The Dawn of Miniature Green Lasers

Semiconductors can generate laser light in all colors except one. But new techniques for growing laser diodes could soon make brilliant full-spectrum displays a reality

By Shuji Nakamura and Michael Riordan

On a rainy Saturday morning in January 2007, Henry Yang, chancellor of the University of California, Santa Barbara, took an urgent phone call. He excused himself abruptly from a meeting, grabbed his coat and umbrella, and rushed across the windswept U.C.S.B. campus to the Solid State Lighting and Display Center. The research group there included one of us (Nakamura), who had just received the Millennium Technology Prize for creating the first light-emitting diodes (LEDs) that emit bright blue light. Since that breakthrough over a decade earlier, Nakamura had continued his pioneering research on solid-state (semiconductor) lighting, developing green LEDs and the blue laser diodes that are now at the core of modern Blu-ray disc players.

As Yang reached the center about 10 minutes later, people were milling about a small test lab. "Shuji had just arrived and was standing there in his leather jacket asking questions," he recalled. Nakamura's colleagues Steven DenBaars and James C. Speck were speaking with a few graduate students and postdoctoral researchers as they took turns looking into a microscope. They parted for Yang, who peered into the eyepiece to witness a brilliant blue-violet flash emanating from a glassy chip of gallium nitride (GaN).

Within days another group of researchers at Rohm Company in Kyoto, Japan—a partner in the U.C.S.B. center—duplicated the feat using similar materials. Although blue laser diodes are not in themselves very revolutionary [see "Blue-Laser CD Technology," by Robert L. Gunshor and Arto V. Nurmikko; Scientific American, July 1996], Nichia Chemical Industries (based in Tokushima, Japan, where Nakamura worked until 2000), Sony and other companies were still struggling to produce inexpensive GaN laser devices for the Blu-ray disc market. These diodes had previously been fashioned using a method with stubborn limitations that have kept manufacturing yields down and diode costs high.

The groups from U.C.S.B. and Rohm are developing a new way to grow the crystalline layers of gallium nitride and related alloys that make up a laser diode. The early successes of the approach not only promise greater yields but also buoy hopes of an even bigger payoff: rugged, compact GaN diodes that emit green laser light—a goal that has long eluded scientists and engineers. The technique should also lead to

KEY CONCEPTS

- Solid-state lasers can produce light in the red and blue parts of the spectrum but not the green.
- Recent research suggests that this "green gap" could be plugged as early as this year.
- The advance will allow for laser-based video displays that are small enough to fit in a cell phone.

—The Editors

CASPAR BENSON

high-efficiency green LEDs that emit much more light than existing devices.

These achievements would fill a gaping void in the visible spectrum where evolution has trained our eyes to be most sensitive, plugging the "green gap" in the red-green-blue triad needed for full-color laser projection and displays. They should help speed the introduction of laser projectors for televisions and movie theaters—which will display much richer colors than other systems—and of tiny, handheld "pico projectors" to be used, for example, in cell phones. And high-power green diodes might even be employed in such diverse applications as DNA sequencing, industrial process control and underwater communications.

A New Angle

The key advance that led to bright blue solid-state lighting was the mid-1990s conversion to LEDs and laser diodes made of gallium nitride and its alloys [for a profile of Nakamura, see "Blue Chip," by Glenn Zorpette; Scientific American, August 2000]. Before that, most researchers had focused their efforts on zinc selenide and related compounds. In the new approach, an exceedingly smooth, nanometers-thin layer of indium gallium nitride (InGaN) is sandwiched between two layers of GaN, forming what is called a heterostructure or quantum well [*see box on next page*].

By applying a suitable voltage, researchers set up an electric field perpendicular to these layers that drives electrons and holes—positively charged quasiparticles corresponding to the absence of electrons—together within the InGaN active layers. Inside this narrow trench, the electrons and holes recombine, annihilating one another and generating photons with an energy precisely determined by the properties of the active semiconductor material. By increasing the indium concentration in the alloy, one can lower this energy, thereby increasing the wavelength of the light and changing its color from violet to blue to green.

