the years through various corporate structures until it is finally part of a large domestic infrastructure. Widegap Technology, LLC (d/b/a WiTech), performed research and development on wide-bandgap materials with BMDO SBIR funding. The company later changed its name to Nitres, Inc. During that time, BMDO provided more than $2.5 million in research, primarily for gallium-nitride (GaN) electronic-materials research, starting in 1996, when the company had four employees.

In May 2000, Cree, Inc., acquired Nitres, Inc., and renamed it Cree Lighting Company. Cree Lighting served as a subsidiary of the company and provided expertise in nitride-based semiconductors. Cree Lighting now serves as SBTC, a division of Cree, Inc.

Stemming from the research funded by BMDO, SBTC used a sapphire substrate and a proprietary sequence of nitrides layers to develop blue, green, and ultraviolet indium-gallium-nitride (InGaN) light-emitting diodes (LEDs) that may be eventually produced in mass quantities. In the tests at the end of the BMDO-funded program, SBTC's InGaN-based LED possessed a quantum efficiency of 20 percent, the highest reported by a U.S. company at that time. (Quantum efficiency measures the number of output quanta, in this case photons, to the number of input quanta, or electrons.) It displays 405-nanometer (nm) emission and has an overall energy conversion efficiency of 12 percent. By converting the 405-nm violet emission to white light with phosphor materials, these LEDs started to compare favorably with the 8 percent output of incandescent lamps.

Where they are today

SBTC resides in a 35,850-square-foot facility, of which, a little more than 10,000 square-feet is leased to another entity. The center is engaged in the development of new LED device technology, with the goal of developing higher-efficiency LEDs to compete with incandescent and fluorescent lighting technology for conventional lighting markets. Research at the facility has contributed to more than doubling the typical brightness of Cree LED products, with the introduction of XBright™ and MegaBright™ products. To compete with incandescent and fluorescent lighting technology for conventional lighting markets, the brightness of products must further increase, which will take a few years. In the interim, Cree is marketing products for applications such as automotive dashboards, outdoor video displays, and backlighting.

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Other MDA-related stories about SBTC's Work

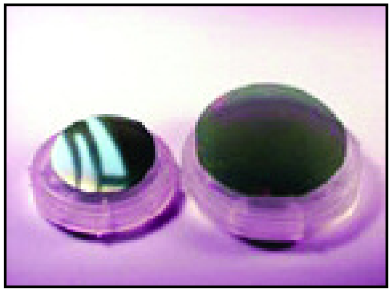
Monolithic, Full-Color, Light-Emitting Diodes
Web: www.mdatechnology.net/techsearch.asp?articleid=492#listing

White LEDs Illuminate a New Lighting Path
BMDO Update, Winter 2000

Future So Blue
BMDO Update, Spring 2000

LED Lamp to Outshine today's Light Sources
BMDO Update, Fall 1999

Cree is marketing products toward applications such as automotive dashboards, outdoor video displays, and backlighting.



Technologies and Devices International, Inc.

- MATERIAL: Gallium nitride
- DEVICES: Bulk crystals, epitaxial structures, high-electron mobility transistors
- PURSUED APPLICATIONS: High-brightness lighting, RF electronics

TDI has recently moved into a 32,000-square-foot facility to manufacture products based on silicon carbide and gallium nitride.

Technologies and Devices International, Inc. (TDI; Silver Spring, MD), received SBIR funding from MDA/BMDO starting in 1999 to deposit high-quality gallium-nitride (GaN) layers onto sapphire and silicon-carbide (SiC) substrates using a process called hydride vapor-phase epitaxy (HVPE) to improve ballistic missile defense communications systems, as well as applications in the commercial sector. The company is addressing manufacturing problems contributing to the high cost of producing GaN devices.

