Nichia's 1cd Blue LED Paves Way for Full-Color Display

by Shuji Nakamura, Nichia Chemical Industries Ltd

The 1cd blue LED, when used together with already available red and green LEDs with a high luminous intensity, can produce full-color LED display panels, traffic signals and other outdoor displays.

Nichia Chemical Industries Ltd of Japan has developed a blue light emitting diode (LED) registering as high as 1cd in luminous intensity by using GaN-based materials. The blue diode is 100 times brighter than currently available blue LEDs. With a few tens of thousands of hours in service life, the blue LED is considered fit for commercial applications. Nichia started mass production of the LED in January 1994.

Prolonged LED Life

The newly developed diode has a peak wavelength of 450nm and a full width at half maximum of 70nm (Fig 2). An output power of nearly 1.5mW is recorded at a forward current of 20mA (Fig 3). External quantum efficiency is 2.7%. Brightness reaches 1.2cd when packaged in a lens shape with a 15-degree full width at spread angle of emitted beam. At a forward current of 20mA, the forward voltage drop is 3.6V. Lifespan is at the practical level of a few tens of thousands of hours until the brightness halves.

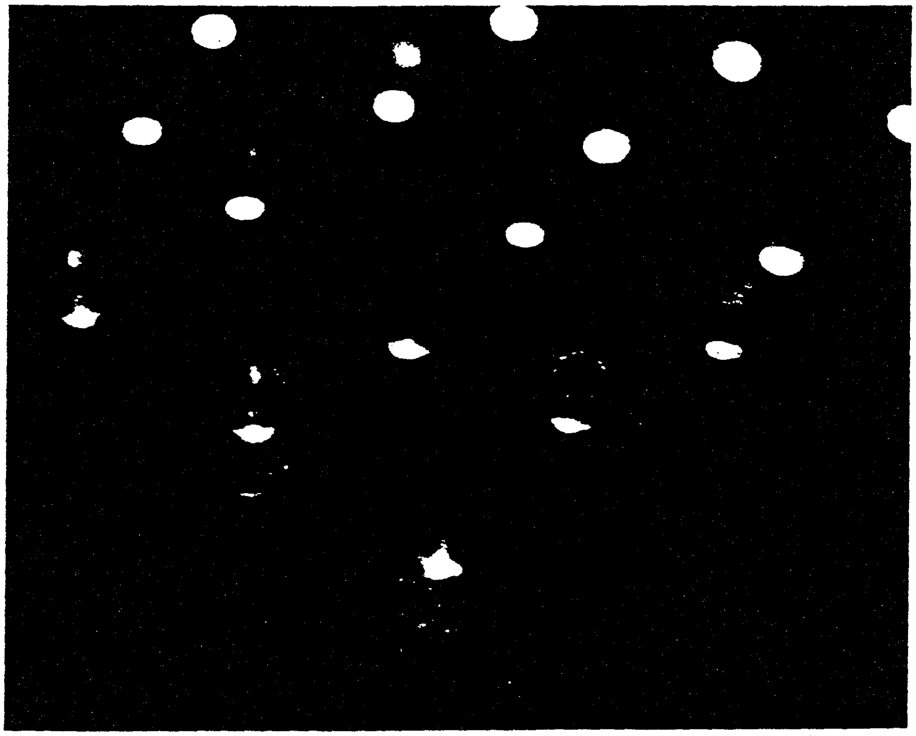

Fig 1 Nichia's 1cd Blue LED The diode registered a luminous intensity 100 times stronger than that of currently available blue LEDs.

Compared with commercially available blue LEDs, brightness performance is 100 times better (Table 1).

Conventional brightness levels (about 10mcd) are insufficient for outdoor displays. With Nichia Chemical's 1cd blue LEDs, however, such applications are feasible. Also, since the peak wavelength of 450nm is 20nm shorter than the SiC-based type, a pure blue light untainted by green is produced.

Forward voltage drop, which presented a problem for GaN-based diodes with a conventional MIS structure, is kept to 4V or less. This performance is equivalent to SiC-based diodes.

Green Diode Becomes Bottleneck

Even in comparison to the widely-used red LEDs, the brightness of the Nichia Chemical blue LED is up to par (Table 2). Compared with red-light diodes at 2cd and the new blue-light diode at 1cd, green LEDs with only about 60mcd are under pressure to catch up.

