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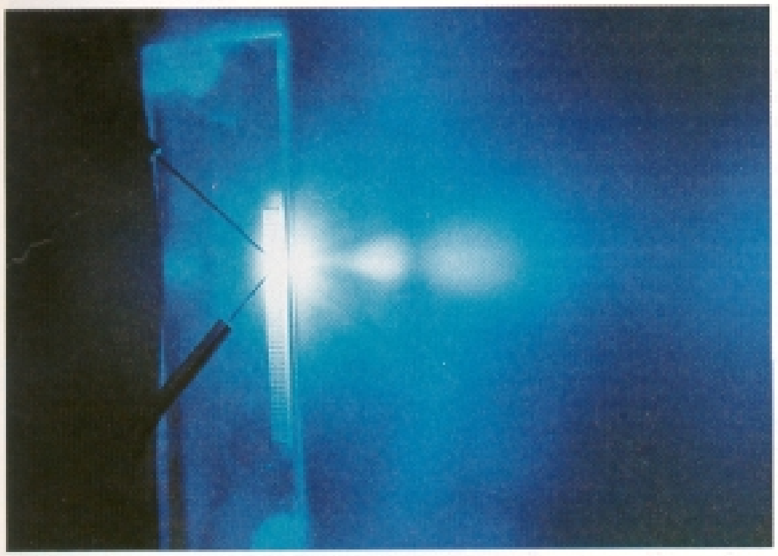
GaN Laser Diode Brightens Hopes for a Long-Lived, Short-Wavelength Device

Researchers at Nichia Chemical Industries in Tokushima, Japan, reported in January that they had succeeded in getting a diode based on gallium nitride to lase at a wavelength of 417 nanometers, giving forth a blue-violet light.[1] (See the figure on page 19.) Since then, at the International

In the race to produce a short-wavelength semiconductor laser, diode lasers based on gallium nitride were late leaving the starting gate, but they have the potential to challenge the current leader.

NICHIA CHEMICAL INDUSTRIES



BLUE LIGHT streams from the edge of a GaN-based laser diode in the laboratory of Shuji Nakamura and his group at Nichia Chemical Industries in Tokushima, Japan. The light is made visible by its scattering off smoke particles, and the fluctuations in intensity of the light reflect the fluctuations in the density of smoke. Two needle-like electrodes are applied to the electrically pumped diode.

Symposium on Blue Lasers and Light-Emitting Diodes held in Chiba, Japan, last month, a team from Meijo University in Nagoya announced GaN-based diode lasers operating both in the blue (402 nm) and ultraviolet (376 nm).

The Nichia device was not the first semiconductor diode laser to operate in the short-wavelength region of the visible spectrum; zinc-selenide lasers emitting light at 490 nm hold that distinction. Indeed, the ZnSe materials have been the focus of much of the research on shorter-wavelength diode lasers over the past five years. (See the article by Gertrude F. Neumark, Robert M. Park and James M. DePuydt in PHYSICS TODAY, June 1994, page 26.) But GaN, the material on which the new lasers are based, has superior materials properties that should simplify the task of making reliable and long-lived devices.

Researchers around the world are trying to develop laser diodes with shorter wavelengths in part because of the potential application to optical storage. With their shorter wavelengths, blue-violet lasers should be able to imprint information on a CD-ROM with a storage density about four times greater than those of today, according to Steve DenBaars of the University of California, Santa Barbara. The US Navy is also interested in blue lasers for optical communication underseas; blue light is absorbed by seawater less than longer wavelengths.

Operating lifetimes

Ever since ZnSe laser diodes were demonstrated in 1991,[2] researchers have been striving to extend the lifetime of the devices to commercially acceptable values. The record lifetime to date, reported recently[3] by Akira Ishibashi and his colleagues at Sony Corp's Research Center in Yokohama, Japan, is 101.5 hours at room temperature for a 514.7-nm laser with a power output of 1 milliwatt. Ishibashi pointed out that the operating voltage was high (11 volts) because the p-electrode design was not fully optimized; at a lower voltage, he told us, the lifetime should improve.

It is too early to say anything about the lifetime of the GaN laser diode recently operated at Nichia Chemical. The team leader, Shuji Nakamura, told us that the devices he and his colleagues have now can operate only under pulsed current at room temperature; his group will conduct lifetime tests after they achieve continuous wave operation. Nevertheless, said Nakamura, one laser diode was operated in the pulsed current mode for 24 hours and showed no signs of degradation.

It did not take long to commercialize light-emitting diodes based on GaN: Nakamura and his colleagues demonstrated high powered blue (5 mW) and green (3 mW) GaN LEDs in 1994,[4] and their company is now shipping about two million GaN-based LEDs each month. Nichia extrapolates the lifetime of these LEDs to more than 50 000 hours.

