High-Power Short-Cavity AlGaInP Laser Diodes

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AlGaInP laser diodes (LDs) are used in a wide range of digital equipment, such as MO/CD/DVD optical pick-up units, laser printers and barcode scanners. These lasers are expected to be used for the next-generation hard disk drives (HDDs) using thermally-assisted magnetic recording systems, mobile devices and other digital products. To keep up with the increasing demand, we have undertaken the development of higher-output and lower-power-consumption LDs. By optimizing our 4-inch-wafer process, we have succeeded in the development of a 660 nm short-cavity ridge-waveguide laser (L = 300 μm) that can demonstrate the output power per unit cavity length as high as 100 mW/mm (CW operation, 25°C to 80°C). This output power far surpasses 64 mW/mm by a high-power laser (L = 2200 μm) designed for high-speed recordable DVD systems.

Keywords: laser diode, AlGaInP, short cavity, high power, HDD

1. Introduction

AlGaInP laser diodes (LDs) with wavelengths 630 - 690 nm are used in a variety of digital equipment, such as MO/CD/DVD optical pickup units, laser printers and barcode scanners. These lasers are currently expected to expand the application to projectors, displays, and next-generation hard disk drives (HDDs), and therefore, it is vital to improve their characteristics and cost efficiency. Furthermore, downsizing of the laser chips is also required especially for HDDs and other commercial devices such as micro projectors and mobile barcode scanners. More specifically, heat-assisted magnetic recording (HAMR) technique, which is highly expected to realize the next generation high density HDD, will use laser beams as the energy source to heat the recording media [(1)]. In this case, the laser needs to be installed inside the HDD and the incorporation of the laser chips into the magnetic recording head is also being considered [(2)].

To respond to the market demands of productive LD design, future development needs to be based on a market-oriented concept rather than merely extending conventional technology of DVD optical pickup units and other existing products. Take the laser chip assembly as an example, not only conventional techniques for general CAN packages but also flexible tailor-made design need to be considered for customer convenience. We have proactively worked to develop lasers, sticking to the market-oriented production concept.

In this paper, we report the study of a 660 nm short-cavity (L = 300 μm) ridge-waveguide laser, which demonstrates a high output power of 100 mW/mm in continuous wave (CW) operation at the temperature range from 25°C to 80°C. This output power is far higher than 64 mW/mm by a high-power laser (L = 2200 μm) designed for high-speed recordable DVD systems.

2. Mass Production Process of AlGaInP LD

For the commercial production of devices, not only their performance improvement but also reduction in production costs needs to be considered at the early stage of designing the devices. In our study, we adopted a laser that has a simple ridge-waveguide structure with a silicone nitride (SiNx) current blocking layer. This layer was fabricated by one-step metal-organic chemical vapor deposition (MOCVD) growth and mesa-etching procedure for the ridge waveguide formation. The ridge formation plays the key role in the LD production process [(3) - (5)].

In order to maintain the single-transverse-mode operation and stabilize the beam divergence angle, the size and shape of the ridge need to be uniformly controlled over the entire wafer. We adopted inductively coupled plasma (ICP) dry etching techniques to realize the excellent controllability of ridge formation process. By using this novel etching technique, we succeeded in the mass production of the LD with a small beam aspect ratio, which had previously been impossible with conventional ridge lasers [(6)].

Furthermore, the optimization of ICP etching process eliminated the damage to the dry etching layer, thereby enabling to curtail the wet etching process. In conventional ridge formation, dry process needed to be followed by wet etching process, in which residual plasma-induced damage caused by dry process were removed. However, because of the poor reproducibility of ridge fabrication in the wet process, only dry etching was required for mass production.

The deposit condition and properties of SiNx dielectric film, which act as a current blocking layer, determine the reliability of the laser. **Photo 1** shows the transmission electron microscope (TEM) image of the interface between the dry etched AlGaInP surface and the SiNx film. By controlling the formation and structure of the SiNx film, the distortion of the AlGaInP surface became as small as approximately 10 nm, and the lattice stress was kept about 0.3% or lower.

