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Research Article

Gain of TlBr/BrCl Quantum Dot Semiconductor Optical Amplifier

Baqer O. Al-Nashy,[1] **Buraq T. Sh. Al-Mosawi**,[2] **Mushtaq Obaid Oleiwi**,[3] **and Amin H. Al-Khursan**[4]

[1]*Department of Physics, College of Science, University of Misan, Amarah, Iraq*
[2]*College of Education, University of Misan, Amarah, Iraq*
[3]*Department of Physics, College of Education for Pure Science, University of Thi-Qar, Nasiriya, Iraq*
[4]*Nasiriya Nanotechnology Research Laboratory (NNRL), College of Science, University of Thi-Qar, Nasiriya, Iraq*

Correspondence should be addressed to Amin H. Al-Khursan; ameen_2all@yahoo.com

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This work studies the thallium halogenide TlBr/BrCl quantum dot (QD) semiconductor structure and specifies its optical properties. This QD structure is poorly studied. High gain is obtained, with two peaks at 800 and 3000 nm. Doping is shown to increase the gain by one order. Then, TlBr QD semiconductor optical amplifier (SOA) characteristics are studied. High dB gain is shown mainly at the doped structure, which can be used in various inline applications.

1. Introduction

The superior characteristics of quantum dot semiconductor optical amplifiers (QDSOAs), such as high gain, ultrafast (picosecond) recovery time, wide bandwidth, low noise figure, and polarization-insensitive makes the quantum dots (QDs) in the milestone of today's all-optical applications [1, 2]. These merits result from the complete quantization of QD and discrete energy states [3]. Other types of semiconductor optical amplifier (SOA), such as multiquantum-well SOA, vertical cavity SOA, and distributed feedback SOA, possess a lower recovery time than QDSOA due to their carrier lifetime. Their signal processing is limited to 40 Gbps, which is very low compared to the 160 Gbps of QDSOAs [4].

Thallium bromide (TlBr) is a promising candidate with a highly efficient wide bandgap (2.68 eV) and strong ionic-binding semiconductor material. Their band structure is near the lead chalcogenides, not the alkali halides, as they have two more s-valence-electrons than the band structure of the filled shell of the rare gases. They are expected to work above room temperature due to their high atomic numbers (Br: 35 and Tl: 81) and high density (7.56gm/cm^3) [5–10]. Their simple cubic lattice (CsCI structure) gives a simple electronic structure and optical spectra, different from other halides with anisotropic structures [11].

Mir et al. [12] prepared TlBr nanocrystals that suppress the defects compared to other wide-bandgap semiconductors (>2.5 eV). They exhibit high photoluminescence efficiency, which results from their high carrier mobility and long diffusion length. The work in our laboratory on thallium-based quantum dot (QD) structures began after investigating the well-known III–V semiconductor structures. First, it starts with InTlSb QD structures [13], InTlAsSb QDs [14], then TlGaN QDs [15], and finally, InTlSb, InTlP, InTlAs, and InTlN QDs are studied [16]. As the III–VII semiconductors are poorly studied, this work studied the thallium halogenide TlBr QD structure, which is not poorly studied. Then, the structure is examined as a semiconductor optical amplifier characteristics, with high gain obtained, mainly at a doped structure.

2. Inhomogeneous Gain

An inhomogeneous density of states function describes the broadening function $D(E)$ to cover the QD fluctuations in

size and shape during the self-organization growth mode. This function locates the theory similarly to the experiment. Then, the optical linear gain per QD layer of the self-organized QDs is given by [17]

$$g^{tr}(\hbar w) = C_0 \sum_i \int dE \left|M_{env}\right|^2 \left|\hat{e}.\vec{p}_{cv}\right|^2 D(E) L_g(E, \hbar w)\left[f_c(E_c, F_c) - f_v(E_v, F_v)\right]. \quad (1)$$

