To search page

2021
Development of
10W-class high-power blue semiconductor laser diode
(Nichia)

~ Discrete Semiconductor/Others ~

Nichia succeeded in the room temperature continuous operation of a blue-violet (wavelength: 410nm) GaN-based semiconductor laser diode (LD) in 1996 (1). As a result of the development of advanced technologies, including the development and mass production of low dislocation defects density GaN substrates in 2001, the performance of blue-violet GaN-based semiconductor LDs has improved dramatically, and Blue-ray Discs (BDs) using them were launched in 2003 (2, 3).

GaN-based semiconductors (AlGaInN quaternary alloy) change their energy band gap widely depending on their composition, enabling light-emitting devices with a wide wavelength range from deep UV (Ultra Violet) to IR (Infra Read). However, the increase in In composition for longer wavelengths light-emitting causes many problems such as phase separation. The development of LD structures and manufacturing technologies to solve this problem has led to the development of blue (wavelength: 450 nm) and green (wavelength: 525 nm) band high-power semiconductor LDs, which have realized laser displays such as laser projectors, laser TVs, and digital cinemas (4). Furthermore, in the field of laser processing, blue LDs with high absorption wavelengths for copper, a difficult-to-process material with low absorption at conventional gas or fiber laser wavelengths (in the infrared region) have attracted attention. The development of higher output power blue LD has been proceeding (5).

It is virtually impossible to grow ingots of GaN crystal from melt due to the high equilibrium partial pressure of nitrogen. For this reason, GaN-based semiconductor devices began practical use with growing GaN thin-film crystals on dissimilar substrates such as sapphire or GaAs. In this case, due to the difference in lattice constants and thermal expansion coefficients between the substrate and the growth layer, there were high-density stacking dislocations in the 10^8~10^9/cm^2 range in the GaN layer. The influence of dislocations was not severe for LEDs with low current density, and they have been put into practical use. However, for LDs with current densities that were orders of magnitude higher, it was necessary to prepare GaN crystals with lower dislocation density.

The growth facet of GaN crystal changes under the growth condition. Epitaxial Lateral Overgrowth (ELO) technology utilizing this property and a technology to detach the GaN crystal from the dissimilar substrate during or after crystal growth in order to prevent crystal cracking due to stress caused by the different thermal expansion coefficient between the dissimilar substrate and the GaN crystal have been established. The DEEP (Dislocation Elimination by the Epitaxial-growth with inverted-pyramidal Pits) method by Sumitomo Electric (6), the proprietary HVPE (Halide Vapor Phase Epitaxy) method by Mitsubishi Chemical, and the VAS (Void Assisted Separation) method (Figure 1, Figure 2) (7, 8) by Sciocs (former Hitachi Cable, now Sumitomo Chemical) have been developed, enabling the supply of free-standing GaN single-crystal substrates with dislocation density in the $10^5/cm^2$ range and higher output power for GaN-based semiconductor LDs.

A typical example of the cross-sectional structure of a GaN-based semiconductor blue LD is schematically shown in Figure 2 (9). The LD consists of ridge-waveguide structure with dielectric covering the outside of the ridge stripes. The active layer consists of several pairs of GaInN/AlGa(In)N Multiple Quantum Well (MQW) layers. The active layer is sandwiched between p-type and n-type GaInN optical guide layers with high refractive index, and p-type and n-type AlGa(In)N cladding layers with low Al composition ratios (2 to 5%) are placed on their outside. An electron blocking layer of p-type AlGaN (Al composition ratio 20%) is inserted between the MQW active layer and the p-type GaInN guide layer in order to prevent electron overflow into the p-type layer.

Nichia developed and commercialized a blue (wavelength: 455 nm) LD with a ridge stripe width of 45 μm and length of 1.2 mm emitting output power of 5.67 W and a power conversion efficiency (WPE) of 48.1% in 2018 (10). Expanding a ridge stripe width to 90 μm, Nichia developed an LD with an output of 11.2 W (wavelength: 465 nm) and a WPE of 33.8% in 2021 (11). LDs were fabricated by Metal Organic Chemical Vapor Deposition (MOCVD) on free-standing C-plane GaN single-crystal substrates. Dielectric insulating film covering the outside of the ridge stripe was selected to provide a refractive index difference in the horizontal directions to stabilize transverse oscillating modes. On the other hand, a Separate-Confinement Heterostructure (SCH) was invented by confining carriers efficiently in the MQW emission layer and light in the guide layer, respectively as a technology to control vertical transverse modes. The LD was mounted with junction-down method in a proprietary package (Side Lead Package: SLP) that achieves low thermal resistance of 2.3 K/W. (Figure 4)

By combining the light beams of multiple blue semiconductor LDs in various ways, high-power blue laser module such as output 1 kW of blue light through an optical fiber with core diameter of 300 μm for laser processing has been developed by Shimadzu (12), Furukawa Electric (13), and others.