TDI's scale-up of the HVPE process serves as an improvement to the metal-organic chemical vapor-deposition process for fabricating GaN-on-sapphire wafers and thus can improve the mass production of blue light-emitting diodes (LEDs) and other devices. The company's approach reduces growth time by more than 30 percent and allows an increase in production throughput of 30 percent to 50 percent—without incurring extra cost. The blue LED is grown directly on the surface of the substrate, eliminating the need for sapphire nitridization, GaN low-temperature nucleation deposition, and thick GaN buffer layer growth. The quality of the GaN LED structure is ensured by pregrowth inspection of the wafer, which is not possible with other methods of fabrication.

TDI's process involves reacting gallium metal with hydrogen chloride to make gallium chloride. The gallium chloride reacts with ammonia gas, forming a GaN layer on sapphire. Blue LED structures can be grown by LED manufacturers (TDI customers) directly on the surface of the substrate. The HVPE process usually is carried out at atmospheric pressure in a quartz-walled reactor heated by a resistive furnace. While HVPE has been used for more than 30 years, it has neither been scaled up in a manufacturing environment, nor used to produce aluminum nitride (AlN) and aluminum gallium nitride, until TDI's recent work.

Where they are today

TDI is currently manufacturing about 1,000 GaN-on-sapphire wafers per month.

Founded in 1997, the company has sales both in the United States and internationally. It has recently moved to a new 32,000-square-foot development and manufacturing facility in Silver Spring, MD, where it develops, manufactures and markets bulk crystals, epitaxial structures, and devices using SiC, aluminum gallium nitride, and GaN semiconductor materials. It has received several contracts with the MDA SBIR program. Its research areas are in: templates of GaN and AlN used as substrates for the LED market; GaN and AlN bulk substrates for the laser diode market, and wide bandgap materials for high electron mobility transistors (HEMTs) for the wireless communication base station and radar market.

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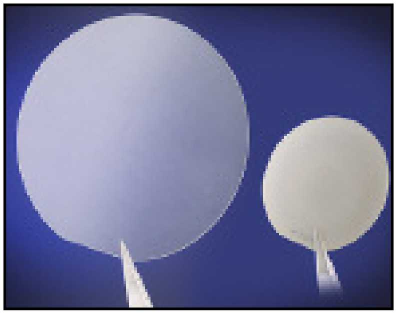
Suggested Reading

Future So Blue
BMDO Update, Spring 2000

GaN on Sapphire Wafers
2003 MDA Technology Applications Report

TDI's scale-up of the HVPE process serves as an improvement over others for fabricating gallium-nitride on sapphire substrates.



University of South Carolina
Sensor Electronic Technology, Inc.

- MATERIAL: Aluminum indium gallium nitride on gallium nitride
- DEVICES: MOSHFET and MOSDFET wafers
- PURSUED APPLICATIONS: X-band microwave amplifiers, UV light emitters, solid-state lighting

The University of South Carolina has established a Center of Excellence for Gallium Nitride Materials.

Over the years, the University of South Carolina (USC; Columbia, SC) has received several million dollars from MDA and its predecessors, BMDO and SDIO, to set up a center of excellence and explore new fabrication techniques for gallium nitride (GaN) materials. Such materials could prove useful for applications such as X-band microwave amplifiers while also having a wide range of commercial uses. University of South Carolina, through its subcontractor Rennselaer Polytechnic Institute (RPI), transferred much of this technology to a small business—Sensor Electronic Technology, Inc., (SET; Columbia, SC). SET has subsequently received several MDA SBIR contracts and now sells 2-inch, 3-inch and 4-inch wafers for commercial use.

SET and its parent university fabricate aluminum indium gallium nitride (AlInGaN)-GaN devices such as metal-oxide semiconducting double-heterostructure field-effect transistors (MOSDHFETs) and metal-oxide semiconducting heterostructure field-effect transistors (MOSHFETs) using a technique called pulsed atomic layer epitaxy (PALE) and, lately, a more advanced and patent-pending Migration Enhanced Metalorganic Chemical Vapor Deposition (MEMOCVD™). MEMOCVD™ technique is expected to bridge the gap between conventional metal-organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). It enables processors to grow higher quality material and allows for precise thickness and composition control, and wafer growth at reduced temperatures.