In addition, to achieve the high-power operation while preventing the catastrophic optical damage (COD) [*1], we applied Zn-diffused window structure [*2] to the proximity of the edge facets of the laser. **Figure 1** shows the photoluminescence (PL) spectra profiles of the window region measured by micro-PL spectroscopy. The vertical axis indicates the distance from the edge facet (0 μm position) in the cavity direction of the laser. **Figure 1 (a)** shows the PL profile of an almost optically transparent structure for the 660 nm lasing wavelength, in which PL peak wavelengths in the window region (about 0 - 10 μm position) are substantially shifted towards the shorter wavelength. On the other hand, **Fig. 1 (b)** shows the PL profile of an imperfect window structure, in which a substantial optical absorption exists. We optimized the Zn-diffusion process by controlling the PL profiles uniformly over the wafer to obtain a proper window structure as shown in **Fig. 1 (a)**.

To reduce the fabrication costs of LD chips, we have developed new techniques of epitaxial growth and wafer process for large-scale GaAs substrates (3 to 4 inch in diameter [(3), (4)]). Moreover, we employed Mg as a p-type dopant, which has a lower diffusion coefficient and more stable doping characteristics compared with Zn [(5)], so as to obtain the better temperature characteristics of the laser. Although 6 inch GaAs substrates are widely used for electric devices, such as field effect transistors and high electron mobility transistors, enlarging LD substrates is not easy due to a strict requirement for a low dislocation density (a hundred times lower than that of electric device wafers).

Most of the 4 inch LD wafer processing has been well established on our GaAs-IC manufacturing technology.

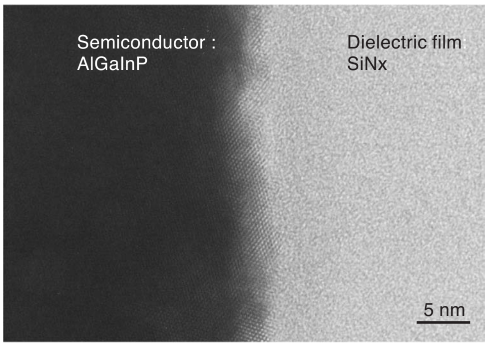

Photo 1. Transmission electron microscope (TEM) image of interface between dry etched AlGaInP surface and SiNx film

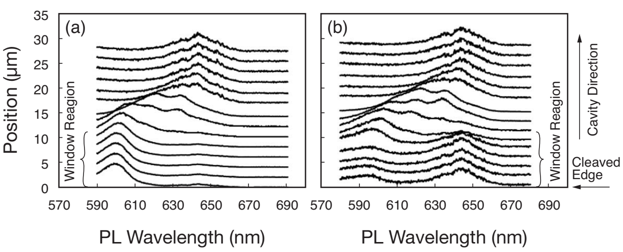

Fig. 1. PL spectra profiles of Zn-diffused window region
(a) Transparent window for 660 nm lasing wavelength and
(b) Imperfect window structure

3. Shortening Laser Cavity

We have examined the feasibility of shortening the cavity length of the high power laser by using aforementioned mass-production process. The target power was set at 30 mW at 80°C to meet the requirement of mobile device application.

AlGaInP-based LD has several inherent disadvantages, compared to AlGaAs-based LD. More specifically, because of the small conduction band offset in the GaInP/AlGaInP heterostructure, AlGaInP LD induces a poor electron confinement, which increases the electron carrier leakage from the active layer to the p-cladding at a high temperature, resulting in a decrease in the output power. Nevertheless, the AlGaInP LD for commercial use needs to be capable of operating at 80°C or higher. To stabilize the operation at high temperature, electron over flow from an active layer needed to be prevented by reducing the threshold carrier density. Our high-power LD which have been optimized to be used for high-speed recordable DVD drivers even in high temperature conditions achieved industry-leading levels of performance [(5)]: kink-free high-power operation of over 400 mW, the lasing wavelength of 660 nm, and the cavity length of L = 2200 μm under the pulsed operation.