Note that i runs over the conduction and valence QD energy sub-bands considering all the radiative transition energies. $|M_{\text{env}}|$ is the envelope function between the QD energy sub-bands of the electron and hole. $|\hat{e}.\vec{p}_{cv}|$ is the momentum matrix element of the QD that depends on the polarization of light and $\hat{e}$ is a unit vector along the polarization direction. Regarding the parabolic shape of bands, the QDs momentum matrices are the same as those of the quantum well near the zone center ($k_t = 0$). They are expressed as $|\hat{e}.\vec{p}_{cv}|^2 = 3/2\,(M_b^2)$ for the heavy hole band, with $M_b^2 = (E_p m_0/6)$ is the bulk momentum matrix element and E_p is the parameter of the optical matrix energy and is given by [17]

$$E_p = \left(\frac{m_0}{m_e} - 1\right)\left(\frac{E_g.\left(E_{g+}\Delta_0\right)}{E_g + (3/2)\Delta_0}\right), \quad (2)$$

where m_0, m_e are the free and effective electron masses, respectively; E_g is the QD bandgap energy and Δ_0 spin-orbit splitting energy. In equation (1)

$$C_0 = \frac{\pi e^2}{n_b c \varepsilon_0 m_0^2 w}, \quad (3)$$

where e is the electron charge, w is the angular optical frequency, n_b is the background refractive index of the QD material, c is the free space light speed, and ε_0 is the permittivity of the free space. The self-assembled QDs density of states, including the inhomogeneous broadening, is defined by [18]

$$D(E) = \frac{s^i}{V_{\text{dot}}^{\text{eff}}} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[\frac{-\left(E - E_{\max}^i\right)^2}{2\sigma^2}\right]. \quad (4)$$

Here, s^i is the degeneracy degree at each QD energy sub-band. In this model, $s^i = 2$ for the QD ground sub-band energy and $s^i = 4$ for the QD excited sub-band energy. Considering N_Q is the surface density of QDs, and h is the average height of QDs. The QDs effective volume $V_{\text{dot}}^{\text{eff}}$ is defined as $V_{\text{dot}}^{\text{eff}} = h/N_Q$. In equation (4), $E_{\max}^i$ is the peak optical transition energy in the QD distribution, and σ is the spectral variance of the QD distribution. The quasi-Fermi distribution functions in the respective conduction and valence bands are represented by fc and fv. The Lorentzian function of line shape for the gain spectrum is defined by [17]

$$L(E, \hbar w) = \frac{\hbar\gamma_{cv}/\pi}{(E - \hbar w)^2 + (\hbar\gamma_{cv})^2}. \quad (5)$$

With γ_{cv} is the interband relaxation. The QDs have a quantum disk shape, and the QD energy sub-bands are calculated using the quantum disk model. This model is described well in [17] and compared with the experiment [19].

3. Gain of TlBr QD Structure

The data used in the calculations are listed in Table 1.

The TlBr/BrCl QD structure is studied, where the TlBr is taken as the QDs and BrCl as the substrate. Of course, the substrate is chosen from a material of bandgap higher than the QD active region and of crystal structure similar to that of the active region to get lattice matching [22].

Figure 1 shows the gain spectrum of TlBr/BrCl QD with high gain. Two peaks appear; the first is near 800 nm while the second is at 3000 nm. These two peaks come from the first excited and ground state transitions, respectively. The first excited state transition occurs when the ground state is fully occupied, and thus, the ground state peak becomes lower than the excited. Such a result for QDs is assigned earlier [23].

Figure 2 shows the gain spectrum for doped TlBr/BrCl QD structure where the gain is increased by one order under doping. While the increment in the ground state transition curves with doping is similar to those in the undoped curves, Figure 1, all the excited state curves are increased by a higher ratio than the undoped ones, as shown in the first peak on the left.

The polarization phenomenon is a result of the applied fields on the TlBr. It screens the external electric field, reducing the efficiency. In addition to increasing gain, as shown here, the acceptor dopants can suppress the polarization phenomenon via binding charged vacancies and render them immobile. The acceptors used for the TlBr dopant can be Se or S. Acceptor doping in TlBr is also possible with Te [24, 25].

4. TlBr QD Amplifier

The rate equations are used to study the amplification characteristics of the TlBr QD structure. The dynamical system studied is shown in Figure 3. In this case, the current

Table 1: The parameters used in the calculations [20, 21].