In order to achieve white-light

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*The author: Shuji Nakamura, chief researcher, Department of Research and Development,
Nichia Chemical Industries Ltd, Anan City, Tokushima, Japan.*

emission with high brightness by mixing these three colors, the performance of green LEDs must be improved. The main issue for blue LEDs may be a broad full width at half maximum of the emission spectrum (Fig 2). Red and green LEDs offer sharper emission spectra.

The blue LED's broad emission spectrum can be attributed to the emission centers of the emission layer at deep-energy levels. If the broad emission spectrum presents difficulties for practical applications, this will have to be revised.

In Fig 4, white-light emission is shown using the above-mentioned red, green and blue LEDs. The currents for these diodes are 5mA, 20mA and 4mA, respectively. The highest current is required for the green LED to compensate for its lower brightness performance. With a balance among these three colors, white light is produced and a full-color display with high brightness is possible. Using LEDs could greatly simplify maintenance of traffic signals. Other applications include medical equipment and lighting.

Direct-Transition GaN Picked

SiC, ZnSe, GaN and other materials have been used to fabricate blue LEDs. The first of these materials to be commercialized has been SiC. There have also been research-level announcements that high power blue/green LEDs and laser diodes can be formed with ZnSe-based materials.

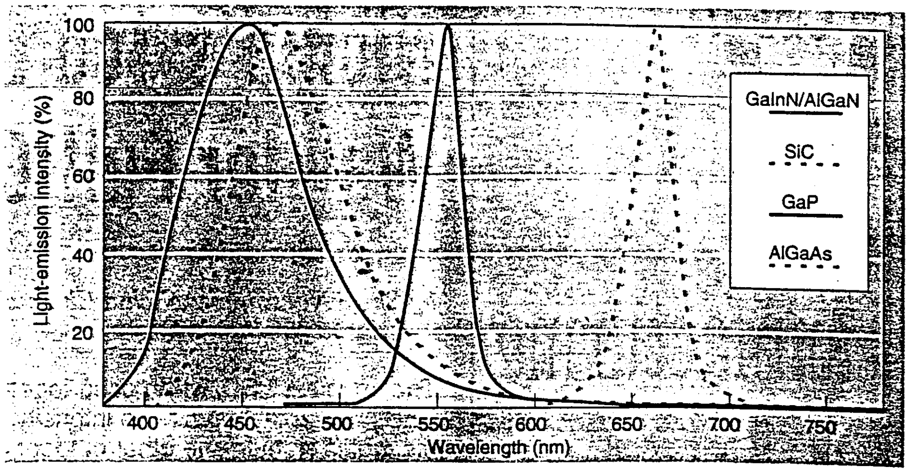

Fig 2 Light Emission Spectra—Blue LED Becomes More Blue Commercially available LEDs—AlGaAs red LED, GaP green LED and SiC blue LED—and the newly developed GaInN/AlGaN blue LED are shown.

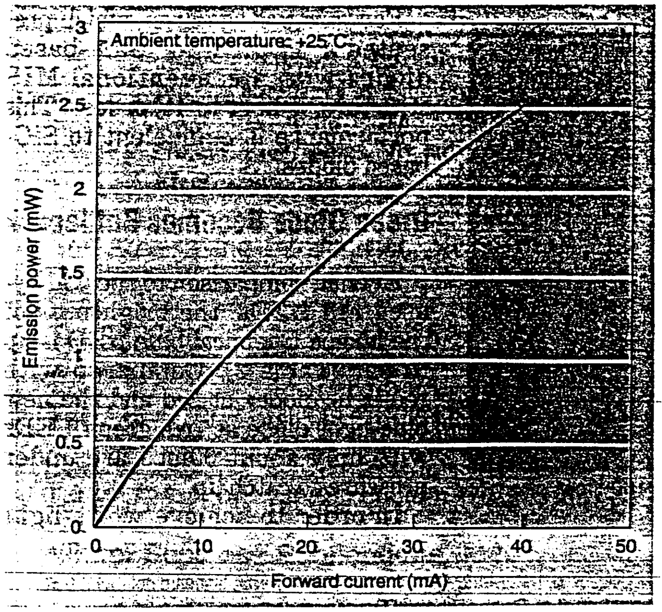

Fig 3 New Blue LED—Output Power, Forward Current

The primary reason for Nichia Chemical's selection of GaN is its direct transition energy bandgap. Semiconductor crystals can be classified as direct transition and indirect transition types depending on the energy band structure. The direct transition type includes GaAs, ZnSe, ZnS, GaN, InN and AlN, and the indirect transition type Si, Ge, GaP and SiC.