In LEDs the photons leave the well almost immediately, perhaps rebounding once or twice before exiting the device or being absorbed in the other layers. But in laser diodes, which produce coherent light, the photons stay largely confined within the trench. Two highly reflective mirrors—generally polished crystal surfaces at ei-

WHAT ABOUT GREEN LASER POINTERS?

The green lasers that have long been available employ a complicated two-step process to generate light. Semiconductor lasers inside these devices emit infrared radiation with a wavelength around 1,060 nanometers. This radiation then pumps a crystal that oscillates at half this wavelength—about 530 nanometers, solidly in the green. The process is costly, inefficient and imprecise—the second crystal can heat up, altering the wavelength of the resultant green light. Laser diodes that generate green light directly would avoid these problems.

ther end of it—recycle the photons back and forth inside, further stimulating electron-hole recombination. The laser light generated by this "stimulated emission" process is a tight pencil beam of exceedingly pure color.

To make conventional GaN diodes, workers place a thin wafer of sapphire (or, increasingly, gallium nitride) inside a reaction chamber. There hot gases deposit successive layers of gallium, indium and nitrogen atoms on that substrate, with the exact proportions of each element varying from layer to layer. The atoms in these layers automatically align with the existing crystalline structure, as predetermined by the substrate. Atom by atom, the layers grow in parallel with what is called the substrate's *c*-plane, which is perpendicular to the crystal's axis of hexagonal symmetry [*see box on opposite page*].

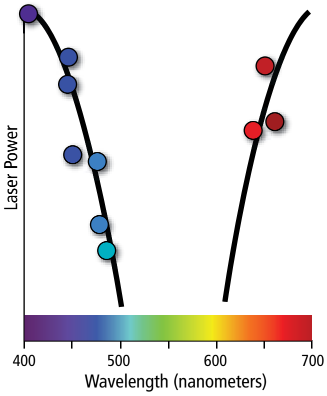
Unfortunately, electrostatic forces and internal stresses between successive layers of positively charged gallium or indium ions and negatively charged nitrogen ions create strong electric fields perpendicular to the *c*-plane. These fields, which can reach up to 100 volts per micron—equivalent to nearly 200 million volts across an average person's height—counteract the applied external voltage. They pull electrons *away* from holes—making it harder for them to recombine and yield light. In effect, the electrons pile up at one side of the long quantum dance hall and holes at the other, both reluctant to cross over and meet.

Known as the quantum-confined Stark effect, this nagging problem becomes particularly acute as the color of the emitted light shifts from violet to blue to green. And as the current through the diode increases, the greater number of charge carriers partially blocks the internal electric fields that keep electrons and holes apart. With these fields partially screened out, the electrons and holes then recombine at higher energies, shifting the light toward the blue end of the spectrum. These problems are the main reason why green laser diodes and high-efficiency green LEDs have remained but a dream for more than a decade. (The familiar green laser pointers used by lecturers have semiconductor lasers that emit infrared radiation and pump another laser in a complicated, inefficient frequency-doubling scheme.)

The approach pioneered by the U.C.S.B. and Rohm groups attempts to sidestep these prob-