Parameters	TlBr	BrCl
Energy gap (eV)	2.68	3.4
Electron effective mass (m_0)	0.2	0.3
Hole effective mass (m_0)	0.4	0.5
Dielectric constant	35.1	37.6

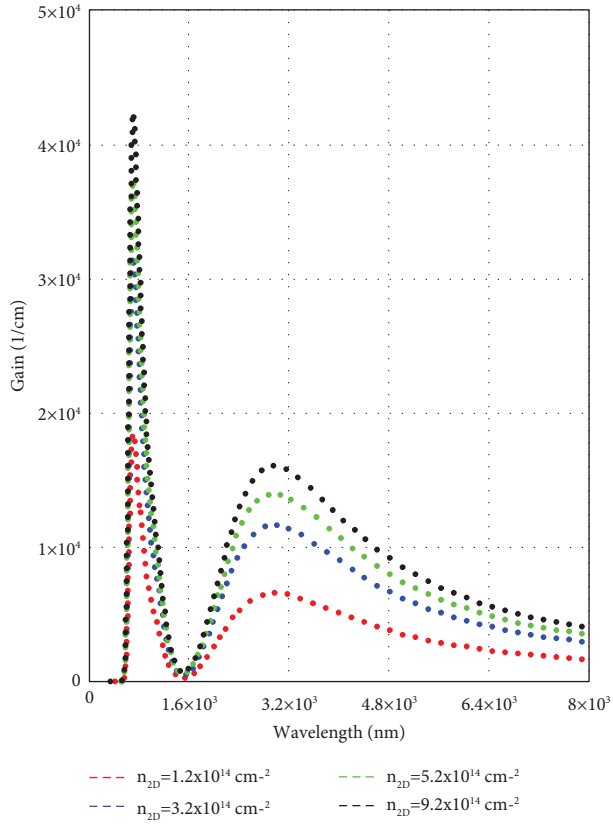

Figure 1: TlBr/BrCl QD gain at different carrier densities.

is injected at a density J on the wetting layer (WL). The WL is a layer where the QDs are grown on it. It is in the form of the quantum well layer with only one quantized dimension. The carriers are then relaxed from WL to ES at a rate $1/\tau_{w2}$ and a part of these carriers can be spontaneously radiative with a rate of $1/\tau_{w2R}$. From the QD ES, the carriers can escape to the WL at a rate $1/\tau_{2w}$. Then, the dynamics in this system can be described by the following rate equations [26]

$$\frac{\partial N_w}{\partial t} = \frac{J}{eL_w} - \frac{N_w(1-h)}{\tau_{w2}} + \frac{N_w h}{\tau_{2w}} - \frac{N_w}{\tau_{w2R}},$$

$$\frac{\partial h}{\partial t} = \frac{N_w L_w (1-h)}{N_Q \tau_{w2}} - \frac{N_w L_w h}{N_Q \tau_{2w}} - \frac{(1-f)h}{\tau_{21}} + \frac{f(1-h)}{\tau_{12}},$$

$$\frac{\partial f}{\partial t} = \frac{(1-h)f}{\tau_{21}} - \frac{f(1-h)}{\tau_{12}} - \frac{f^2}{\tau_{1R}} - \frac{g_{\max} L}{N_Q}(2f-1)S_{av}\frac{c}{n_g}\Gamma, \quad (6)$$

where f and h are the ground state (GS) and excited state (ES) electron occupation probability in the QD, N_w is the WL carrier density, e is the electronic charge, t is the time, L_w is the effective thickness of the active layer, L is the SOA length, Γ is the confinement factor, $g_{\max}$ is the maximum optical gain, and S_{av} is the average density of photons [27]

$$S_{av} = \frac{p_{in} n_g}{\hbar \omega_p A c}. \quad (7)$$

p_{in} is the power of the input signal, g_s single-pass gain, and $\hbar\omega_p$ is the energy of the signal at the peak, A is the active region area, and c is the velocity of light in free space.