UV-to-Green Lights Covered

In the direct transition type, almost all energy of electrons is converted into light when the electrons transit from the conduction band to the lower levels. This energy band structure is suitable for light-emitting devices. On the other hand, in the indirect transition type, a part of the electron energy converts to heat and electron momentum is changed in this process. As a result, the conversion efficiency from energy to light drops considerably.

As members of the direct transition group, ZnSe and GaN have the potential to improve brightness.

However, ZnSe faces reliability problems. Its lifespan as a laser diode is just a few seconds.

On top of this, forward voltage is high. Crystals of ZnSe-based materials are grown at temperatures of +300°C or lower. This is a source of concern that crystals will break down if exposed to temperatures which exceed +300°C in post-growth steps. As a result, annealing processes which involve high temperatures cannot be used, making an ohmic contact between the electrode and ZnSe-based materials difficult and requiring a high forward voltage.

The GaN-based materials also have the direct transition bandgap, prompting expectations of high brightness. The band gap energy for GaN is 3.4eV. This value can be adjusted from 2.0eV to 6.3eV by compounding the GaN crystal with InN (band gap = 2.0eV) or AlN (band gap = 6.3eV). In other words, a GaN-based diode can emit light at colors ranging from ultraviolet to green.

Efficient pn Junction

The biggest stumbling block for GaN-based materials has been the inability to produce p-type layers. This has forced LEDs to assume a metal-insulator-semiconductor

Table 1 GaInN/AlGaN Blue LED vs SiC Blue LEDs—Specifications

Electrical and optical characteristics (ambient temperature =25°C)	Conditions	SiC Product A			SiC Product B			SiC Product C			GaInN/AlGaN		
		Minimum	Typical	Maximum	Minimum	Typical	Maximum	Minimum	Typical	Maximum	Minimum	Typical	Maximum
Forward voltage (V)	Forward current = 20mA	—	3.0	3.5	—	4.0	—	—	3.0 *1	4.0 *1	—	3.6	4.0
Reverse current (μA)	Reverse voltage = 5V	—	—	100 *2	—	—	100	—	—	50 *3	—	—	50
Luminous intensity (mcd)	Forward current = 20mA	5	10	—	—	8	—	8	15	—	500	1,000	—
Emission power (μW)	Forward current = 20mA	—	—	—	—	—	—	—	—	—	600	1,200	—
Peak wavelength (nm)	Forward current = 20mA	—	470	—	—	470	—	—	470	—	—	450	—
Spectrum FWHM (nm)	Forward current = 20mA	—	70	—	—	70	—	—	70	—	—	70	—

Catalog values are used for commercial products. *1 Forward current = 10mA. *2 Reverse voltage = 4.3V. *3 Reverse voltage = 3.0V.

Table 2 Red, Green, Blue LEDs—Performance Balance

	Material	Resin	Peak wavelength (nm)	Luminous intensity (mcd)	Emission power(μW)	Forward voltage (V)	External quantum efficiency (%)
Red LED	AlGaAs	Colorless, transparent	660	1,790	4,855	1.8	12.83
Green LED	GaP	Colorless, transparent	555	63	30	2.1	0.067
Blue LED	SiC	Colorless, transparent	466	9	11	2.9	0.021
	GaInN	Colorless, transparent	450	1,000	1,200	3.6	2.160

Values are measured by Nichia Chemcal. Note) Electrical and optical measurement data show values at a forward current of 20mA and an ambient temperature of +25°C.

structure. Diodes with the MIS structure[1)] sandwich a light-emitting insulation layer between an electrode and a semiconductor layer.

The forward voltage of a GaN-based LED with an MIS structure is about 10V. Furthermore, the thin insulation layer tends to break down under the application of a strong electric field. Another problem is that the achievement of high brightness is difficult.

Red LEDs and other widely-used LEDs all have pn-junction structures. If both n-type and p-type GaN can be produced, it is possible to increase emission efficiency and lower forward voltage to about 3V.