At present, most of the development work in industry and Defense has focused on conventional high-electron-mobility transistor (HEMT) circuits on sapphire and insulating silicon carbide (SiC) substrates. But several key problems impede commercial development of these devices, such as gate leakage and current collapse, which reduces radio frequency (RF) power capacity. By using PALE or MEMOCVD™ to deposit AlInGaN, the researchers can pulse the material into the heterojunction vapor-phase epitaxy system layer by layer, thus forming a high-quality heterointerface between the various layers of the device. Owing to the deposited silicon-dioxide layer, gate leakage is reduced by four to six orders of magnitude, saturation current goes up, and DC and RF characteristics stay the same as, or are even better than, those for conventional HFETs.

Where they are today

The University of South Carolina's Photonics and Microelectronics Laboratory is a vertically integrated 10,000-square-foot research facility. For AlInGaN growth, the facility uses two single-wafer and one multiwafer industrial MOCVD systems, as well as one hydride vapor-phase epitaxy system. The facility also uses several furnaces for growing SiC boules as well as extensive equipment for materials characterization, processing, and testing.

In 2001, SET received financial support from the semiconductor industry and moved its operations from the RPI incubator to a newly established manufacturing facility in Columbia, SC. The company has 15 employees and is pursuing three key commercial and military areas. One area is RF electronics for military radar systems and wireless communications, such as ultra-high-power base stations and satellite communications. Another is deep ultraviolet (UV) light emitters and UV semiconductor lamps. They serve as low-voltage, environmentally friendly, and right-on-spot-impact alternatives to mercury lamps. They can be used for bio-agent detection, microsurgery, disinfection, tissue and blood analysis, semiconductor processing equipment, and water and air purification systems. The third area is solid-state lighting. In this market, the company is exploring applications such as digital "smart" lighting modules for general illumination. SET currently has available AlInGaN/GaN HFET wafers on sapphire and SiC substrates.

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Suggested Reading

Large Periphery Aluminum Indium Gallium Nitride Metal Oxide Semiconductor . . .
Web: www.mdatechnology.net/techsearch.asp?articleid=573#listing

Southbound SET Marks a Trail of University Research
MDA Update, Fall 2002

SET is commercializing university research in RF electronics, lighting, and UV sensors.

Acronyms and Abbreviations

AlInGaP	aluminum indium gallium phosphide
AlN	aluminum nitride
BMDO	Ballistic Missile Defense Organization
DOD	Department of Defense
EPRI	Electric Power Research Institute
FACTS	flexible alternating-current transmission systems
FME	flow modulation epitaxy
GaAs	gallium arsenide
GaN	gallium nitride
HBT	heterojunction bipolar transistor
HDTV	high-definition television
HEMT	high-electron mobility transistor
HFET	heterostructure field-effect transistors
HVPE	hydride vapor-phase epitaxy
IC	integrated circuit
InGaN	indium gallium nitride
IS&T	Innovative Science and Technology
LED	light-emitting diode
LPCVD	low-pressure chemical vapor deposition
MBE	molecular beam epitaxy
MDA	Missile Defense Agency

MEMOCVD™	Migration Enhanced Metalorganic Chemical Vapor Deposition
MESFET	metal semiconducting field-effect transistors
MMIC	monolithic microwave integrated circuits
MOCVD	metal-organic chemical vapor deposition
MOSDHFET	metal-oxide semiconducting double heterostructure field-effect transistor
MOSHFETS	metal-oxide semiconducting heterostructure field-effect transistors
OMVPE	organometallic vapor phase epitaxy
PALE	pulsed atomic layer epitaxy
RF	radio frequency
SAD	seasonal affective disorder
SBIR	Small Business Innovation Research
SDIO	Strategic Defense Initiative Organization
SiC	silicon carbide
STTR	Small Business Technology Transfer
TA	Technology Applications
UV	ultraviolet
VJFET	vertical-junction field-effect transistors
ZnO	zinc-oxide

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