THE GREEN GAP PROBLEM

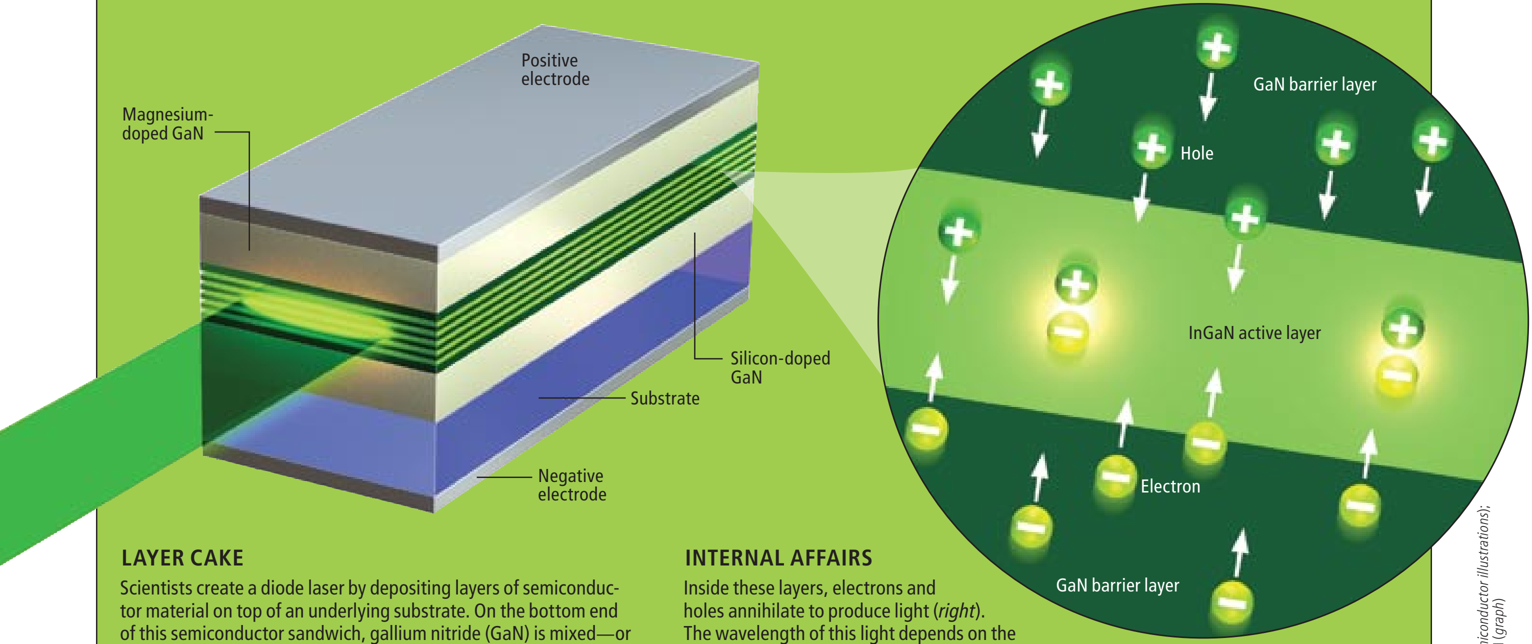
Scientists have long been able to build semiconductor lasers that create light in red parts of the spectrum, and in the past decade they have conquered the blue and violet sections as well. Yet as they try to push these lasers into the green part of the spectrum, the amount of power produced drops precipitously.



[THE BASICS]

HOW SEMICONDUCTOR LASERS WORK

Inside a solid-state laser, electrons meet positively charged entities called holes, annihilating one another and creating light. To adjust the wavelength of this light, scientists must alter the material inside the semiconductor. But doing so can lead to other problems.



LAYER CAKE

Scientists create a diode laser by depositing layers of semiconductor material on top of an underlying substrate. On the bottom end of this semiconductor sandwich, gallium nitride (GaN) is mixed—or "doped"—with silicon impurities to produce an excess of negatively charged electrons. On the other end, GaN is doped with magnesium to give it an excess of positive charges, or "holes." A voltage across the electrodes sets up an electric field that drives the electrons and holes together inside the central active layers.

INTERNAL AFFAIRS

Inside these layers, electrons and holes annihilate to produce light (*right*). The wavelength of this light depends on the indium (In) content of the active layer—more leads to longer wavelengths and thus greener light. But the more indium in these layers, the more that indium is likely to pool into small "islands" during manufacture. The islands can alter the light's wavelength—an unacceptable flaw in a laser.

GEORGE RETSECK (*semiconductor illustrations*); SCIENTIFIC AMERICAN (*graph*)

[THE SOLUTION]

A NEW FOUNDATION

A substrate is a slice of a crystal, and anything grown on top of it inherits its crystalline structure. The blue diode lasers that power Blu-ray disc players and PlayStation 3 game consoles are usually grown on top of sapphire, which, as substrates go, is relatively cheap and readily available. Yet it is difficult to use these substrates to make green laser diodes. In response, scientists have turned to alternative crystal facets for help.

