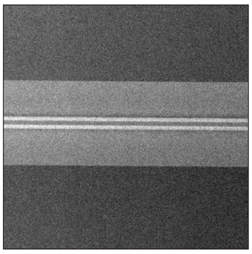

1.3 µm-Wavelength Laser with Type-II Active Layer on GaAs Substrate

Takuma FUYUKI*, Takashi GO, Hiroyuki YOSHINAGA, and Susumu YOSHIMOTO

To meet the rapidly increasing demand for optical communication traffic, a high-capacity solution is required through the high-density integration of optical devices. The challenge lies in the potential degradation of device performance due to heat generation. Consequently, there is a need for a semiconductor laser exhibiting superior temperature attributes. Addressing this, we have developed a 1.3 µm-wavelength laser, employing a GaInAs/GaAsSb/GaInAs type-II active layer on a GaAs substrate, suitable for optical communication. This has been achieved utilizing our proprietary low-temperature growth technology from highly productive Organic-Metal Vapor Phase Epitaxy. Our solution exhibits a characteristic temperature of the threshold current density of 152 K between 25°C and 100°C, a value significantly larger than the traditional 60 K of InGaAsP lasers on InP substrates. This result demonstrates the feasibility of a 1.3 µm semiconductor laser with a type-II active layer, less susceptible to performance degradation in high-temperature environments.

Keywords: GaInAs, GaAsSb, GaAs, type-II, OMVPE

1. Introduction

While various applications provided by advanced information and communication technologies, such as generative AI, cloud services, and automated driving, are improving convenience in our daily lives, communication traffic is rapidly increasing. Therefore, network switches in data centers are required to simultaneously increase capacity and reduce power consumption, and next-generation architectures such as Co-Packaged Optics (CPO) and optical devices combining III-V compound semiconductors and silicon (Si) photonics have been proposed as solutions.

In these proposals, optical devices are densely integrated to achieve large capacitance, but the degradation of characteristics due to heat generation from the optical devices is a problem. Usually, a temperature control mechanism using a Peltier element is employed to address the heat generation problem, but this has disadvantages in terms of integration, power consumption, and cost. Therefore, there is a need for Peltier element-free semiconductor lasers with excellent temperature characteristics that do not easily degrade even in high-temperature environments.

Semiconductor lasers, which are primarily used in optical information communications, operate in the 1.3 µm band, where fiber dispersion is minimal, and in the 1.55 µm band, where losses are minimal. Semiconductor lasers in these wavelength bands generally use InGaAsP-based materials on InP substrates, but they mainly suffer from issues such as Auger recombination[1] and carrier overflow,[2] and there is significant degradation of laser characteristics such as increased threshold current and decreased optical output power with temperature rise.

Auger recombination is a non-luminescent recombination process in which an electron and a hole recombine to excite other carriers without emitting light, which is converted into thermal energy. The probability of Auger recombination increases as the band gap energy of the semiconductor where the optical transition occurs decreases. In addition, the higher the carrier concentration, the more pronounced the Auger recombination is, which further increases the rise in the threshold current due to temperature rise and leads to degradation of the temperature characteristics.

Career overflow is a phenomenon in which electrons leak out of the active layer and no longer contribute to light emission recombination due to thermal energy. In materials suitable for the growth of InGaAsP-based materials on InP substrates with lattice-matched semiconductor materials, there is no material with a large band gap, and electron leakage becomes significant due to the small band offset between the active layer and the clad layer. On the other hand, on GaAs substrates, lattice-matched semiconductor materials with a large band gap can be used, enabling the realization of semiconductor lasers with excellent temperature characteristics. However, in GaInAs-based materials used for the active layer, it is possible to increase the emission wavelength by increasing the In composition. Nevertheless , as the In composition increases, the crystal quality deteriorates significantly due to lattice strain with the GaAs substrate, making it extremely difficult to achieve long wavelength extension up to the wavelength band for optical communication.

Therefore, we focused on the GaInAs/GaAsSb system, which can be extended to longer wavelengths with low In composition and suppressed Auger recombination by using type-II transitions on GaAs substrates. We have succeeded in fabricating GaInAs/GaAsSb superlattice on InP substrates for near-infrared sensors by the Organic-Metal Vapor Phase Epitaxy (OMVPE) method, which has excellent mass-producibility, and have realized and commercialized a high-performance near-infrared sensor.[3],[4] In this study, we report on the development of the growth technology of GaInAs/GaAsSb type-II active layers on GaAs substrates by applying our original low-temperature OMVPE growth technology cultivated in the development of these lasers, and on the fabrication of type-II active-layer ridge-waveguide lasers on a 1.3 μm-band GaAs substrate suitable for optical communications, that is Fabry-Perot (FP) lasers.