5. Amplifier Characteristics of TlBr QD

The optical confinement factor is defined as $\Gamma = \zeta\Gamma_z$ with Γ_z is the vertical direction confinement factor and the area

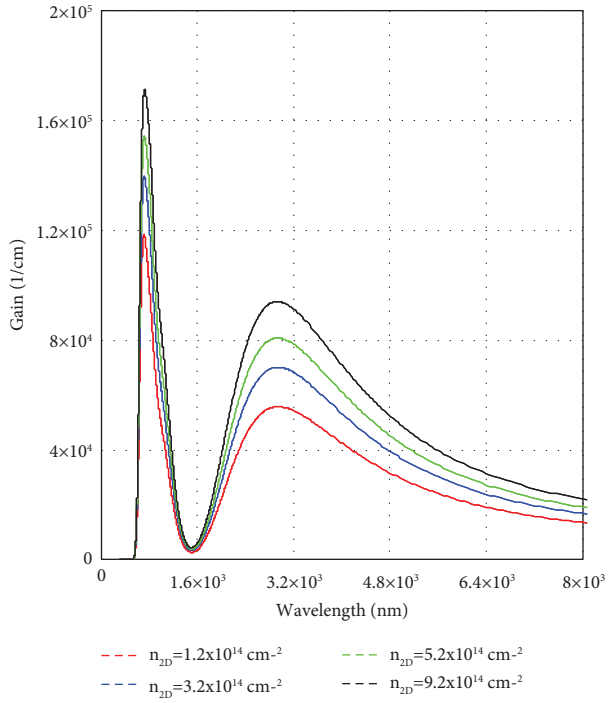

Figure 2: The doped TlBr/BrCl QD gain at different carrier densities.

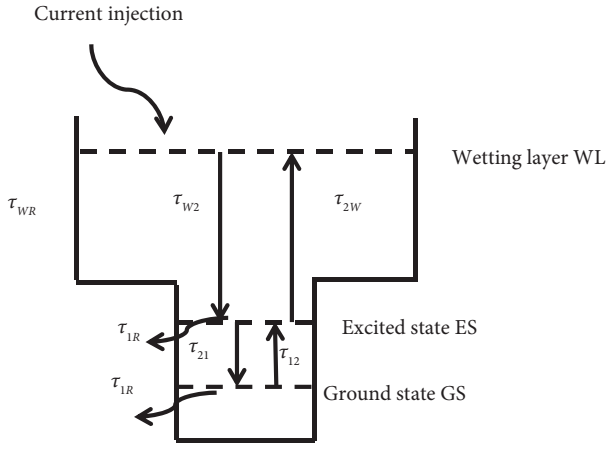

Figure 3: Schematic diagram of the energy band of TlBr QD.

coverage is ζ, and its value is $\zeta = 0.02$, which corresponds to the QD density N_Q that used here while $\Gamma_z = 0.7\%$ [23].

Figure 4 shows the gain in the units of (dB) as a function of the input power for the TlBr QDSOA and doped-TlBr QDSOA. The times and SOA parameters are listed in Table 2. It is shown that the doped SOA outperforms the undoped one and can be used for inline applications. The obtained gain is higher than the counterpart InGaAs [26] and InGaSb [28] QDSOAs. Figure 5(a) shows the WL carrier density time series, and Figure 5(b) shows the time series of GS and