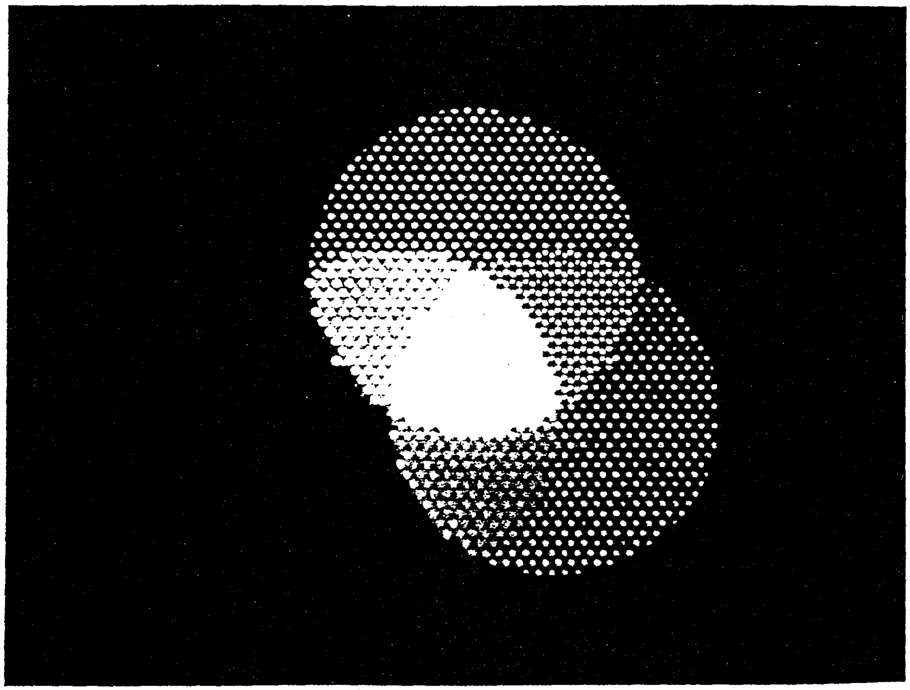

Fig 4 Full-Color LED Display Full-color LED display is made of AlGaAs red LEDs, GaP green LEDs and the new GaInN/AlGaN double-heterojunction blue LEDs. The LEDs' current values are 5mA for red, 4mA for blue and 20mA for green. The red and green LEDs are commercially available.

Two-Flow Method Developed

A pn-junction structure requires the formation of a p-type GaN film. This in turn requires technology for fabricating GaN monocrystalline films with few defects.

Since GaN films are grown at a temperature of +1,000°C, the GaN has a tendency to dissolve and form N vacancies easily. Also, the 15.4% lattice mismatch between GaN and the substrate prevents the formation of an acceptable monocrystalline film using conventional metalorganic vapor phase epitaxy (MOVPE) techniques.

To solve these problems, Nichia Chemical developed a new reactor which uses the two-flow MOVPE method and applied this to GaN crystal growth (Fig 5). This reactor features the introduction of a sub-flow gas which pushes the main-flow reaction gas towards the substrate from above to overcome heat convection which occurs during GaN growth. It supports the formation of GaN films with high mobility.[2),3)]

NH_3 is used as the source material gas for N and trimethyl gallium for Ga. H_2 is the carrier gas. All source materials are delivered to

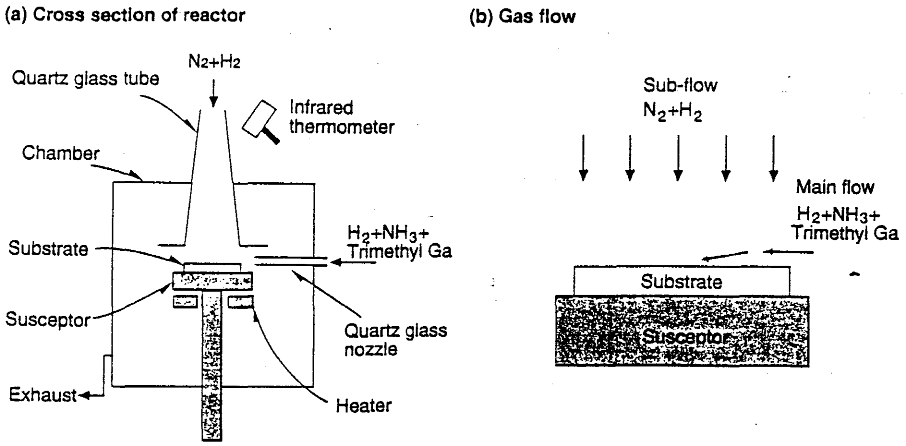

Fig 5 Two-Flow MOVPE Method The sub-flow gas forces the main flow gas onto the substrate and reduces the effect of heat convection.

the substrate in a gaseous form and the GaN film is grown at a substrate temperature of about +1,000°C.