2. Type-II Quantum Well Structure and Growth

2-1 Type-II quantum well structure

First, a quantum well (QW) structure consists of semiconductors with different band gaps stacked on the order of several nm. Unlike the bulk structure, the optical gain is greatly improved, making it an indispensable structure for the active layer of semiconductor lasers. Almost all semiconductor lasers used in the field of optical information and telecommunications employ the type-I structure, in which electrons and holes are confined in the same well layer and optical transitions occur in the active layer. On the other hand, there are type-II quantum wells, such as the GaInAs/GaAsSb system shown in Fig. 1, in which the wavefunctions of electrons and holes are spatially separated and optical transitions occur due to the overlap of the wavefunctions near the hetero-interface. Advantages include the following:

(1) Enables longer wavelengths by reducing the effective transition energy while using semiconductors with a large band gap

(2) Suppression of Auger recombination[5]

When utilizing this type-II transition in the active layer of semiconductor lasers, a GaInAs/GaAsSb/GaInAs structure (so-called "W" type), in which a hole-trapping GaAsSb layer is sandwiched by an electron-trapping GaInAs layer, is used. The overlap of the wavefunctions increases, which is expected to improve the laser characteristics by increasing the recombination probability.[6],[7]

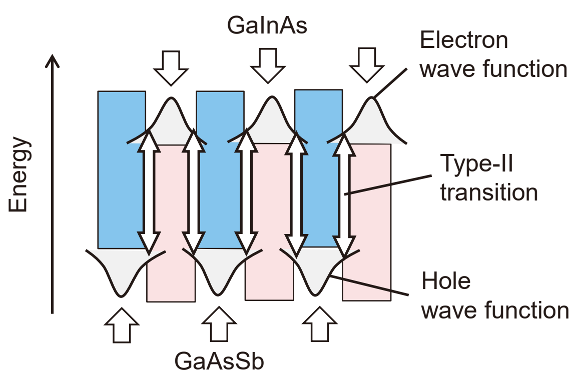

Fig. 1. Band structure of GaInAs/GaAsSb type-II quantum wells

2-2 Growth of type-II quantum well structure

The OMVPE method, known for its high productivity, was employed as the growth technique. Firstly, to verify the effect of long-wavelength extension through type-II transitions, GaAs/$GaIn_{0.34}As$-QW with a thickness of 4 nm, GaAs/$GaAsSb_{0.23}$-QW, were combined to form $GaIn_{0.34}As$/$GaAsSb_{0.23}$/$GaIn_{0.34}As$"W"-QW. Additionally, for further long-wavelength extension, $GaIn_{0.34}As$/$GaAsSb_{0.30}$/$GaIn_{0.34}As$"W"-QW was grown by increasing the Sb composition. The band structure and photoluminescence (PL) measurements at room temperature are shown in Fig. 2. 1030 nm wavelength for GaAs/$GaIn_{0.34}As$-QW, 1130 nm for GaAs/$GaAsSb_{0.23}$-QW and $GaIn_{0.34}$ As/$GaAsSb_{0.23}$/$GaIn_{0.34}As$ "W"-QW emits at a wavelength of 1230 nm, confirming the effect of longer wavelengths due to type-II transitions, as expected, and $GaIn_{0.34}As$/$GaAsSb_{0.30}$/$GaIn_{0.34}As$ "W"-QW emission at 1360 nm was achieved.

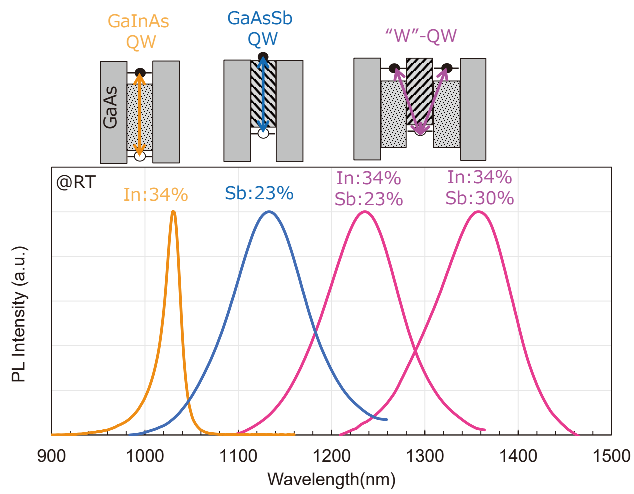

Fig. 2. Band structure and PL spectra of GaAs/GaInAs-QW, GaAs/GaAsSb-QW, and GaInAs/GaAsSb/GaInAs "W"-QW at room temperature