3-1 Output Power Per Unit Cavity Length

As the first step to develop the high output power LD with a short cavity length, we considered shortening the cavity length of the above mentioned high power laser (L = 2200 μm). Meanwhile, the threshold current density J_{th} was remained constant through the optimization of the front and rear facet reflectivity, R_f and R_r, so as for the good temperature characteristics of the shortened cavity length to be maintained. Here, the external quantum efficiency η_d for the total optical output stays constant. And the optical output power P_{out} from the front facet is described as follows with the constant injection current density J_o and the output power ratio of the front to the rear facet η_f.

$$P_{out} = \eta_f \cdot \eta_d \cdot W \cdot L \cdot (J_o - J_{th}) = a \cdot \eta_f \cdot L$$

where W is the stripe width of the injection current and a is a constant value,

$$\eta_f = 1/\left\{1 + (1 - R_r) / (1 - R_f) \sqrt{R_f / R_r}\right\}$$

To simplify the calculation, the influence of the spontaneous emission and the loss in the window region and facet coating film were ignored in our study. In general, the rear fact reflectivity R_r is set high in order to extract light efficiently from the front facet. When $R_r = 1$, $P_{out} = a'L$ (a': a constant value) and the output power per unit length stays constant regardless of the value of L. In addition, on a realistic heat sink which has a large thermal capacity, the self-heating effect of the LD is not affected by the value of L in the current injection. This is because the thermal resistance of the laser is proportional to $1/L$[7], while the injection power to the laser is proportional to L under the constant current density J_o. Consequently, it is clear that the output power per unit cavity length (P_{out}/L) remains constant with changing cavity length and constant current density, even after the thermal dependence is considered. Thus, we may conclude that P_{out}/L should be widely used as a parameter to compare laser characteristics.

3-2 Test Results of Laser Characteristics

Figure 2 shows the temperature dependence of the light output power-current (L-I) characteristics of the high power L = 2200 µm LD under CW operation. As the thermal rollover is observed around 140 mW, P_{out}/L at 80°C is approximately 64 mW/mm at the highest.

The facet reflectivity of the L = 2200 µm LD is designed to be R_f = 3% and R_r = 95%. When the R_f is adjusted depending on the cavity length L with the threshold current density J_{th} remaining constant, the dependence of R_f on the value of L is as shown in **Fig. 3**. Furthermore, we have fabricated a 660 nm short cavity LD with L = 300 µm by optimizing the reflectivity R_f based on the resulting data in **Fig. 3**. We have concluded that the cavity length can be shortened to no more than approximately 300 µm when the manageability of the laser chip in a production phase is considered.

Figure 4 shows the temperature dependence of L-I characteristics of the L = 300 µm LD under CW operation. The front facet reflectivity R_f is set at 58%. The thermal rollover is observed around 18 mW, and thus P_{out}/L was estimated to be no higher than 60 mW/mm at 80°C. This result indicates that simply shortening the long cavity high power laser can not generate 30 mW-class output.

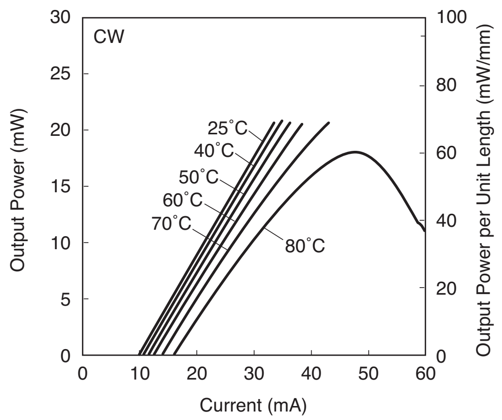

Fig. 4. Temperature dependence of L-I characteristics (L = 300 µm LD, CW operation)

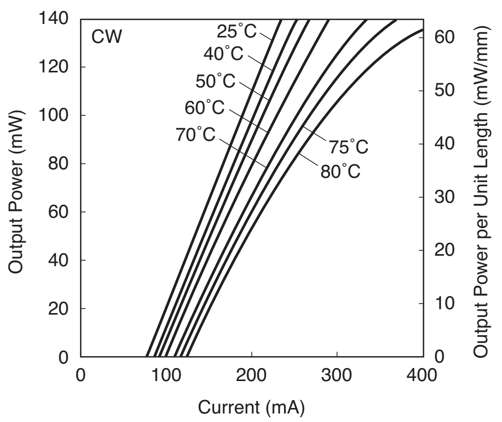

Fig. 2. Temperature dependence of L-I characteristics (L = 2200 µm LD, CW operation)