However, when GaN is grown directly on a sapphire substrate at a temperature of +1,000°C, hexagon-shaped pyramids form on the film surface creating cracks throughout the crystal (Fig 6(a)). This is avoided by first growing a GaN thin buffer layer at a lower temperature of +500°C to +600°C and then growing the GaN film at +1,000°C (two-stage growth method). With this technique, a film with a planar surface can be grown (Fig 6(b)), and the number of defects within the film is reduced.

Once a GaN single crystal film can be formed, the next issue is a p-type film. In 1989, Professor Isamu Akasaki at Nagoya University of Japan discovered that low-resistance p-type GaN can be produced by irradiating Mg-doped GaN with electron beams.[4)]

p-Type Made with Annealing

Subsequently, Nichia Chemical discovered that low-resistance, p-type GaN could be obtained by annealing in a nitrogen atmosphere without the application of electron beams (Fig 7).[5),6)] Compared to the electron-beam approach, this technology makes p-type film more uniform at any depth in the wafer.

In 1991, however, 3M Co of the US announced success with a blue laser diode using II-VI family semiconductors.[7)] This and other announcements of high-power blue LEDs shifted attention to II-VI family blue LED and laser diode research.

Amid these activities, GaN-based material research lost ground temporarily. To recover that ground, it was necessary to move beyond the homojunction type to double-heterojunction LEDs and laser diodes.

A double-heterojunction diode has a structure which sandwiches the emission layer between a p-type layer and an n-type layer (cladding layers) with a larger bandgap energy than the emission layer. In this structure, the carrier injected in the emission layer is confined by the energy barrier between the emission layer and the cladding layers. The result is a considerable improvement in emission recombination probability and better emission efficiency compared to a simple homojunction structure.

1cd with Double Heterojunction

In 1993, Nichia Chemical completed a GaInN crystal growth process by applying this GaN crystal growth technique and produced a double-heterojunction LED with a GaInN/GaN structure.[9)]

After that, the GaInN layer was doped with Zn to form the emission

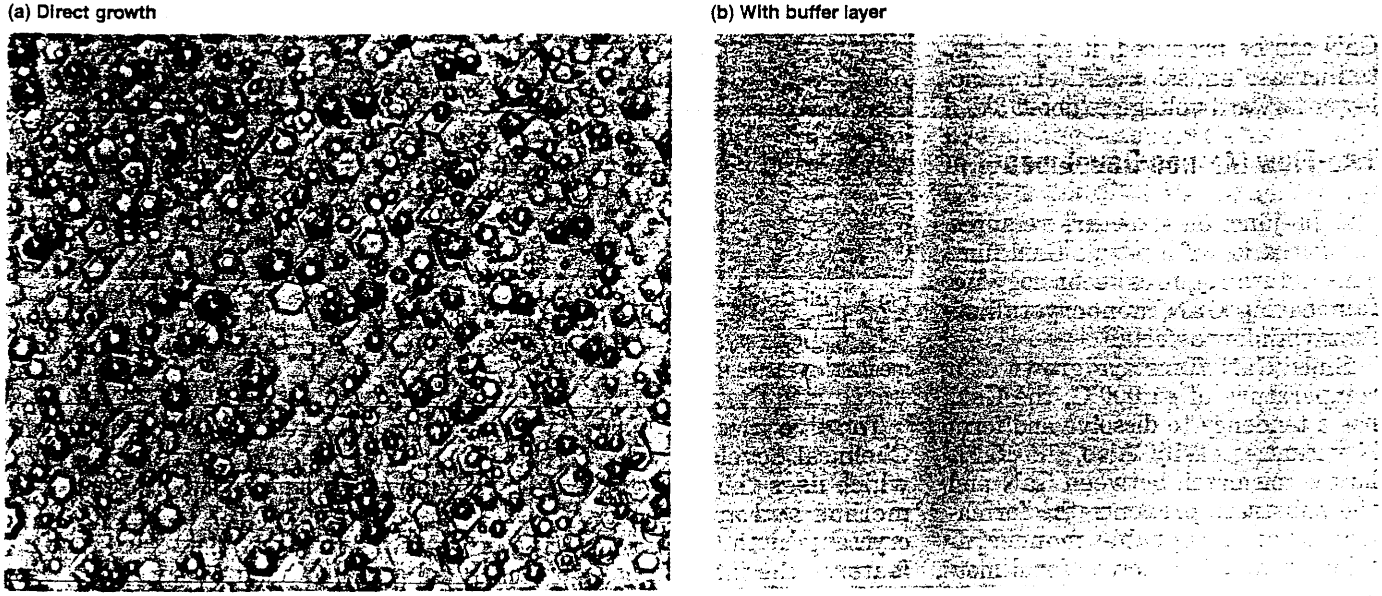
(a) Direct growth
(b) With buffer layer

Fig 6 GaN Surface Morphology (a) When crystal of the GaN layer is grown directly on the substrate, the crystal surface becomes rough. (b) In contrast, the surface becomes smooth with the introduction of a buffer layer.