As mentioned above, type-II transitions occur at hetero-interfaces, so the quality of the interface is very important. Generally, the formation of element-rich hetero-interfaces is difficult due to the effects of elemental interdiffusion and segregation, which make the formation of steep interfaces difficult. In this study, we attempted to improve the interface quality using our original low-temperature OMVPE growth technique. Figure 3 shows PL spectra before and after the improvement of interface quality. Specifically, by lowering the growth temperature (T_{sub}) from 550°C to 475°C, the PL intensity was improved by a factor of three, and the Full Width at Half Maximum (FWHM) was improved from 88 nm to 75 nm. Figure 4 shows a cross-sectional transmission electron microscope (TEM) image of the GaInAs/GaAsSb hetero-interface at 550°C. The black contrast in the figure indicates the presence of an intermediate layer at the GaInAs/GaAsSb hetero-interface. Since the contrast of this intermediate layer is close to that of the GaAs layer, it is assumed to be a component with atomic weight similar to that of GaAs, and it is inferred that In atoms segregate in the initial growth stage of the GaInAs layer and Sb atoms segregate in the initial growth stage of the GaAsSb layer. On the other hand, the formation of the intermediate layer was suppressed in the 475°C growth, suggesting that the low-temperature growth suppressed the segregation of In and Sb and improved the steepness of the hetero-interface, which contributed to the improvement of luminescence properties.

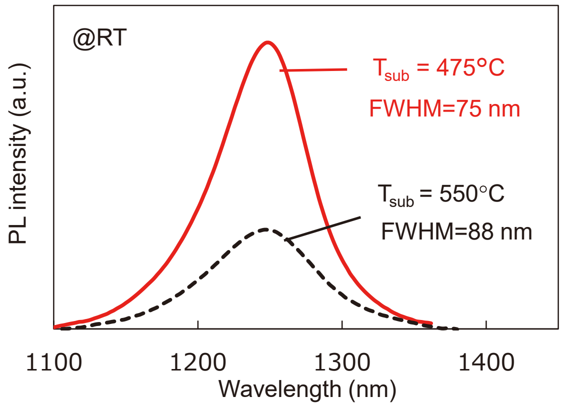

Fig. 3. PL spectra at growth temperatures of 550°C and 475°C

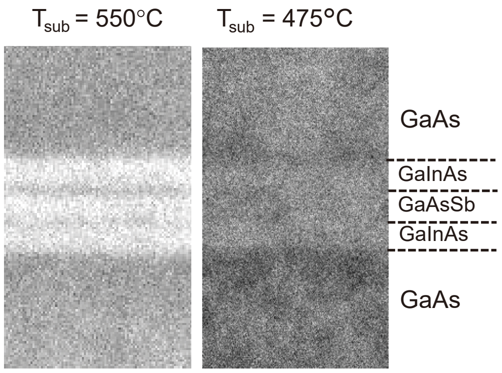

Fig. 4. Cross-sectional TEM images at growth temperatures of 550°C and 475°C

3. Fabrication of Ridge-waveguide FP Lasers

Figure 5 shows the cross-sectional structure of the fabricated ridge-waveguide FP laser. The structure was grown on an n-type GaAs substrate using OMVPE method, which consists of an n-$Al_{0.45}GaAs$ cladding layer (1500 nm), GaAs SCH layer (150 nm), GaInAs (4 nm)/GaAsSb (4 nm)/GaInAs (4 nm) "W"-QW active layer with 2 pairs, a GaAs SCH layer (150 nm), p-$Al_{0.45}GaAs$ cladding layer (1500 nm), and p-GaAs contact layer (200 nm). Subsequently, a multi-level ridge structure was fabricated with a mesa width of 2-30 µm using common photolithography and wet etching techniques. The entire surface of the wafer was passivated with an insulating film, and an ohmic electrode was deposited by vacuum evaporation with the insulating film opened only directly above the p-GaAs contact layer. The backside of the wafer was polished to reduce the thickness to approximately 100 µm, and then the backside electrode was formed. The end face was formed by cleavage, and multiple levels of ridge-waveguide FP lasers with resonator lengths of 1-3 mm were fabricated. Finally, the element was epi-up mounted in a C-mount.