In the US, Cree Research in Durham, North Carolina, sells comparable numbers of GaN-based LED chips, largely used for indoor displays. The blue and green GaN-based LEDs completed the color triad (red, green, blue) available in high-power semiconductor devices, opening the door for full-color displays.

The reason GaN has better materials properties than ZnSe is to be found in the periodic table. As Manijeh Razeghi of Northwestern University explained to us, ZnSe is an example of a II–VI material, so called because Zn comes from column II of the periodic table and Se from column VI. The bond between the atoms is ionic, not as strong as the covalent bonds that link column-III materials, such as Ga, to column-V elements, such as N.

Another propitious property is the large mass difference between the cations (gallium and aluminum, for example) and the anions (nitrogen); the mass difference hinders energy loss to acoustical phonons and hence leads to higher optical efficiencies. Furthermore, commented Max Yoder of the US Office of Naval Research, GaN-based devices seem to operate well even when the defect densities are at levels that would destroy the light output in other devices.

The GaN laser diodes that have been operated so far by the team at Nichia Chemical have output power levels between 1 and 250 mW, depending on the laser structure and operating current, and have threshold current densities of between 4 and 10 kiloamperes per square centimeter.

To make the devices, one deposits a series of doped semiconductor layers on top of one another, starting with the substrate and buffer layers, using metallo-organic chemical vapor deposition. At the center of the stack is a multiple-quantum well structure, which is the active region where holes and electrons can combine to emit photons. On either side are light-guiding layers and cladding layers to confine the light and the carriers near the active region. Electrical contact is made at the top and bottom of the stack.

Steps in the development

The GaN laser did not appear totally out of the blue. Researchers saw gain from optically pumped stimulated emission in GaN more than 20 years ago, but they recognized that significant work was needed to make a laser. If GaN was so much more promising than ZnSe, why has it taken so long? One factor that slowed the development of the GaN-based diode was the absence of a substrate to which the GaN could be bonded. Sapphire was a candidate, but there is a large mismatch between it and GaN in both the lattice constants and the thermal expansion coefficients, leading to the formation of cracks. Moreover, sapphire is expensive. Another candidate, silicon carbide, is even costlier, but it provides a better lattice match than sapphire wafers and is a conductor rather than an insulator.

Progress was made in the substrate problem in 1986 when Isamu Akasaki (now at Meijo University) and his colleagues at Nagoya University found a way to grow high-quality GaN on a sapphire substrate.[5] The trick was to lay down a thin film of aluminum nitride at low temperature to serve as a buffer layer between the sapphire and the upper crystalline layers of GaN grown at higher temperatures. The buffer layer helped to decrease the dislocation due to lattice mismatch.

A second hurdle for the GaN materials was the absence of a p-type nitride. Researchers were having trouble getting acceptor ions, such as magnesium, to occupy the Ga sites. In 1989 the Nagoya University group found a way to dope GaN successfully with magnesium by irradiating the sample with an electron beam immediately after deposition.[6] With that sample, grown on a GaN buffer layer, the Nagoya group demonstrated that one could get a p–n junction. Three years later, Nakamura and his colleagues got p-type GaN by heating the sample in a hydrogen-free atmosphere.[7] The Nichia Chemical researchers deduced that hydrogen from the ammonia used in growing the laser devices was surrounding and deactivating the acceptors.

A third challenge in developing a GaN-based laser was to make suitable mirrors on opposite sides of the cavity to reflect the light back and forth through the active region. With many conventional semiconductor lasers, one produces mirrored surfaces by cleaving one side of the stack along a crystal face. But the cleavage plane of GaN is rotated 30 degrees with respect to that of a sapphire substrate. Instead of cleaving, then, the Nichia Chemical team used reactive ion etching to expose opposite sides of the stacked semiconductor layer. They then applied a dielectric coating to the etched edges to serve as the mirrors. The resulting mirror is not as smooth as that of a cleaved surface. An alternative approach with future lasers might be to fabricate a vertical cavity laser, in which the light would shine out of the top of the laser rather than emerging from the sides. John Edmond of Cree Research told us that cleaved faces are possible with SiC substrates, whose crystal planes line up with those of GaN.

Akasaki, who announced the ultraviolet laser diode last month, and his colleague Hiroshi Amano at Meijo University told us of other important steps, made by a number of research groups, in the development of a GaN laser diode. The steps included control of the conductivity in n-type nitrides, growth of both aluminum gallium nitride and gallium indium nitride alloys by metallo-organic chemical vapor deposition (AlGaN is used in the cladding layers and GaInN is used in the quantum well structure) and fabrication of a multiple quantum well structure.

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