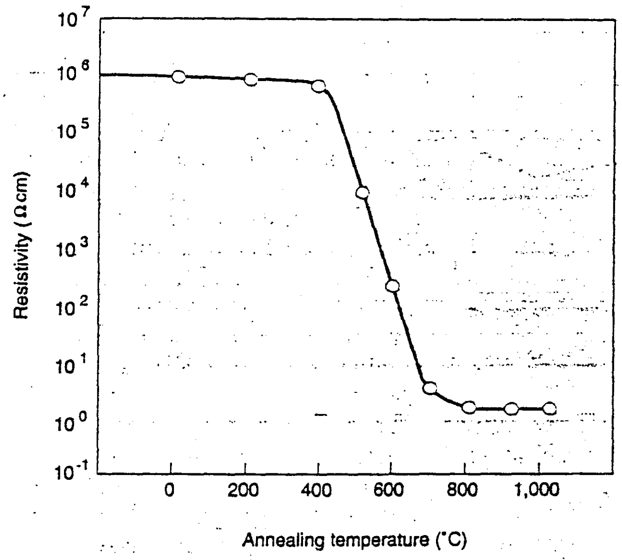

Fig 7 Resistivity Depends on Annealing Temperature An Mg-doped GaN film is annealed in a nitrogen atmosphere.

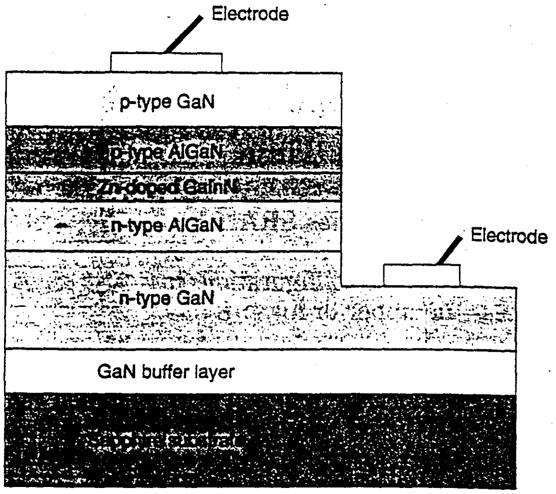

Fig 8 GaInN/AlGaN Double-Heterojunction Blue LED—Structure

center in order to raise spectral luminous efficacy of the LED. Doping with Zn increased the peak wavelength from 440nm to 450nm. Also, the cladding layers were changed to AlGaN to increase the energy difference between the emission layer band gap and the cladding layer bandgap. With these revisions, brightness performance of the GaN blue LED improved to over 1cd.

The structure of the newly developed GaInN/AlGaN double-heterojunction, high-brightness, blue LED is shown in Fig 8. First, a GaN buffer layer is grown at a temperature of about +550°C on the sapphire substrate and n-type GaN is deposited at about 1,000°C. Then, n-type AlGaN, Zn-doped GaInN, p-type AlGaN and p-type GaN films are formed in that order. After film growth, the wafer is annealed to lower the p-type layer resistances. Next, a portion of the p-type GaN film is etched to the point of exposing the n-type GaN film and electrodes are metallized on the p-type GaN and n-type GaN films. The diode chip is then placed in a lead frame and molded with epoxy to complete the product.

Sights Set on Blue Laser

The next target is a blue laser diode using GaN-based materials. In this area as well, the GaN type[10),11)] lags behind the II-VI family and other materials.

In order to achieve laser operation with the new GaN blue LED, band-to-band emission and a cavity for light amplification are required.

This diode does not use band-to-band emission because of the Zn dopant in the GaInN layer to lengthen the wavelength. In other words, if Zn is not doped, band-to-band emission can be easily achieved even though the emission wavelength will be a bit shorter.

To make the resonance cavity, it is not possible to use the cleavage facet as is done in conventional laser diodes because GaN does not have such cleavage characteristics. It is necessary to create a resonance cavity by etching or other methods.

These are rather minor problems compared to the more fundamental one of how to make a double heterojunction to achieve high-power blue-light emission. The completion of a laser diode is just a matter of time.

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