Development of a Compact Deep-Ultraviolet Laser Source for Precision Microstructure Measurement

微細構造計測に向けた小型深紫外レーザー光源の開発

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This article presents advancements in deep-ultraviolet (DUV) laser diodes (LDs) based on nitride semiconductors, particularly focusing on achieving room-temperature continuous-wave lasing. DUV LDs emitting in the UV-C wavelength range (<280 nm) hold promise for various applications, including disinfection, medical diagnostics, and industrial processes. Key breakthroughs in AlGaN-based DUV LDs are discussed, including crystal quality improvement through pseudo-morphic AlGaN growth on single-crystal AlN substrates and electrical conductivity control using distributed polarization doping. The process of suppressing process-induced crystal defects and achieving room-temperature continuous-wave lasing will also be discussed. This achievement is a successful realization of a room-temperature continuous-wave oscillation laser, which expands the possibilities of DUV LDs in various technological fields.

本稿では，窒化物半導体をベースとした深紫外(DUV)レーザーダイオード(LD)の進展について，特に室温連続発振の実現に焦点を当てて紹介する。UV-C波長領域(<280 nm)で発光するDUV LDは，殺菌，医療診断，工業プロセスなど，さまざまな用途への応用が期待されている。AlGaNベースのDUV LDにおける主要なブレークスルーとして，AlN単結晶基板上の擬似格子整合AlGaN成長による結晶品質の改善や，分布分極ドーピングを用いた電気伝導度の制御などが議論されている。さらに，プロセスに起因する結晶欠陥を抑制し，室温連続波発振を達成した経緯についても解説する。本成果は室温での連続波発振レーザーの実現に成功したものであり，多様な技術領域におけるDUV LDの可能性が広げるものである。

Introduction

Our research group is studying the deep-ultraviolet (DUV) laser diodes (LDs) based on nitride semiconductors. The DUV laser sources in the wavelength range of 280 nm or less, called UV-C, are attracting attention because of their high absorption property by biomolecules such as DNA. They can be applied to disinfection and in medical fields. UV-C-emitting lasers can also be used in a wide range of industrial applications, such as the detection of minute particles, high-accuracy distance measurement, and semiconductor exposure apparatuses. In addition, if the laser output is improved to watt levels, UV-C-emitting lasers may be used for laser machining apparatuses capable of printing and machining without causing thermal damage because of their high absorbance by materials. Our research group has been at the forefront of DUV LD technology; room-temperature pulsed oscillation with a wavelength of 271.8 nm was demonstrated in 2019[1] and room-temperature continuous-wave lasing was achieved in 2022[2]. In this article, we explain the key technologies employed to realize the room-temperature continuous-wave lasing of DUV LDs and present the characteristics of the lasers used in the demonstration.

Breakthroughs in DUV LDs

The LDs in the UV range have been studied using AlGaN-based nitride semiconductors after the oscillation of InGaN-based blue-violet LDs was achieved. AlGaN is a direct transition semiconductor with high luminous efficiency. Light emission in a wide wavelength range, including UV-C, can be obtained by controlling the mixed ratio of the crystals. Control of refractive index is also possible. In addition, AlGaN is suitable for Fabry–Perot LDs because a resonator end face that is smooth at the atomic level can be formed by cleaving crystals. However, after the report of laser oscillation with a wavelength of 336 nm in the UV-A range in 2008[3], there had been no report about the lasing of LDs with a shorter wavelength. The major issues preventing such an achievement were the quality of AlGaN crystals and inadequate control of the electrical conductivity.

Figure 1(a) shows the DUV-LD structure we proposed to solve the above issues. First, we worked on the fabrication of LDs by the pseudo-lattice matching of AlGaN grown on a single-crystal AlN substrate with the aim of improving the crystal quality. The dislocation density of the single-crystal AlN substrate is less than $10^4/cm^2$. The dislocation density of pseudo-morphic AlGaN grown on this substrate was equal to that of the substrate, which meant a high-quality laser structure. The results of the characteristic evaluation by optical excitation showed that the threshold excitation power density was significantly reduced in the laser structure fabricated on the single-crystal AlN substrate compared with the laser structure fabricated on a dissimilar substrate.