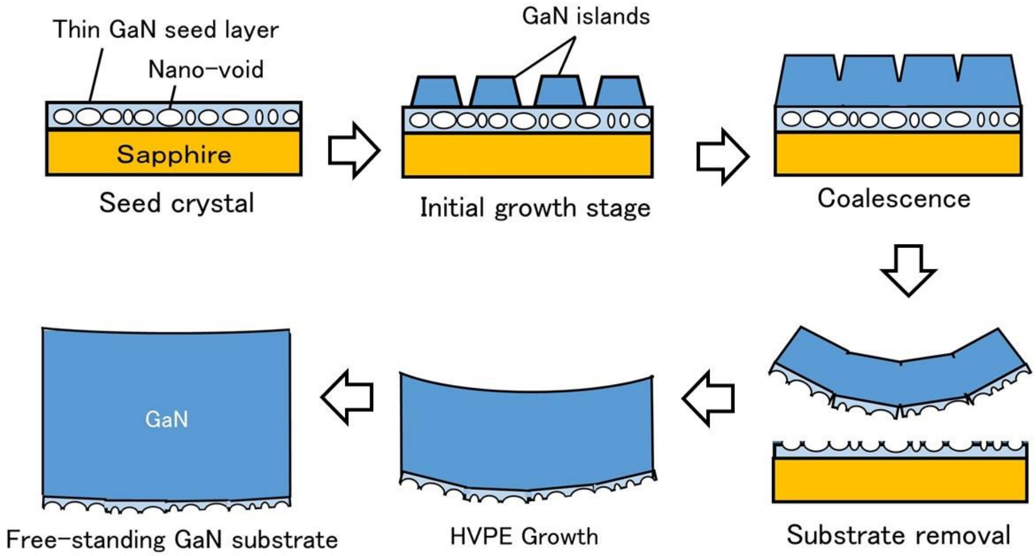

Figure 1 Fabrication process of free-standing GaN single-crystal substrates by the Void Assisted Separation (VAS) method
(Prepared by Semiconductor History Museum of Japan based on references (7) and (8))

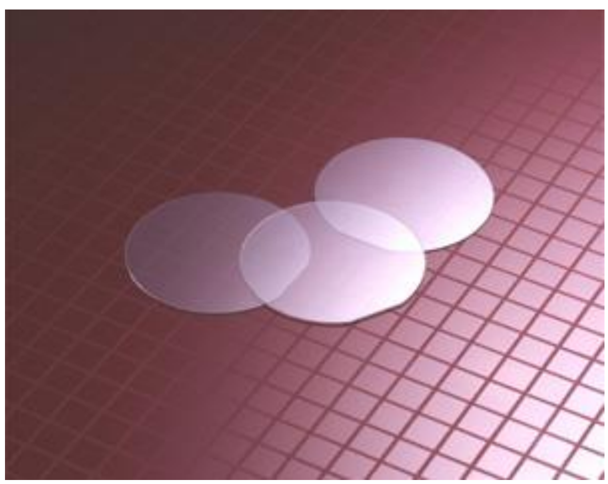

Figure 2 Free-standing GaN single-crystal substrates (2-inch diameter) by the Void Assisted Separation (VAS) method
(Courtesy of SUMITOMO CHEMICAL COMPANY, LIMITED)

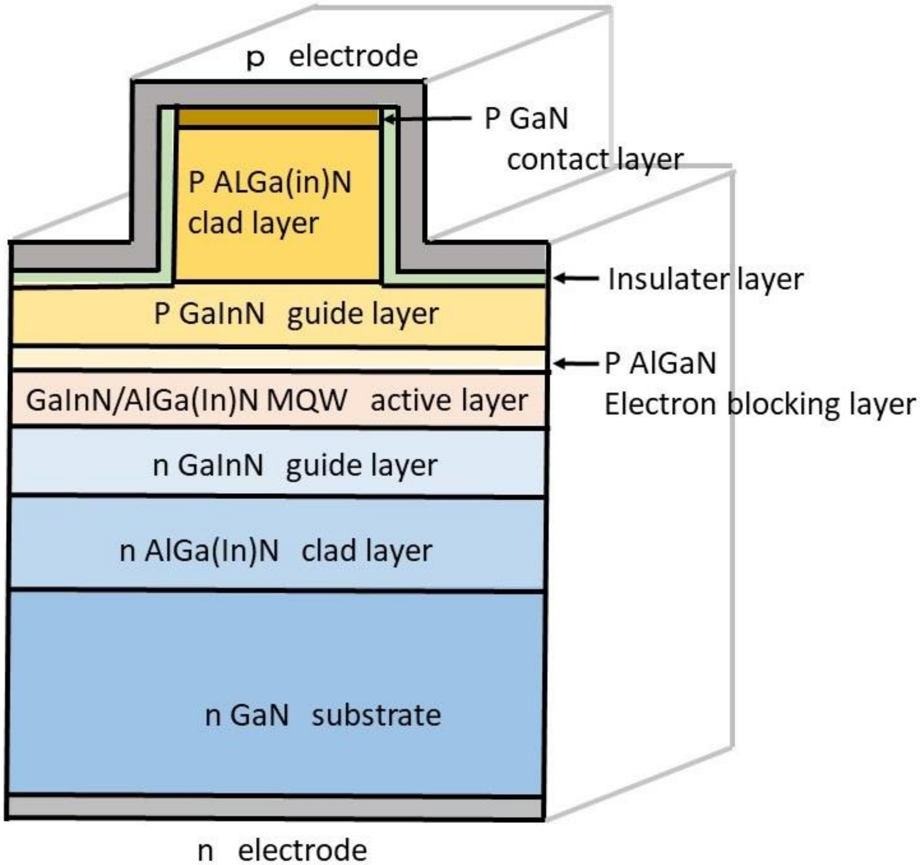

Figure 3 A cross sectional view example of GaN-based semiconductor blue LD structure
(Prepared by Semiconductor History Museum of Japan based on reference (9))

Figure 4 High output blue LD (Side Lead Package: SLD)
(6.9mm(w) x 6.0mm(d) x 6.55mm(h))
(Courtesy of NICHIA CORPORATION))

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