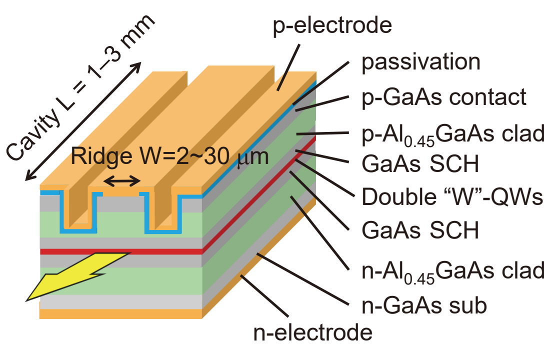

Fig. 5. Structure of the fabricated ridge-waveguide FP laser

4. Laser Characteristics

4-1 Basic characteristics

Figure 6 (a) shows the current density-optical output characteristics of the device with a mesa width of 5 µm and a resonator length of 1 to 3 mm at room temperature and pulse driving (pulse width: 10 µsec, duty ratio: 1%), and (b) shows the oscillation spectrum. For the 1 mm resonator length device, a threshold current density of about 1.8 kA/cm^2 and laser oscillation at a wavelength of 1286 nm were achieved. The evaluation of the mesa width dependence of the threshold current in a device with a resonator length of 1 mm confirms the absence of reactive current flowing beyond the active layer. From the resonator length dependence of the threshold current density and slope efficiency, the transparency current density per "W"-QW is estimated to be 155 A/cm^2 and the mode gain is 12.7 cm^{-1}, which are comparable to those of InP-based materials. On the other hand, the internal quantum efficiency*[1] is estimated to be 33%, which is lower than that of a typical type-I laser. It is assumed that the internal quantum efficiency is lower for type-II quantum wells because the overlap of wavefunctions is reduced compared to type-I. In order to isolate whether the obtained values are due to intrinsic or process-induced factors of the type-II active layer, we fabricated a gain-guided FP laser device without a ridge structure with an electrode width of 13 µm.

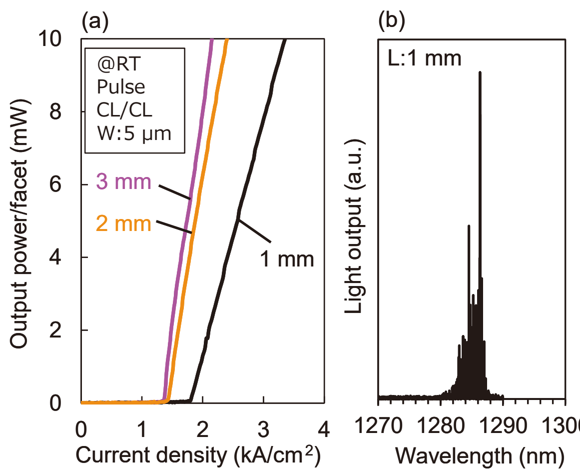

Fig. 6. (a) Current density-optical output characteristics of an element with a mesa width of 5 µm and a resonator length of 1 to 3 mm at room temperature and pulse driving (pulse width: 10 µsec, duty ratio: 1%)
(b) Oscillation spectrum

Consequently, an internal quantum efficiency of 58% was attained, attributed to a decline in luminescence recombination efficiency prompted by the ridge waveguide sides, necessitating enhancement.

4-2 Temperature characteristics

Figure 7 (a) shows the current density-optical output of a 5 µm mesa width, 1 mm resonator length device at 25-100°C in pulsed operation (pulse width 10 µsec, duty ratio 1%). Clear laser oscillation was achieved at each temperature. The characteristic temperature*2 T_0 for the threshold current density was 333 K at 25-50°C, 164 K at 50-75°C, 92 K at 75-100°C, and 152 K at 25-100°C (Fig. 7 (b)), while the existing InGaAsP-based laser on an InP substrate has a characteristic temperature of about 60 K.[(8)] It has also been reported that the characteristic temperature increases with a smaller threshold current density per unit quantum well layer due to the Auger effect.[(9)] Considering that the threshold current density per "W"-QW at 25°C is slightly higher than that of InGaAsP-based lasers due to the lower internal quantum efficiency compared to type-I,[(9)] the temperature characteristics of type-II active layer lasers on GaAs substrates are extremely good.