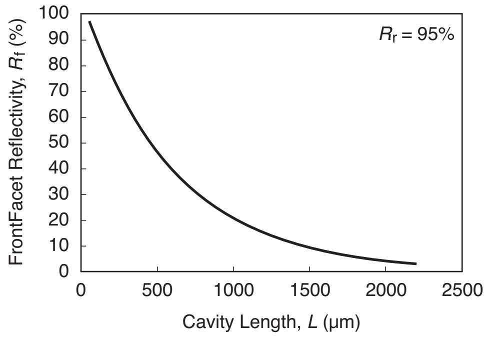

Fig. 3. Dependence of front facet reflectivity R_f on cavity length L with constant J_{th}

4. High Power and Short Cavity LD

In order to improve the high temperature characteristics of the short cavity laser, we optimized the thickness of barrier and guide layers to enlarge the optical confinement. Furthermore, we controlled the Al composition in the barrier and cladding layers to reduce the carrier leakage. The optimization of the window structure was also performed along with the regulation of the epitaxial structure.

Compared with the long-cavity laser, the short-cavity laser has lower output power, however, its optical density near the laser facet is not necessarily low due to the facet reflectivity which has been designed to become higher than that of the long-cavity laser, and therefore the window structure is necessary even for a 30 mW-class short cavity LD. However, the window structure optimized for the high-power long-cavity LD do not always work well for short-cavity LD, namely, the window can fail to improve the temperature characteristics of the short-cavity laser. Hence, a specially-designed window optimization method is vital for the short-cavity laser.

Figure 5 shows the temperature dependence of L-I characteristics of a 300 µm LD whose epitaxial and window structures have been optimized for the short cavity. The lasing wavelength was adjusted to 660 nm, which is equivalent to the basic LD. As shown **Fig. 5**, its output power reached over 30 mW at 80°C and the P_{out}/L rose above 100 mW/mm.

The result of reliability test for the improved short-cavity laser under a CW operation (20 mW) at 80°C is shown in **Fig. 6**. The laser chips were intentionally mounted on a heat sink with the junction side up, which resulted in higher thermal impedances than junction-down mounting, and thus, the temperature of the laser chip was remarkably increased by its self-heating effect. Despite such difficult conditions, the laser exhibited stable operation for over 1000 hours.

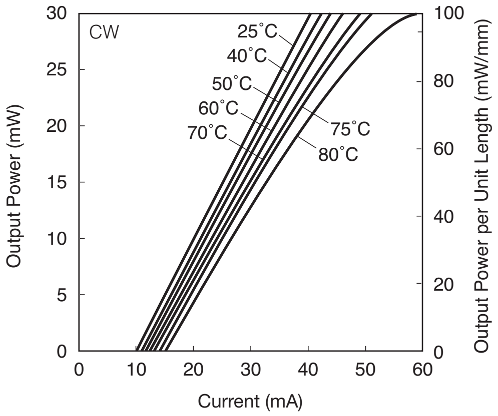

Fig. 5. Temperature dependence of *L-I* characteristics (Improved L = 300 μm LD, CW operation)

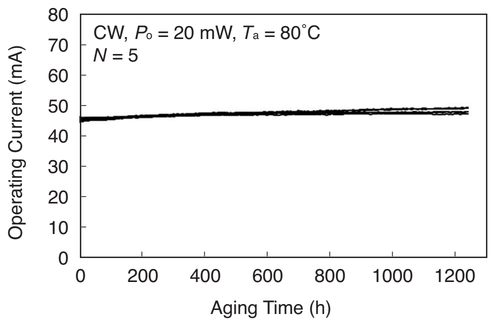

Fig. 6. Reliability test result under 20-mW CW operation at 80°C

5. Conclusion

We have successfully developed a high power and short cavity (L = 300 μm) 660 nm AlGaInP LD by applying the 4-inch full-wafer process so as to meet the market needs. An output power of over 30 mW was obtained under CW operation at 25°C to 80°C, and output power per unit length was over 100 mW/mm, which is much higher than that of the high-power laser designed for high-speed recordable DVD systems (64 mW/mm).

*1 Catastrophic optical damage (COD): A phenomenon of an LD fact suddenly melting due to a large absorption of produced laser light energy. In general, it causes an irreparable and catastrophic failure to a semiconductor laser.

*2 Window structure: A structure fabricated near an LD facet to minimize the optical absorption at the laser facet.

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