LETTER

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Letter

Modification of InGaAs/GaAs heterostructure density of states and optical gain using hybrid quantum well-dots

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Abstract
We show that the density of states and gain spectra of InGaAs/GaAs quantum well-dot (QWD) hybrid nanostructures qualitatively differ from that of quantum wells (QWs) and quantum dots. In QWDs, the density of states does not increase to higher energies and ground-state lasing is maintained up to shorter cavities (higher output loss) as compared to QW lasers emitting in the same optical range. The QWD lasers show lower threshold current densities and better temperature stability than the QW ones.

Keywords: semiconductor lasers, edge-emitters, quantum wells, quantum well-dots

(Some figures may appear in colour only in the online journal)

1. Introduction

Electronic density of states (DOS) is one of the main characteristics of semiconductor heterostructures that greatly determine their optical properties and capability for device applications. In quantum well (QW) lasers the DOS can be represented by a step-like function, i.e. near the absorption edge, it is higher than that of bulk materials and does not grow to higher energies. This results in an increased optical gain and differential gain, higher efficiency, lower threshold current density, improved temperature stability, etc [1]. In ideal quantum dot (QD) arrays, the energy spectrum represents a δ-function. However, in actual QD arrays formed by a self-organized growth, it is necessary to take into account homogeneous and inhomogeneous broadening, multiple electron and hole levels (excited state transitions), continuum states of the wetting layer and matrix as well as many other effects [2]. Due to these effects, combined with a relatively low surface density of QDs, present InAs/GaAs QD lasers show significantly lower ground-state optical gain than QW counterparts that result in lasing switching from the ground to excited states with decrease in cavity length [3]. Meanwhile, high speed data communication requires short cavity lasers operating at ground-states with low threshold current density and high temperature stability.

Recently we have developed a novel hybrid (0D/2D) type of nanostructures suitable for the laser active region that we refer to as quantum well-dots (QWDs). The QWDs exhibit itself a dense array of carrier-localizing $In_xGa_{1-x}As/GaAs$ islands inside an $In_yGa_{1-y}As/GaAs$ ($x > y$) quantum well. QWDs are intermediate in properties between QWs and QDs and possess some assets of both, such as high optical gain, low threshold current densities, suppressed lateral carrier diffusion, etc [4]. However, the density of states of QWDs has not been well studied yet. In this paper, we compare lasers with the active regions based on QWs and QWDs, study how the DOS of the planar uniform QW is changed due to the QWD formation and consider the benefits of this modification from the viewpoint of the laser applications.

2. Methods

The laser structures under study were grown by a metal-organic vapor phase epitaxy (MOVPE) and contained either two QWs or two QWD layers in the active region. The QWDs emitting near 0.98 µm and 1.08 µm were formed by the deposition of 1.2 nm (4 monolayers, 4 MLs) and 2.4 nm (8 MLs) of $In_{0.4}Ga_{0.6}As$, respectively, on the GaAs (100) substrates misoriented by 6° toward (111). The QWs were grown by the deposition of 8.5 nm of $In_{0.15}Ga_{0.85}As$ also using a misoriented GaAs substrate. The QWD and QW layers were separated with 40 nm thick undoped GaAs spacers. In this paper, we refer to the lasers with these active regions as QW, 4 ML-QWD, and 8 ML-QWD ones.

All the lasers have the same broadened waveguide design based on the coupled large optical cavity (CLOC) approach [5]. The composite CLOC waveguide consists of a 175 nm thick GaAs single-mode narrow passive waveguide optically coupled to a 1.35 µm thick GaAs active multimode waveguide. The active region is placed in the center of the active waveguide. The active waveguide is separated from the passive one with the 250 nm $Al_{0.25}Ga_{0.75}As$ layer. The thickness of the upper p-$Al_{0.25}Ga_{0.75}As$ cladding layer is as low as 500 nm to reduce electrical resistance and improve heat dissipation from the active region. The laser wafers were processed into broad-area devices with 100 µm wide shallow-mesa ridges and different cavity lengths.