The main point of the issue of electrical conductivity control was whether a sufficient hole density can be achieved in the p-cladding layer. A sufficient hole density was not achieved by conventional electrical conductivity control using doping owing to the limitation of the material properties. To solve this issue, we applied distributed polarization doping (DPD)[4] to the p-cladding layer. This technique used the polarization generated in AlN and GaN crystals and AlGaN crystals as a result of distortion from a regular tetrahedral structure, as shown in Figure 1(b). The amount of polarization differs among AlGaN crystals with different AlN molar fraction. The higher the AlN molar fraction, the greater the polarization. This means that there is a polarization difference on the interface between the AlGaN crystals with different AlN molar fractions. As a result, an amount of free carriers corresponding to the difference in the amount of polarization accumulates on the interface so that the charge neutral condition is satisfied. As shown in Figure 1(c), the polarization charge is dispersed in the thickness direction when the amount of polarization is distributed in the thickness direction (the direction toward [0001]) by continuously varying the AlN molar fraction of AlGaN crystals. Because the accumulation of free carriers is also dispersed in the thickness direction corresponding to the dispersion of polarization charge, a state where free carriers exist across the entire film is produced effectively (Figure 1(c) shows the accumulation of holes). We became the first in the world to demonstrate the room-temperature pulsed oscillation of the DUV LD through the development of technologies and the design of laser structures based on the above concepts[1].

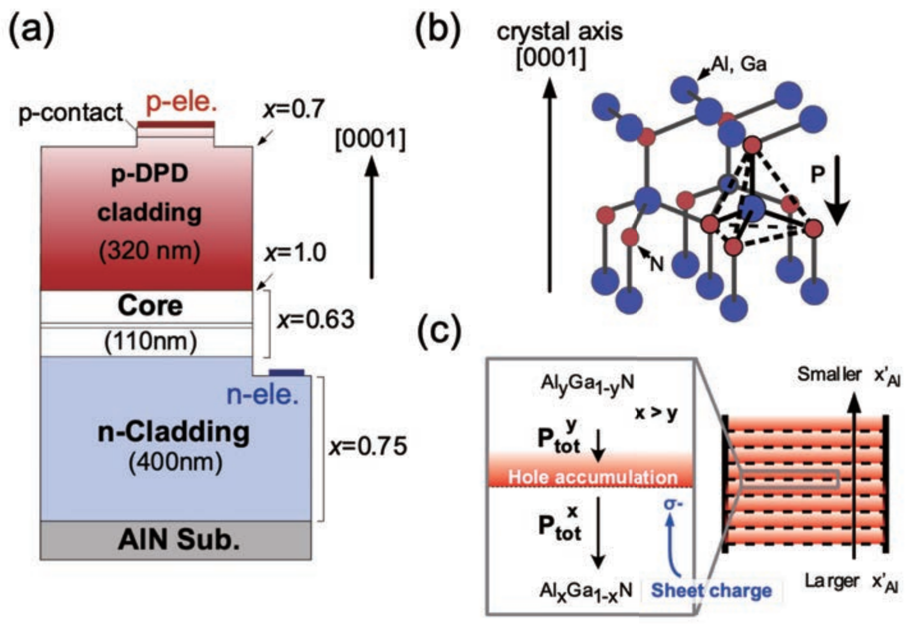

Figure 1 (a) Schematic of DUV LD. (b) Polarization in wurtzite structure. (c) Diagram of DPD.

