

令和2年度 学位論文内容要旨

論文題目

(邦文)

p-AlGaN クラッド層の開発および AlGaN UVB レーザダイ
オードの研究

(欧文)

Development of p-AlGaN cladding layer and study of
AlGaN ultraviolet-B laser diode

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Ultraviolet (UV) laser diodes (LDs) based on ultrawide bandgap semiconductors are small, lightweight and cost-effective light sources being friendly for the environment and the human body. There are many applications in UV LDs depending on the emission wavelengths such as medical treatments of eye surgery or phototherapy, material processing of PET or ITO, fine-patterned exposures or analyses of DNA or protein. In 2018, the shortest wavelength of reported UV LDs was 328 nm in a UVA band (315-380 nm) in which AlGaIn films were grown on the low-dislocation $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ layer grown on a patterned GaN on a sapphire substrate. There was no report of UVB (280-315 nm) or UVC (10-280 nm) LDs because of the difficulties of a development of a conductive and durable p-AlGaIn cladding layer with high Al composition over 0.6 to confine light within the guide layers. From the estimation of the required current density for laser oscillation calculated from the best value of 36 kW/cm^2 of the threshold power density by an optically pumped measurement, the required threshold current density for laser oscillations in UVB LDs is estimated over 40 kA/cm^2 . This dissertation describes the development of p-AlGaIn cladding layers with Al compositions over 0.6 and realization of AlGaIn based UVB LDs. The AlGaIn structure are further investigated to reduce the power consumptions and threshold current densities of the UVB LDs.

The electrical properties of bulk p-AlGaIn, p-AlGaIn superlattices and Al-composition graded p-AlGaIn are investigated by Hall measurements or resistivity measurements along a horizontal direction and by voltage-current measurement of a pin diode along a vertical direction. The conductivity and the durability for operation strongly depend on the Al compositions and lattice-strains in p-AlGaIn. The best durability is obtained with double graded p-AlGaIn layers composed with a 1st graded p-AlGaIn (260 nm) with Al compositions changing from 0.9 to 0.45, and a 2nd graded p-AlGaIn (75 nm) with Al composition changing from 0.45 to 0. The light confinement is achieved with the 1st graded p-AlGaIn with average Al composition of 0.68. The maximum current density of pin diodes reached at 47.8 kA/cm^2 over the target current density of 40 kA/cm^2 .

AlGaIn UVB LDs are realized by combining the technologies of the lattice-relaxed high-quality of n- $\text{Al}_{0.6}\text{Ga}_{0.4}\text{N}$ growth previously developed in our group, and the Al-composition graded p-AlGaIn cladding layers. The UVB LDs were fabricated without a ridge formation and coatings on the mirror facets. The multi modal approximately 100% TE polarized UVB laser emission is observed at the wavelength of 298 nm operated with a pulse width of 50 ns and a duty ratio of 0.0001. The lowest J_{th} of 25 kA/cm^2 is obtained with a p-metal width of $10 \mu\text{m}$ and a cavity length of $2000 \mu\text{m}$ with the forward voltage of 34.2V.

The high forward voltage mainly derives from the high turn on voltage of the diode at 15.2 V. The differential resistance at 20 kA/cm^2 is acceptable value of $7.65 \times 10^{-4} \Omega\text{cm}^2$. The high turn on voltage derived from the insulation of the 1st graded p-AlGaIn and the rough p-GaN contact with a stacked SiO_2 layer between the semiconductor and the p-metal. The existence of Mg-related donors is indicated from both fundamental experiments and simulations. Electrons generated with these donors compensate with polarization doped holes within the 1st graded p-AlGaIn. By applying an undoped 1st graded AlGaIn as p-type cladding layer, the turn on voltage drops approximately 10 V. The rough surface is observed because of the lattice-relaxation during the

growth of the 2nd graded p-AlGaN. The roughness of the p-GaN is critical parameter for the stacking of the SiO₂ during the device fabrication. The stacking is prevented with a smooth p-GaN surface developed by growing an additional 1.1- μm -thick p-GaN layer on the rough surface. With the thick p-GaN, the turn on voltage is reduced approximately 2 V. In addition, the maximum current density of 288 kA/cm² is achieved with this smooth and thick p-GaN surface. This will be because of the uniform current injection with smooth surface to prevent the breaking caused by current and heat crowding in specific small areas.

The high threshold current density derives from several factors; the high internal loss at 10 cm⁻¹ confirmed by optically pumped measurement with variable striped method, the high mirror loss at 7.8 cm⁻¹, the low light confinement factor of 3.5% and the low carrier injection efficiency at 1.5% calculated from the relationship of the threshold current density on the inverse of a cavity length. This dissertation focused on the carrier injection efficiency which is much lower than that of GaInN-based visible LDs over 70%. From the analysis of the sub peak emission at 270-280 nm from the u-Al_{0.45}Ga_{0.55}N guide reducing the carrier injection into well by fundamental experiments and simulations, the mechanisms are estimated as the carrier traps by the energy valley at the interface of the 2nd u-Al_{0.45}Ga_{0.55}N guide and the u-Al_{0.9}Ga_{0.1}N electron blocking layer, and within the 2nd u-Al_{0.45}Ga_{0.55}N guide. To prevent the carrier trap over the quantum wells several approaches are investigated; inserting electron blocking layer between the wells and the 2nd u-Al_{0.45}Ga_{0.55}N guide and applying a little thicker single quantum well.

The structural modified UVB LDs incorporating the several techniques above show the improved performances. The minimum forward voltage of the threshold of a laser oscillation drops to 23.7 V with the threshold current density of 89.3 kA/cm² with the p-metal width of 4 μm and the cavity length of 100 μm . On the other hand, the minimum current density is 34.2 kA/cm² at 29.9 V with the p-metal width of 19 μm and the cavity length of 500 μm . The threshold current density strongly depends on the p-metal width and the cavity length indicating the poor confinement of carriers along a perpendicular direction without a ridge formation and high mirror loss with as etched AlGaIn mirror facets. The threshold current density of the modified UVB LDs is almost the same with the pre-optimized UVB LDs above. The increase of the carrier injection efficiency will also relate to the crystal quality of AlGaIn films. In addition, one of the modified UVB LDs do not show a laser oscillation. From the analysis, V shaped pits deriving from the threading dislocation penetrating from the underlying layer is confirmed.

AlGaIn based UVB LDs developed in this dissertation become the fundamental structure of future researches of UV LDs. The electrical and optical characteristics of the UVB LDs will improved by developing technologies suggested in this dissertation in future works. Furthermore, ultrawide bandgap semiconductor devices such as UV LEDs, UV sensors or high-power conversion devices will be developed utilizing physical findings clarified in this dissertation.