3. Results and discussion

Cross-section transmission electron microscopy (TEM) images of the QWD layers and QW used in the laser active regions are shown in figures 1(a)–(c). TEM images of the QWD samples (figures 1(b)–(c)) reveal the lateral thickness modulation which is more pronounced in the 8 ML-QWDs (figure 1(c)). The modulation exceeds 100% in the QWDs formed by 8 ML of $In_{0.4}Ga_{0.6}As$, whereas in the QWDs formed by 4 ML of $In_{0.4}Ga_{0.6}As$ it is less than 50%. Besides, the lateral size of the modulations is much larger in the 8 ML-QWDs. TEM image of the QW demonstrates a planar uniform InGaAs layer (figure 1(a)).

In the case of the losses absence, spontaneous emission and gain spectra are interdependent through the Einstein equations of stimulated and spontaneous emissions. The gain spectrum can be derived from the measured spontaneous emission spectrum (and vice versa) and the shape of spontaneous emission spectra qualitatively corresponds to the shape of gain spectrum, especially at high injection currents when all energy levels are filled with carriers [3].

Figures 1(d)–(f) shows electroluminescence (EL) spectra of the QW, 4 ML-QWD, and 8 ML-QWD lasers measured in a wide range of injection current densities (from 100 A cm^{-2} to > 10 $kAcm^{-2}$). Cavity length is chosen to be as short as 100 µm to prevent lasing up to the highest injection currents and minimize self-absorption in the active region that could cause EL spectra shape distortion.

In the EL spectra of the QW laser, there are two well-pronounced peaks at 965 nm and 925 nm. The full width at half maximum of the ground state transition measured at the lowest injection is 40 nm. At the higher injection current of 2 $kAcm^{-2}$, the shape of the EL spectrum reflects the step-like DOS typical of QWs with the higher-energy peak 2.1 times more intense than the lower-energy one. At 10 $kAcm^{-2}$ the peak caused by recombination in the GaAs waveguide has the highest intensity since the DOS in the thick GaAs matrix is greater than in QW. With the increase in the injection current up to 17 $kAcm^{-2}$ the lasing starts via the states of the GaAs waveguide (the lasing spectrum is shown by black curve).

The 4 ML-QWD laser exhibits inhomogeneously broadened (FWMH ≈ 47 nm) ground-state peak with the maximum at ~975 nm. In contrast to the case of QW laser, in 4 ML-QWD laser there is no any pronounced higher-energy peak in the optical region of 900–950 nm. EL intensity in this optical region slowly increases with increasing the current density. At 10 kA cm^{-2} it is only 1.3 times greater than the peak of the ground state transition. An increase in the deposited $In_{0.4}Ga_{0.6}As$ from 4 ML to 8 ML results in a red-shift of the ground state transition up to 1070 nm and its broadening up to 56 nm. In 8 ML-QWD laser the EL intensity at shorter wavelengths is suppressed to a greater extent. Even at 30 $kAcm^{-2}$, the EL intensity in the optical region from 1050 nm to 920 nm remains lower than the intensity of the ground state transition. Note that at such an extremely high injection level the states of GaAs waveguide are already filled with carriers. There is no peak due to the residual InGaAs QW surrounding QWDs or peak due to the wetting layer as could be expected for lasers based on Stransky-Krastanov QDs [2].

To study the gain characteristics of the lasers, we measured chips with different cavity lengths (L). Each device is characterized by lasing wavelength, threshold current density, differential efficiency, and output loss. The dependence of the lasing wavelength on L is shown in figure 2(a). The lasing wavelengths of the devices with the same cavity length as in figure 2(a) as well as their threshold current densities are also depicted in figures 1(d)–(f). The shorter the cavity (the higher the output loss), the higher the threshold current density and the shorter the lasing wavelength. Lasing occurs via the ground state transition until $L \geq 400$ µm for the QW-based laser, $L \geq 250$ µm for 4 ML-QWD laser and $L \geq 200$ µm for 8 ML-QWD laser. Thus, ground-state lasing is maintained in QWD devices up to shorter cavities (higher output loss) than in QW ones.