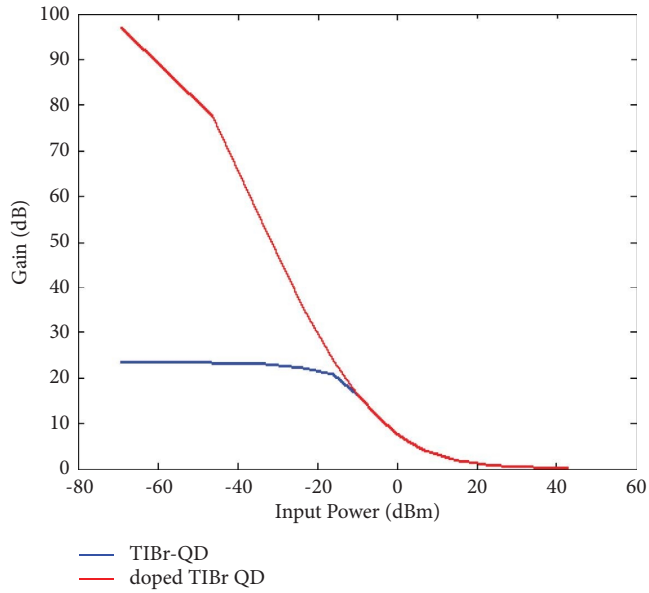

Figure 4: Gain (dB) versus input power (dBm) for doped (red) and undoped (blue) TlBr/BrCl QDs.

Table 2: QD-SOA parameters used in the calculations [27].

Parameters	Values	Units
τ_{w2}	3	ps
τ_{2w}	1	ns
τ_{w2R}	1	ns
N_Q	3×10^{10}	cm^{-2}
τ_{21}	0.16	ps
τ_{12}	1.2	ps
τ_{1R}	0.4	ns
L	2000	μm
d	800	μm
L_w	0.2	μm
J	2.033	kA/cm^2

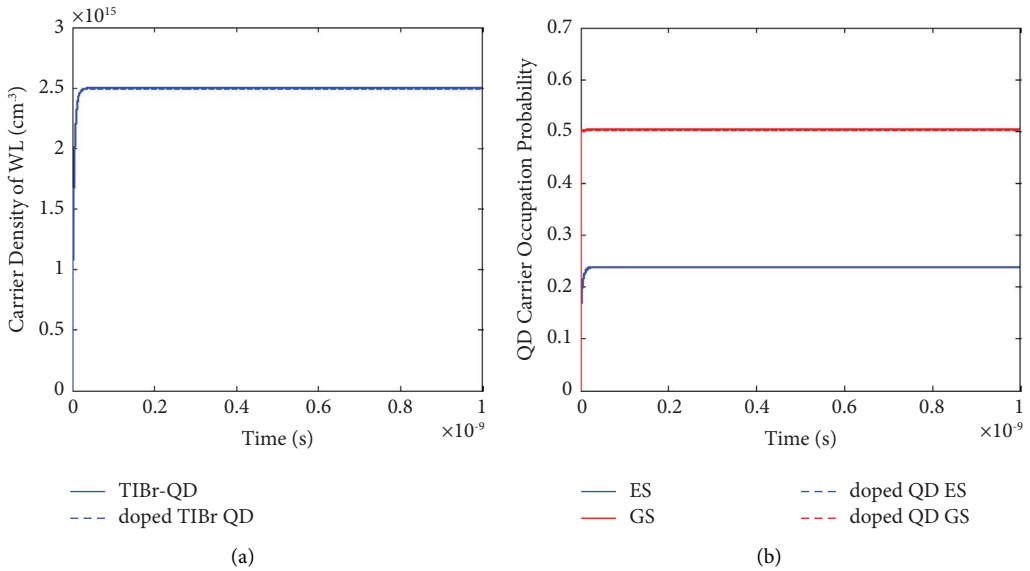

Figure 5: Times series of (a) WL carrier density and (b) QD occupation of GS (red curve) and ES (blue curve).

ES of this QD structure. They show that the TlBr QD structure is at the lasing case, as shown from the red curve of GS in Figure 5(b).

6. Conclusions

The thallium halogenide TlBr/BrCl quantum dot (QD) is examined in this work. A high gain with two peaks at 800 and 3000 nm is obtained. Doping is shown to increase the gain by one order. The peaks result from the ground state saturation, allowing the excited state transition. Examining TlBr QDSOA shows high dB gain and promises in various applications.

Data Availability

The data used are included within the article.

Disclosure

Note that, TlBr QDs are few addressed. This work is a series of works in our laboratory. So, the authors refer attention to our published work (thallium bromide quantum dot structure [29]): https://www.sciencedirect.com/science/article/pii/S2666950123000433?via%3Dihub. But it is entirely different from this work.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

The authors contributed equally to this work.

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