Barrier to continuous-wave lasing : process-induced formation of crystal defects

Although we demonstrated the pulsed lasing of the DUV LD, we could not achieve the continuous-wave lasing because of the high driving power of the DUV LD. The major cause was the process-induced formation of crystal defects. While the generation of new dislocations was suppressed in the thin AlGaN film grown pseudomorphically, strain remained in the thin film. The DUV LD was fabricated by the AlGaN with a large lattice constant on a single-crystal AlN substrate with a small lattice constant. Therefore, new crystal defects were not formed at the time of film growth. However, the strain in AlGaN was relaxed by the heat treatment during the DUV LD fabrication process, resulting in the formation of crystal defects. The upper panel of Figure 2(a) shows the plan-view TEM image of the mesa stripe formed perpendicular to the wafer plane. Numerous dislocation lines were observed in the range of ~12 μm from near the mesa edge to the center of the mesa stripe. Some of the defects passed through the emission layer, which significantly deteriorated the emission properties. The threshold current of the LD with its p-electrode placed in an area containing the dislocation was higher than that of the LD with its p-electrode placed in an area without the dislocation[5]. DUV LDs must have a horizontal conductive device structure with the electrodes placed on the surface side because no fabrication technology for a conductive single-crystal AlN substrate has been established. The current pathway from the p-electrode to the n-electrode is extended if the electrode arrangement is constrained by the presence of crystal defects, which results in increased device resistance. As explained above, the LDs that we developed to demonstrate the pulsed lasing had the problem of a trade-off between threshold current density and driving voltage because of the crystal defects.

Improvement of device properties by suppressing crystal defect

With the aim of suppressing the formation of crystal defects, we controlled the distribution of the residual-strain-induced stress in the mesa stripe[6]. Figure 2(b) shows the results of the simulation of stress distribution by the finite element method and the maximum shear stress concentrating at the bottom edge of the mesa at each slope angle of the edge of the mesa stripe. The restrain of the mesa edge was released when the mesa stripe was formed by etching. At that time, the shear stress induced by the residual strain in the AlGaN thin film concentrated at the bottom edge of the mesa in the n-cladding layer. The results of the simulation showed that the maximum shear stress reached 9 GPa in the vertically etched mesa stripe. On the other hand, the shear stress was dispersed when the slope angle of the mesa stripe was small, indicating that the stress concentration at the bottom edge of the mesa can be reduced.

Considering the above finding, we fabricated a mesa structure with a slope angle of 15°. Although the stress concentration can be reduced as the slope angle decreases, the disadvantage of the small slope angle is the increased distance between electrodes. The lower panel of Figure 2(a) shows the plan-view TEM image of the LD subjected to heat treatment after the formation of the sloped mesa. The crystal defects observed in the vertical mesa structure were not observed in the sloped mesa structure. These results indicated that the process-induced crystal defects was suppressed by controlling the stress distribution by means of the sloped mesa.

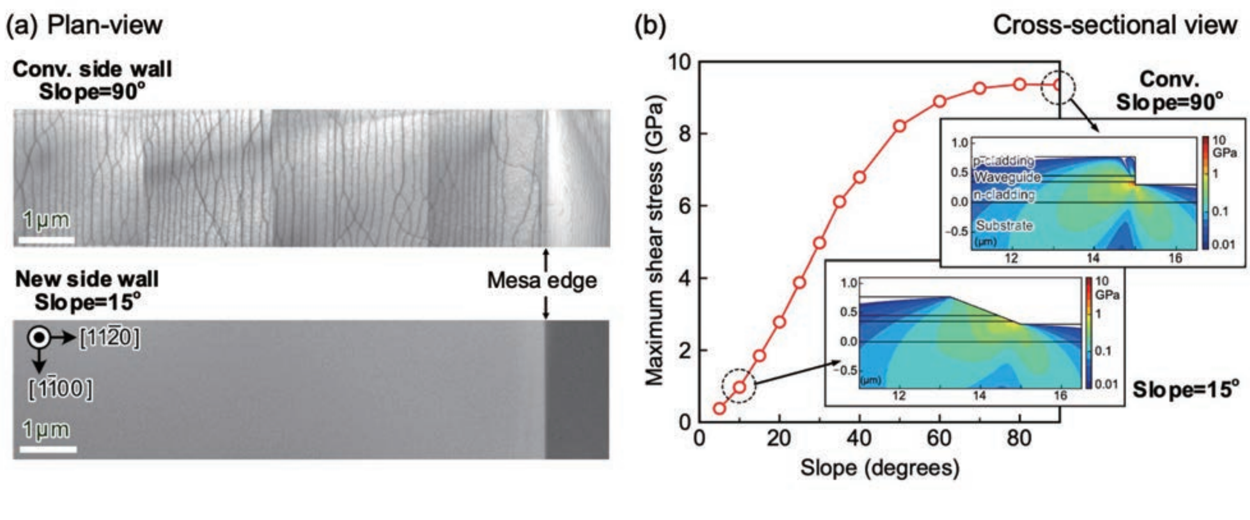

Figure 2 (a) Difference in slope angle of mesa stripes. (a) Plan-view TEM images at the edge of mesa stripe.
(b) Schematics of UV-C LD and conceptual images of residual-film-stress-induced basal plane slip.