_C_-PLANE: THE CLASSIC CUT

Though commonly used for blue lasers, a *c*-plane substrate has drawbacks, such as inducing electric fields that conspire to keep electrons and holes apart. The problem gets worse as the wavelength shifts toward green.

_M_-PLANE: A COSTLY ALTERNATIVE

Two research groups are growing laser diodes on a crystal's *m*-plane, which cuts across the crystal's side. Diodes grown on this plane do not suffer from induced fields, but the substrates are more costly than *c*-plane versions.

SEMIPOLAR: THE COMPROMISE

A third option is semipolar substrates that are cut at a 45-degree angle to the crystal axis. These substrates also do not produce strong fields, and they seem to yield better lasers and LEDs than the *m*-plane substrates do.

lems by starting with a thin wafer of pure, crystalline GaN that has been sliced along a larger crystal's *m*-plane [*see box above*] and then polished. Diodes fabricated on these so-called nonpolar substrates do not encounter the problems of conventional polar *c*-plane devices, because the troublesome fields caused by polarization and internal stresses are much lower.

The diodes grown on GaN also produce light more efficiently than ones grown on sapphire because they suffer from far fewer crystalline defects—submicroscopic irregularities and mismatches at the interfaces between successive layers. Such defects act as centers where electrons and holes recombine to produce unwanted heat instead of light. They can easily propagate upward through the successive diode layers during the growth process (in what are called threading dislocations) and reach the active layers. The presence of these defects played havoc with production yields when Nichia and Sony first tried to manufacture blue laser diodes. Because a GaN substrate will generate nowhere near as many mismatches as sapphire does with the next-above layer of GaN or one of its alloys, diodes grown on nonpolar GaN substrates can therefore produce much more light—and have correspondingly less heat to dispose of.

First suggested in the late 1990s, the nonpolar technique was attempted by several groups beginning in 2000—including DenBaars and Speck at U.C.S.B. The early devices performed only modestly, mainly because of the lack of high-quality GaN substrates. In 2006, however, Mitsubishi Chemical Corporation in Tokyo—another partner in the U.C.S.B. center—began supplying excellent, low-defect *m*-plane GaN substrates to the Rohm and U.C.S.B. research groups. Less than a centimeter on a side, the substrates were sliced from small GaN crystals about the size of a pencil eraser.

With the new material in hand, Rohm and U.C.S.B. fabricated much more efficient LEDs in late 2006, and by early 2007 these groups began trying to make the more challenging laser diodes. On that rainy Saturday morning of January 27, U.C.S.B. graduate student Matthew Schmidt went to the lab to finish the last fabrication step. Then he took the diode over to the nearby test lab and hitched it up to a power supply. Suddenly, as he cranked up the current flowing through the diode, a narrow beam of blue-violet light shot out of it.

"Wow!" Schmidt thought. "I can finally graduate!"

He called his thesis adviser DenBaars, who at first thought he was joking but soon alerted the rest of the group and Chancellor Yang. They arrived within minutes to observe the surprising results. This first nonpolar GaN laser diode op-

[THE AUTHORS]

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RANDY LAMB *University of California, Santa Barbara (Nakamura)*; COURTESY OF DONNA RIORDAN *(Riordan)*; GEORGE RETSECK *(crystals)*

erated at a wavelength of 405 nanometers (nm), as did the first Rohm device a few days later. And the currents flowing through these diodes were only two to three times what was then being achieved in commercially available devices made by Nichia and Sony, indicating that any heating problems were manageable.

Going for Green

After that breakthrough, the U.C.S.B. group decided to drop most of its work on polar diodes and focus on nonpolar ones. It also began investigating a related strategy based on "semipolar" GaN substrates, which are wafers cut at an angle of about 45 degrees to a crystal's major axis [*see box on preceding page*]. Diodes fabricated on semipolar substrates also have much less intense internal electric fields than polar diodes do, though not as low as in nonpolar diodes. The U.C.S.B. researchers hope that one of these geometries will allow them to create the first green laser diodes and to make high-power LEDs at even longer wavelengths. Rohm has forged ahead in these areas, too, concentrating its efforts on nonpolar substrates.

