Edge-emitting lasers based on transitionally dimensional InGaAs/GaAs active region

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Abstract. We present a systematic study of basic characteristics of edge-emitting lasers based on a new type of quantum-sized InGaAs active medium grown on GaAs substrates. The active region referred to as quantum-well-dots (QWDs) comprises properties of quantum wells (QWs) and quantum dots (QDs). We have fabricated and investigated lasers with the active regions consisted of 1, 2, 5 and 10 layers of the QWDs. The low internal loss has allowed us to obtain maximal optical power as high as 8.8 W in the continuous wave (CW) regime. We have shown that QWD-based active media are very promising for devices requiring high gain, stacking a large number of layers in the active region, and suppressing of lateral carrier transport.

1. Introduction

Band-gap engineering is a powerful technique for designing new semiconductor materials and devices [1]. This approach allows modifying properties of quantum wells (QW) and self-organized quantum dots (QDs), the media widely used in modern optoelectronics. Being utilized in semiconductor lasers, both types of active media have inherent advantages and disadvantages. For example, InGaAs/GaAs QWs provide relatively high optical gain per layer (70 cm⁻¹ [2]) and high differential gain. However, because of the elastic stress, it is technologically difficult to stack more than five layers of QWs since it may result in dislocation formation. The elastic stress also limits the thickness of the QW layer and the emission wavelength range achievable with QWs therefore. The longest wavelength of InGaAs QW grown on GaAs typically does not exceed 1.1 µm.

In contrast, self-organized QDs have relatively low gain per layer due to the low surface density. As an example, self-organized In(Ga)As/GaAs QDs provide an optical gain of 5-7 cm⁻¹ per layer [3]. In addition, the optical gain saturates rather fast, leading to a small differential gain. On the other hand, using QDs one can achieve ultra-low threshold current densities with a characteristic temperature exceeding 500 K [4], near-zero linewidth enhancement factor and broad gain spectra.

Recently a new type of InGaAs/GaAs nanostructures with transitional dimension has been proposed [5]. It can be considered as InGaAs QWs comprising ultra-dense arrays of In-rich narrow-gap regions localizing electrons and holes like QDs. And therefore these structures were named quantum-well-dots (QWDs). Being used as an active region in semiconductor lasers, these structures provide narrower gain spectrum and higher maximum gain in comparison with QD-based ones. Besides, carrier lateral diffusion in QWDs is reduced due to the QD-like localization and stacking up
to 20 active layers is possible, therefore. This set of properties is very promising for using QWDs in edge-emitting lasers. Here we present a systematic experimental study of QWD-based edge-emitting lasers with a different number of active layers.

2. Laser wafer design and sample processing

The laser wafers were grown by metalorganic vapor phase epitaxy (MOVPE) on $n$-(100) GaAs substrates misoriented on 6° toward [111] direction. The laser structures consisted of an undoped 780 nm GaAs waveguide sandwiched between the $p$- and $n$-type doped $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ cladding layers. In order to minimize the internal loss in the claddings their doping level of $2 \cdot 10^{18}$ cm$^{-3}$ was reduced down to $7 \cdot 10^{17}$ cm$^{-3}$ in the regions adjoining the waveguide. Zinc and silicon were used as $p$- and $n$-dopants respectively. The active regions consisted of 1, 2, 5 or 10 layers of $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ QWDs separated with 40 nm-thick GaAs spacers. The In fraction of ~0.4 provides formation of transitionally dimensional nanostructures with good optical quality [5,6]. The effective thickness of each QWD layer was 2 nm providing the optical confinement factors of 0.4% multiplied by the number of QWD layers.

The wafers were processed into 50 μm and 100 μm broad-area lasers using standard photolithography. Devices with various cavity length were cleaved and mounted $p$-side down onto copper heat-sinks with indium solder in order to reduce overheating and improve current spread for long (>3mm) devices. No facet coatings were used.

3. Experiment results and discussion

First, devices were tested at room temperature in a pulsed regime with the duty cycle of 0.1%. For each structure, we have measured cavity length dependences of a threshold current density ($j_\text{th}$), lasing wavelength ($\lambda$) and differential quantum efficiency ($\eta_\text{D}$). The internal efficiency ($\eta_\text{i}$) and the internal loss ($\alpha_\text{i}$) were estimated using a linear fit of the dependence of $1/\eta_\text{D}$ on the cavity length. Figure 1 shows an example for the lasers with a single QWD layer in the active region. We have also estimated the current-density-per-layer ($j_\text{QWD}$) for all the lasers investigated [2]:

$$j_\text{QWD} = j_\text{th}/n ,$$

where $n$ is the number of QWD layers in the active medium. The basic lasers parameters are summarized in table 1.