The relationships between the modal gain (G) and the injection current (J) for the lasers under study (figure 2(b)) were derived from the dependencies of the threshold current density and the reciprocal differential efficiency on cavity length as described in detail in [6]. The output loss was calculated

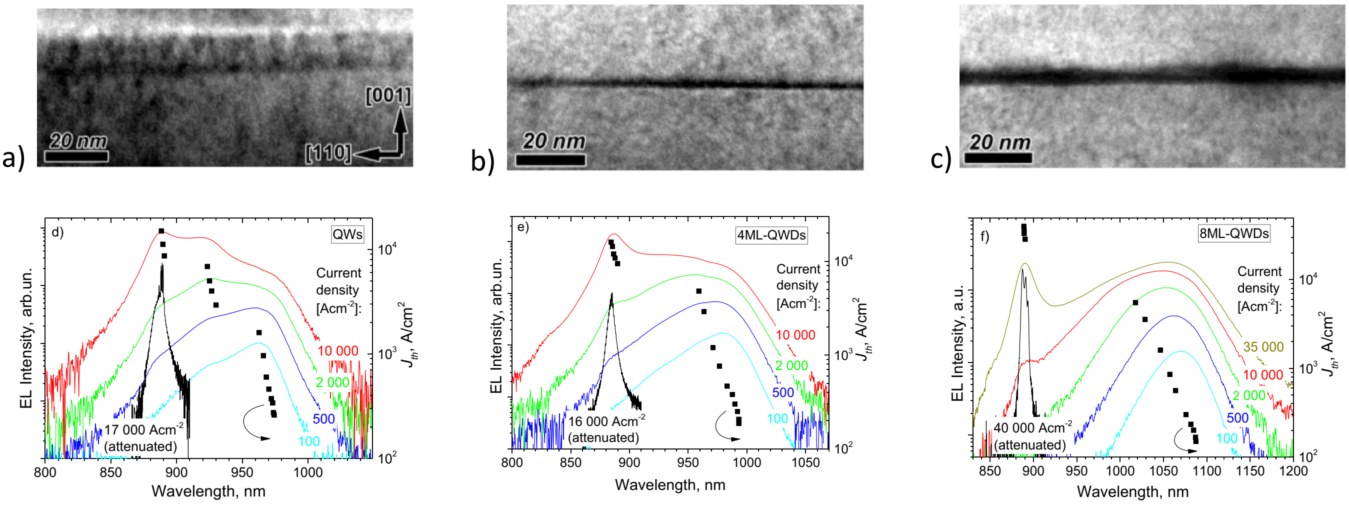

Figure 1. TEM cross-section images in [1–10] zone of QW (a), 4 ML-QWD (b) and 8 ML-QWD (c) structures. Electroluminescence spectra of 100 µm long edge-emitting lasers with the active regions based on QWs (d), 4 ML-QWDs (e) and 8 ML-QWDs (f) at the injection currents below and above (black curves) the threshold. The values of the threshold currents are shown by squares at corresponding lasing wavelengths (measured for the devices with different cavity lengths).