The new substrates, however, are not sufficient on their own to get beyond blue. Green diodes require adding more indium to the InGaN active layer, but the extra indium exacerbates internal stresses and disrupts the crystalline structure. It increases the number of crystal defects, which in turn reduces the light output and generates excess heat. While LEDs can still function despite the added defects, their efficiencies plummet as the color shifts from blue to green. Laser diodes are even more finicky and cannot tolerate so many defects. The highest wavelength thus far achieved in a laser diode is 488 nm, in the blue-green (or cyan) part of the spectrum.

Layers of InGaN must also be grown at substantially lower temperatures—about 700 degrees Celsius versus 1,000 degrees C for the GaN layers around it—to prevent the indium atoms from dissociating from the other atoms. Such dissociation can form areas of inhomogeneous indium alloys, or "islands," which in turn causes the electron-hole recombination energy to vary from point to point. That variation makes the emission spectrum too broad to yield the coherent, monochromatic light expected from a laser. Thus, when workers raise the reactor temperature to grow the next GaN layer atop the delicate InGaN layer just deposited, they must be especially careful so as not to form too many of these islands. But the pro-

[THE APPLICATIONS]

HANDHELD PROJECTORS

The smallest currently available handheld projectors are about the size of a remote control and use LEDs to generate light. By the end of this year the first laser-based models should go on sale. Even though they use frequency-doubling technology to create green laser light, they will produce high-resolution, richly colored images. Future models that rely on green laser diodes will allow for brighter and more efficient displays, and they will also shrink the projectors enough to allow them to fit inside your cell phone. Here is a look at two laser-based prototypes currently in development and a few LED projecters out now. —***The Editors***

MICROVISION SHOW WX ▸

Inside this laser-projector protype, red, blue and green lasers focus onto a single mirror about the size of a pinhead. As light bounces off that reflector, the mirror assembly rapidly scans back and forth to project pixels one by one onto a screen or wall. The lack of lenses means the projector never needs to be focused.

Resolution: 848 × 480 pixels (DVD-equivalent)

Available: Later this year

LIGHT BLUE OPTICS

The start-up Light Blue Optics is also working on a laser projector. These devices use liquid crystal on silicon (LCOS) chips that contain thousands of tiny liquid-crystal windows. The chip opens and closes these pixels in rapid succession to let light through and form an image. The company plans to have a laser-projection system ready for delivery to third-party manufacturers by the start of next year.

Resolution: 854 × 480 pixels

Available: 2010

3M MPRO110 ▸

When it debuted in 2008, the LED-based MPro110 was the first handheld projector to go on sale in the U.S. Although it is a bit larger than the Samsung MBP200 (*below*), this LCOS projector can display television-quality video. 3M is licensing an updated version of the technology that powers the MPro110 for use in other applications, such as cell phones.

Resolution: 640 × 480 pixels (equivalent to standard-definition TV)

Price: $359

◂ SAMSUNG MBP200 PICO PROJECTOR

This LED-based projector uses a miniaturized version of the digital light projection (DLP) chip from Texas Instruments. Light from a white LED first passes through a rapidly changing color wheel. It then hits an array of thousands of mirrors. Each mirror is about one-fifth the width of a human hair and switches on and off thousands of times a second. Reflected light from this mirror forms the pixels that make up an image.

Resolution: 480 × 320 pixels (approximately equivalent to a smart phone)

Available: Later this year

TOSHIBA LED PICO PROJECTOR ▸

This LED competitor also uses the DLP chip technology.

Resolution: 480 × 320 pixels

Price: $399

Suddenly, as Schmidt cranked up the current flowing through the diode, a narrow beam of blue-violet light shot out of it. “Wow!” he thought. “I can finally graduate!”

cess gets ever more difficult as the indium concentration increases.