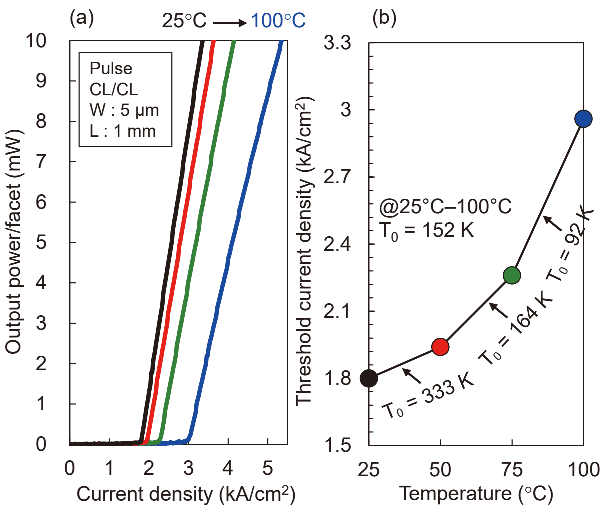

Fig. 7. (a) Current density-optical output at 25-100°C for the pulsed drive (pulse width 10 µsec, Duty ratio 1%) of a 5 µm mesa width and 1 mm resonator length device
(b) Temperature dependence of threshold current density

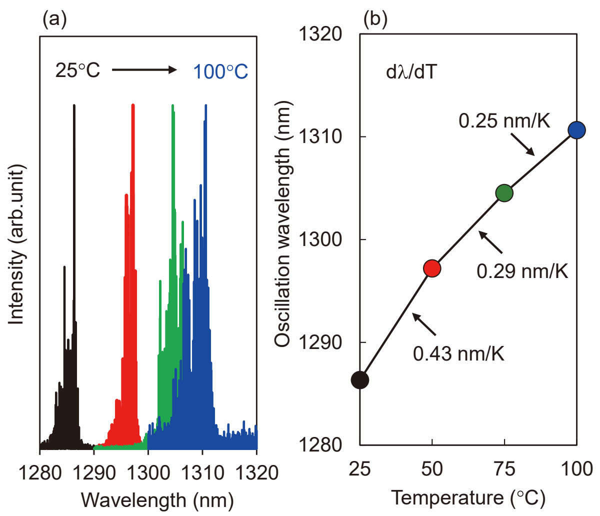

Fig. 8. (a) Oscillation spectra of an element with a mesa width of 5 µm and a resonator length of 1 mm at 25-100°C
(b) Temperature dependence of the oscillation wavelength

The oscillation spectrum at 25-100°C is shown in Fig. 8 (a). For the temperature dependence coefficient of the oscillation wavelength dλ/dT, we obtained 0.43 nm/K for 25-50°C, 0.29 nm/K for 50-75°C, and 0.25 nm/K for 75-100°C (Fig. 8 (b)). The temperature dependence coefficient of the oscillation wavelength became lower than that of the existing InGaAsP-based lasers (0.4 to 0.5 nm/K) in the temperature range above 50°C.[(8)] The temperature dependence of the oscillation wavelength is the subtraction of the gain peak lengthening effect with increasing temperature and the shortening effect due to the band bending effect caused by the injected carriers. The higher the temperature dependence of the injection carrier amount required for laser oscillation, i.e., as the characteristic temperature decreases, the shortening effect becomes stronger and the temperature dependence coefficient of the oscillation wavelength decreases as well.[(8)] Compared to type-I quantum wells, type-II quantum wells exhibit significant band bending effects in relation to the injection carrier amount.[(10)] It is assumed that type-II active layer lasers on GaAs substrates achieved a low temperature dependence coefficient of oscillation wavelength while maintaining a high characteristic temperature. By appropriately designing this band bending effect, it is expected that semiconductor lasers with high characteristic temperature and temperature-independent oscillation wavelength can be realized.

5. Conclusion

In this study, we fabricated ridge-waveguide FP lasers by growing a GaInAs/GaAsSb/GaInAs type-II active layer on a GaAs substrate through the utilization of our proprietary low-temperature OMVPE growth technique. Laser oscillation at 1.3 µm band was achieved, and at temperatures ranging from 25°C to 100°C, the characteristic temperature of the threshold current density significantly exceeded 152 K, surpassing the value of 60 K obtained with conventional InGaAsP lasers on InP substrates. By using GaInAs/GaAsSb/GaInAs type-II active layer on GaAs substrates, it is possible to achieve 1.3 µm semiconductor lasers that are less prone to degradation of laser characteristics even in high-temperature environments.

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Technical Terms

∗1 Internal quantum efficiency: Percentage of carriers injected from electrodes that are converted to light.

∗2 Characteristic temperature: The threshold current density of the laser, J_{th}, is given for the active layer temperature T

$$J_{th} \propto \exp(T/T_0)$$

T_0 at this time is called the characteristic temperature. The higher the characteristic temperature, the more difficult it is for the laser characteristics to deteriorate even at higher.

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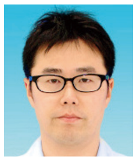

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