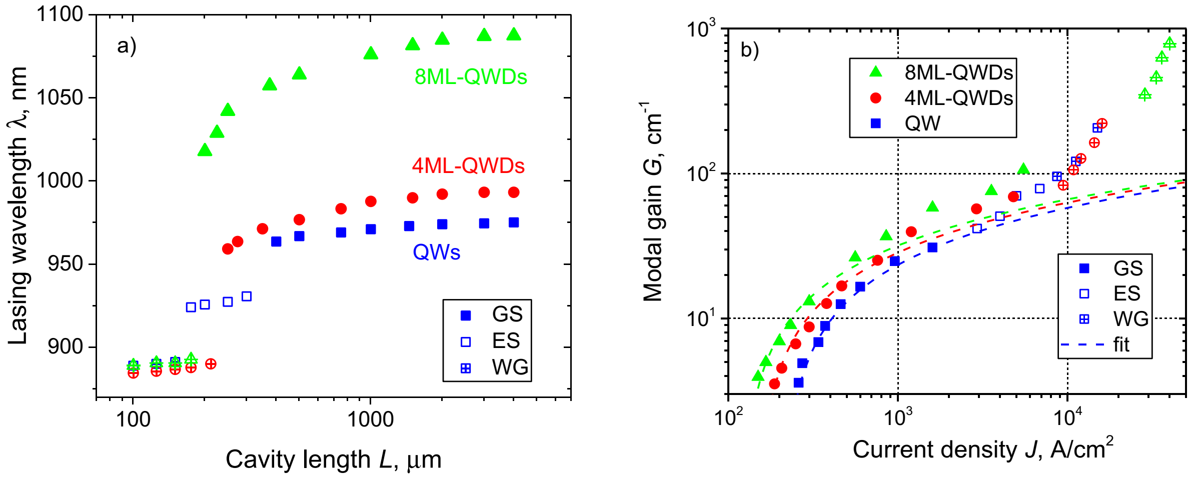

Figure 2. The lasing wavelength vs. the cavity length (a); the maximal modal gain vs. the current density (b). GS, ES, and WG denote lasing via the ground state, excited state, and waveguide, respectively.

as $\alpha_{out} = \ln\left(0.3^{-1}\right) L^{-1}$, where 0.3 is the as-cleaved facet reflectivity.

For the QW lasers, the maximal modal ground-state gain of 30 cm^{-1} is achieved at $J = 1.6$ kAcm^{-2} (figure 2(b)). The modal gain follows the well-known logarithmic dependence on the current density $G = G_0 \ln(J/J_0)$ shown by the dashed curve in figure 2(b) with the gain parameter $G_0 = 15$ cm^{-1} and the transparency current density $J_0 = 210$ A cm^{-2}. With the increase in injection current above 1.6 kAcm^{-2} the lasing switches to the excited-state transition characterized by greater G_0 and J_0 values (~35 cm^{-1} and 850 A cm^{-2}, respectively), which reflects higher DOS of the excited-state levels. Finally, at very high injection currents the lasing occurs via the states of the GaAs waveguide.

In the lasers based on QWDs, the logarithmic gain-current density dependence is maintained only in a limited interval of the current densities near the transparency when the modal gain is below ~25 cm^{-1} and ~15 cm^{-1} for the 4 ML-QWD and 8 ML-QWD lasers, respectively. The J_0 was estimated as 150 Acm^{-2} and 120 Acm^{-2} (see the dashed curves in figure 2(b)). At the higher current densities, the modal gain increases faster than the logarithm function. In 4 ML-QWD lasers the ground-state lasing is maintained up to the injection current of 4.8 kA cm^{-2}. Maximal ground state modal gain achieved in 4 ML-QWD lasers (70 cm^{-1}) is 2.3 times higher than in the QW lasers. The qualitative difference between the QW and QWD lasers is even more pronounced in the case of the 8 ML-QWD laser that shows ground-state lasing up 5.5 kA cm^{-2} and the maximal ground state modal gain exceeds 105 cm^{-1}.