The problems are exacerbated in polar diodes, in which the strong internal fields have led manufacturers to create active layers of InGaN that are exceedingly thin—less than 4 nm, or only about 20 atoms thick. This approach helps to keep electrons and holes huddled closer together, boosting the chances that they will meet and mate to create light. Because nonpolar and semipolar diodes have internal electric fields that are almost negligible, however, their InGaN active layers can be grown substantially thicker—up to 20 nm. The indium islands still form in these more robust layers, but they are thought to occur closer to the interfaces with the surrounding GaN. Confining the islands there should boost the chances of getting the narrower light spectrum needed for laser action. And the thicker, more robust active layers help to simplify manufacturing in other ways, allowing the elimination of extra “cladding” layers in the diode stack, which had formerly been added to help trap and guide the photons.

Since the breakthrough demonstration in January 2007, the U.C.S.B. and Rohm groups have been steadily pushing back the frontiers of the new technology, publishing new results almost every month. In April 2007, for example, U.C.S.B. reported a nonpolar LED emitting blue-violet light at 402 nm that achieved quantum efficiencies—the ratio of photons emitted to electrons flowing in—above 45 percent. This figure represented a 100-fold improvement in these devices in just a year. Several months later the group reported semipolar green LEDs that operated as high as 519 nm, with efficiencies close to 20 percent. (Unfortunately, these diodes experienced substantial blue shifts, for reasons that remain obscure.)

More recently, U.C.S.B. fabricated yellow semipolar LEDs operating at 563 nm with efficiencies above 13 percent. These were the first efficient yellow LEDs made with GaN and its alloys. Nonpolar laser diodes have also begun to approach the performance of their polar counterparts. In May 2008 Rohm reported achieving nonpolar laser diodes that operated at wavelengths as high as 481 nm—approaching the record of 488 nm held by polar diodes.

The Big Time

But fabricating a device in the laboratory is not the same as being able to manufacture it in commercial quantities. Probably the biggest roadblock to large-scale manufacture of nonpolar and semipolar GaN laser diodes and LEDs—whether violet, blue, green or yellow—is the availability of large enough substrates at acceptable costs. So far Mitsubishi has supplied GaN substrates about a square centimeter in surface area that are sliced from small crystals, but the wafer area needs to increase nearly 20-fold.

To produce laser diodes economically, manufacturers must have substrates at least five centimeters in diameter costing about $2,000 per wafer, says Robert Walker, a semiconductor industry expert at Sierra Ventures in Menlo Park, Calif. To manufacture the simpler (and much cheaper) LEDs, he adds, substrate costs must drop by another order of magnitude. And these LEDs will still have to compete with advanced blue and green LEDs, such as those introduced in late 2007 by CREE Research in Durham, N.C. (also a partner in the U.C.S.B. center), which fabricates its devices on silicon-carbide substrates.

Mitsubishi is now streamlining and scaling up its existing fabrication procedure in a move toward commercializing nonpolar GaN substrates. According to Kenji Fujito, who developed the methods used to grow nonpolar GaN substrates, it is a sluggish and painstaking process. At present, Mitsubishi can produce just enough nonpolar (or semipolar) GaN substrates to meet the research needs of Rohm and U.C.S.B. Fujito says it will be at least another year or two before they can produce substrate wafers five centimeters in diameter. Walker concurs, projecting that it should take a few years before nonpolar substrates will be economically available, either from Mitsubishi or other substrate suppliers, such as Kyma Technologies in Raleigh, N.C. But U.C.S.B.’s DenBaars expects commercial nonpolar diodes to be manufactured sooner, citing the higher yields and thus lower overall costs that these substrates should allow.

In the meantime, lab work will continue to lead the way. Both the Rohm and U.C.S.B. groups, as well as several others, have set their sights on achieving the first successful green laser diodes. And in September 2008 U.C.S.B. reported observing stimulated emission at cyan (480 nm) and green (514 nm) wavelengths from nonpolar and semipolar GaN diodes that had been optically pumped with light from another laser. Getting similar emissions using electric current to drive the diodes instead should not be too far off. We would not be surprised to see one or both of these groups succeed later this year. ■

➥ MORE TO EXPLORE

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