Characteristics of DUV LDs

From the results of the calculation in which the characteristic temperature of threshold current and the thermal resistance of the package were taken into account, it was estimated that the driving power should be reduced to 1 W or lower to achieve room-temperature continuous-wave lasing[2]. To reduce the threshold current density, the distance between p- and n-electrodes, *d*, in the conventional vertical mesa structure should be 20 µm. The resistance of the n-cladding layer was proportional to *d* and accounted for at least half of the device resistance of the LD with a cavity length of 600 µm. On the other hand, *d* was reduced to 5 µm in the sloped mesa structure in which the formation of crystal defects was suppressed. As a result, the resistance in LD with the sloped mesa structure was significantly reduced. Also, the n-electrodes were placed on both sides of the mesa stripe in order to reduce the resistance compared with the LD with the n-electrode placed on one side. We significantly reduced the device resistance from the initial value of 16 Ω to 8.3 Ω by adopting those resistance reduction methods in the device design. Finally, we achieved the lasing of DUV LD under DC at room temperature. Figure 3 shows the *L–I–V* characteristics of DUV LDs. The room-temperature continuous-wave lasing of the LD with a sloped mesa structure was observed with threshold current I_{th} = 125 mA, threshold voltage V_{th} = 8.7 V, and lasing wavelength of 274 nm. The input power at that time was 1.1 W, which is close to 1 W, the target value mentioned at the beginning of this section.

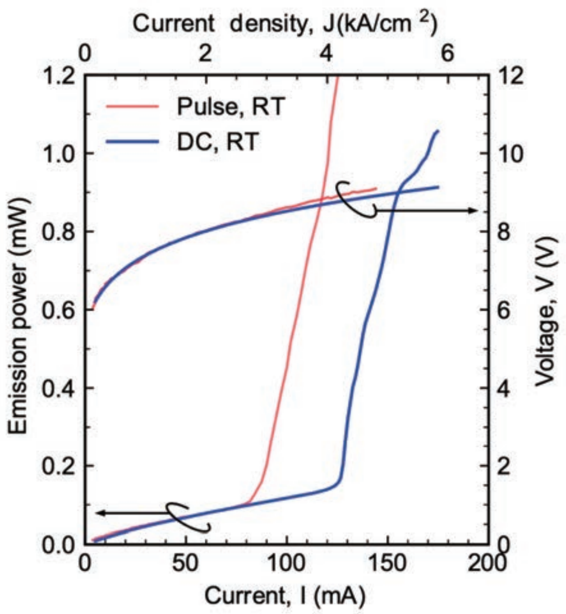

Figure 3 *L–I–V* characteristics of DUV LDs under DC and pulsed current drive.

Conclusion

In this article, we explained two key technologies in realizing AlGaN-based DUV LDs. The improvement of crystal quality by means of pseudo-morphic growth of AlGaN on a single-crystal AlN substrate and electrical conductivity control in the p-cladding layer of high-Al-composition AlGaN using DPD significantly contributed to the realization of the long-desired DUV LDs. Then, we described the process-induced crystal defects, which had prevented the room-temperature continuous-wave lasing of DUV LDs. The crystal defects were induced by the shear stress distribution after LD fabrication, which was caused by residual stress in the thin film. The formation of crystal defects was suppressed by controlling the stress distribution using a sloped mesa structure. The control of residual stress in the pseudo-morphic grown film is an important issue not only in LDs but also in the design of device structures. We were able to reduce the device resistance and realize the continuous-wave lasing of DUV LDs by adopting the measures described above. DUV LDs are brand-new laser sources that can be implemented in a variety of applications. Further improvement of the LD characteristics and increasing the output by using a combination of LDs are expected.

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