![Figure 1. The reciprocal quantum efficiency ($\eta_\text{D}^{-1}$) vs. the cavity length (L) for the devices based on a single QWD layer with the stripe width of 50 μm.](image-url)
Table 1. The characteristics of edge-emitting lasers with the cavity length of 4 mm based on a different number of QWD layers.

| Number of QWD layers | \( j_{\text{th}} \) (A/cm\(^2\)) | \( j_{\text{QWD}} \) (A/cm\(^2\)) | \( \lambda \) (nm) | \( \eta \) | \( \alpha \) (cm\(^{-1}\)) |
|----------------------|----------------|----------------|-------------|-----|---------------|
| 1                    | 100            | 100           | 1088        | 0.79| 0.7           |
| 2                    | 120            | 60            | 1092        | 0.85| 1.0           |
| 5                    | 200            | 40            | 1108        | 0.82| 1.5           |
| 10                   | 375            | 38            | 1117        | 0.78| 2.4           |

One can see that an increase in the number of the QWD layers in the active medium results in redshifts of the lasing wavelength. At the same time, the threshold current density per layer (\( j_{\text{QWD}} \)) decreases from 100 A/cm\(^2\) down to 38 A/cm\(^2\) and is found to be almost the same for the lasers with 5 and 10 layers. Hence, stacking of 10 QWD layers even without strain compensating layers does not deteriorate the device performance as it could be expected for 10 QW layers. The internal differential efficiency remains about 80% in all samples, and the internal loss gradually increases with increasing the number of the QWD layers stacked.

We have investigated true spontaneous emission (TSE) spectra from 0.5 mm long devices in continuous wave (CW) regime. TSE was collected with a 200 \( \mu \)m optical fiber through an \( n \)-contact window (figure 2a). Figure 2b shows TSE spectra from the samples with 1 and 10 QWD layers in the active region at the currents slightly exceeding the thresholds. Sharp spikes correspond to the scattered laser radiation. It is seen that the long wavelength tail of the TSE spectrum from the 10xQWD laser has relatively higher intensity than that from the 1xQWD device. Similar behavior has been previously described in [6] where the authors considered two types of carrier localization centers. They associated the long wavelength peak emerging under lower excitations with QD-like localization centers. Therefore, we may assume that the lasing in the 10xQWD devices having lower current-density-per-layer takes place via the QD-like states and the laser characteristics and behavior would resemble ones of conventional QD-based lasers.

Figure 2. (a) Picture (top view) of the laser intended for TSE spectrum measurements. (b) TSE spectra collected through the window in the \( n \)-contact from the laser with a single QWD layer (solid line) and from the laser with 10 QWD layers (dashed line).

Figure 3a shows light-current characteristics of 3 mm long devices measured in the CW regime. The maximum output power was limited by heat-induced local facet degradations clearly seen in figure 3b for the 2xQWD laser facet taken after the device failure. Increase in maximum output power
from 5.8 W for 1xQWD to 8.8 W for 2xQWD devices is mostly determined by the broadened stripe width of the latter devices. Despite different $\eta_i$ and $\alpha_i$ both lasers demonstrated the same initial differential quantum efficiency of 69%.

![Light-current characteristics of 3 mm long devices](image)

**Figure 3.** (a) Light-current characteristics of 3 mm long devices with a single (squares) and double (circles) QWD layers in the active region obtained in the CW regime. The inset shows a typical laser spectrum from 1xQWD sample taken at the 4A pump current. (b) Picture of the facet of the 2xQWD device taken after the laser failure.

4. Conclusions
In conclusion, for the first time, we have systematically investigated basic characteristics of the edge-emitting lasers based on the new type of InGaAs/GaAs active media. The lasers with single QWD layer showed the internal loss as low as 0.7 cm$^{-1}$. The lasers with the stacked QWD layers possess the internal quantum efficiency no less than 78%. The devices based on 10-QWD layers showed the current-density-per-layer as low as 38 A/cm$^2$. The low internal loss has allowed us to obtain maximal optical power as high as 8.8 W in the CW regime. The obtained results have shown that QWD-based active media are very promising for devices requiring high gain, stacking a large number of layers in the active region, and suppressed lateral carrier transport.

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