We attribute these effects to the modification of the DOS in the QWDs compared to the QWs and stronger localization of electrons and holes in the QWDs emitting near 1.08 µm as compared to the case of QWDs emitting at 0.98 µm. The fact

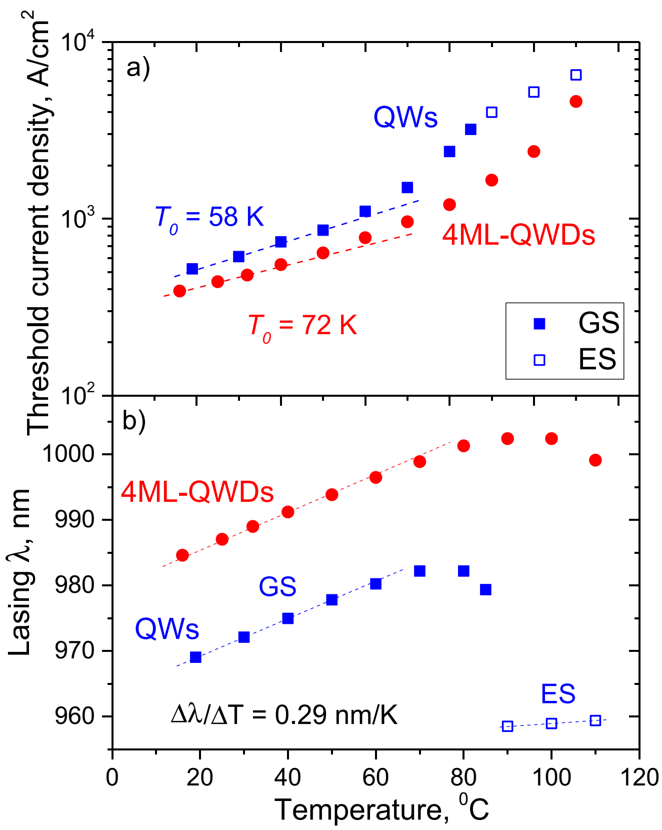

Figure 3. Temperature dependencies of the threshold current density (a) and lasing wavelength (b) of the QW and 4 ML-QWD lasers. In both devices cavity length is 1 mm. GS and ES denote lasing via the ground and excited states.

that in the 8 ML-QWD lasers the lasing wavelength hops from 1020 nm directly to the state of the GaAs waveguides implies that the density of states does not contain the excited-state levels with a higher degree of degeneration compared to the ground-state one, as typical of QWs and Stransky-Krastanov QDs. Maximal ground-state modal gain amounts to 105 cm^{-1} at $J = 5.5$ kAcm^{-2}. Taking into account the optical confinement factor of ~0.5% for the CLOC waveguide the material gain is estimated as ~2.1 · 10^4 cm^{-1} (~1.05 · 10^4 cm^{-1} per one 8 ML-QWD layer).

Figure 3 compares temperature dependencies of the threshold current density and the lasing wavelength for the 1 mm long lasers with the active region based on the QWs or QWDs emitting near 0.98 µm. As temperature rises from 10 °C to 60 °C the QWD laser shows better temperature stability of the threshold current density ($T_0 = 72$ K) and lower values of J_{th} (400 Acm^{-2} at 20 °C) as compared to the QW laser ($T_0 = 58$ K, $J_{th} = 520$ Acm^{-2} at 20 °C). In this temperature range, the lasing wavelengths of both lasers show a regular redshift with the rate of 0.29 nm K^{-1} corresponding to the temperature dependence of InGaAs bandgap. However, the behaviors of lasing wavelength in QW and QWD-based devices qualitatively differ at temperatures above 70 °C (figure 3(b)). In the QWD device, the redshift of the lasing wavelength saturates with temperature increase and above 100 °C changes to a slight blue-shift. In contrast, in the QW laser, the blue-shift begins at lower temperatures (>70 °C). At 85 °C, there is a hop of the lasing wavelength from 980 nm to 958 nm. Thus, in case of moderate or high output loss and enhanced temperatures, the QWD lasers show better temperature stability than the QW ones. In particular, the ground-state lasing is preserved up to higher temperatures.

4. Conclusion

In conclusion, we show that the density of states of uniform planar QW can be modified by the formation of QWDs. Enhanced temperature stability of the lasing wavelength and threshold current together with high optical gain makes QWD lasers promising for applications that require ground-state lasing in short cavities at elevated temperatures.

Acknowledgments

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