ABC recombination model for quantum dot laser

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Abstract. In this paper, we applied the ABC model in quantum dot (QD) semiconductor laser for the first time. We used a 1000µm cavity length InAsP/GaAs quantum dot laser emitting at 761nm, which was improved at Cardiff University. The ABC model is used to estimate the carrier losses that are caused by spontaneous emission and Auger recombination in semiconductor materials. It is shown that the ABC model is applicable in such lasers. The results show that the Shockley-Read-Hall (A) is 2.03 x10^9 sec⁻¹. The radiative coefficient (B) is 2.28 x10⁻¹⁴ cm³⋅sec⁻¹ and the Auger recombination (C) is around 8 x10⁻³⁷ cm⁶⋅sec⁻¹. The results are very close to the actual findings as measured by several different methods. Moreover, the measurement method is feasible, which can pave the path for the use of this procedure to determine the losses mechanism in semiconductor lasers.

1. Introduction
Quantum dot (QD) lasers have shown superior properties in both operation and applications in optoelectronic devices, due to their reduced threshold current [1] and high efficiency [2]. Therefore, understanding the losses coefficients in these lasers is essential because they control the efficiency of such devices; hence, they offer the possibility of finding an effective method to enhance device performance. The ABC model has attracted significant attention because it offers an excellent fitting model of external quantum efficiency (EQE) [3, 4]. Traditionally, the ABC model has been applied for light emitting diodes, such as GaInN, where there is a clear drop of the light emission efficiency with the current pumping the device (i.e., efficiency droop) [5, 6, 7]. The main reason for this drop is the self-heating effect [8, 9]. The ABC model is used to evaluate the losses coefficients, namely Shockley-Read-Hall, radiative coefficients and Auger recombination, only from the optical power–current relation and the radiative recombination time of the carriers [10] instead of using complicated experiments and calculations to find these coefficients. In this paper, we have applied the ABC model for a 1000µm cavity length uncoated facets InAsP QD laser to calculate the basic losses coefficients (i.e., Shockley-Read-Hall, Radiative and Auger recombination coefficients). The InAsP QD laser showed a high quality optical device and it offers many promising applications in optoelectronic devices and photonic integrated circuits [11, 12].

2. Theoretical part
The ABC-model is often employed to investigate the efficiency of a light emitting diode by using the power-current relationship where a drop of EQE happens in a high driven current. In this model, the EQE can be written as[13]:

\[
\text{EQE} = \frac{I}{P} = \frac{1}{A + B + C}
\]

where A, B, and C are the Shockley-Read-Hall, radiative, and Auger recombination coefficients, respectively.
\[ EQE = \eta \frac{Bn}{A + Bn + C} \]  

Here, \( n \) is the carrier density, \( \eta \) is the light efficiency, \( A \) Auger recombination, \( B \) radiative coefficient, and \( C \) is SRH coefficient. The number of variables can be minimized provided equation 1, which is written in normalized optical power \( p = \frac{p_{\text{out}}}{p_{\text{max}}} \) \( P_{\text{max}} \) corresponding to the EQE\(_{\text{max}}\) and thus EQE\(_{\text{max}}\) can be written as \([10]\):

\[ EQE_{\text{max}} = \eta \frac{Q}{Q + \frac{1}{2}p + p^{-1/2}} \]  

Here \( Q = \frac{B}{(A C)^{1/2}} \) represents a unitless combination of \((A), (B),\) and \((C)\) factors, and is called the quality factor. For the purpose of evaluating of quality factor \( Q \), it is possible to refurbish equation 2 in terms of \((EQE_{\text{max}}/EQE)\), while taking into account normalized power \( P \):

\[ \frac{EQE_{\text{max}}}{EQE} = \frac{Q + \frac{1}{2}p + p^{-1/2}}{Q + 2} \]  

Plotting the \((EQE_{\text{max}}/EQE)\) ratio against the normalized optical power allows us to calculate the \( Q \)-factor. In addition, the differential recombination lifetime \((t)\) of the carriers can be expressed by \([13]\):

\[ t = \frac{A^{-1}}{1 + 2Qp^{1/2} + 3p} \]  

Equation 4 allows us to evaluate the (SRH) recombination coefficient \( A \) by plotting the differential recombination lifetime \((t)\) against normalized power. Furthermore, after evaluating \( Q \) and \( A \), \( B \) and \( C \) can be calculated provided that the active recombination volume of the device \((V)\) is recognized by means of the following equations \([13]\):

\[ B = A^2 Q(2 + Q) \left( \frac{e V_T}{I_{\text{max}}} \right) \]  

\[ C = A^3 (2 + Q)^2 \left( \frac{e V_T}{I_{\text{max}}} \right)^2 \]  

Here, \( I_{\text{max}} \) is the value of the driven current caused by EQE\(_{\text{max}}\).

3. Experimental part

The samples were grown by the metal-organic chemical vapor deposition method for arsenides and phosphides to form self-organized QDs. The active area of the device has five layers of InAsP QD in a GaInP quantum well, separated by a matrix layer of AlGaInP. For more details about the growth conditions and sample structure, see \([14]\). Figure 1a. shows the transmission electron microscopy of the active region of the structure. A laser of 1000µm cavity length with 50µm oxide isolated striped width is used to measured the optical power- current curve of the sample, see Figure 1b. To determine the EQE from the \((P-I)\) curves, the following equation was used above the threshold current \((I_{\text{th}})\) \([15]\):

\[ EQE = \frac{\Delta p}{\Delta I} \left( \frac{e}{hf} \right) \]  

Here, \( e \) is the electron charge, \( h \) Planck constant, \( f \) frequency of light, and \( \Delta p/\Delta I \) is the gradient of the \((P-I)\) above the threshold. A multi-section sample was used to measure the radiative recombination time in the InAsP QD laser. We used the segmented contact method described in \([16]\). The spontaneous emission spectrum \( I_{\text{meas}}^{\text{sp}} \) can be calculated by means of:

\[ I_{\text{meas}}^{\text{sp}} = \left[ \frac{l_{\text{meas}}^{2} L_{1}}{l_{\text{meas}}^{2} L_{1}(L + 2) - 2I_{\text{meas}} L_{1}} \right] \frac{1}{l} \ln \left[ \frac{I_{\text{meas}} L_{1}(1 + 2)}{I_{\text{meas}} L_{1} - 1} \right] \]  

Here, \( l \) is the length of the section \((300\mu \text{m})\), \( l_{\text{meas}} L_{1}(1 + 2) \) is the amplified spontaneous emission (ASE) when both section 1 and section 2 are pumped, \( l_{\text{meas}} L_{1} \) is the ASE of section 1 (as described in Figure 1c.). It is then possible to find the radiative current density \((J)\) from the area under the curve.
of the spectra. The radiative recombination time \( t_{\text{sp.on}} \) can then be estimated from the following expression [17]:

\[
J = \frac{2Ne}{t_{\text{sp.on}}} \]

Here, \( J \) stands for the radiative current density, which can be determined from the spontaneous emission spectrum in equation (9); and \( N \) is the carrier density, which in QD is typically around 3 \( \times 10^{10} \) cm\(^{-2}\).

Figure 1. (a) Transmission electron microscopy (TEM) image of the active area, (b) laser device and (c) a multi-section device.

4. Results and discussion

Figure 2 shows the (current-power) curves for 1000\( \mu \)m cavity length of an InAsP QD laser at room temperature under pulse operation. The output optical power is measured in real units (mW) using an integrated sphere. The laser threshold current is around 220 mA and the slope efficiency \( \Delta p/\Delta I \) can be determined at any point at the curve; hence, we can determine EQE by means of equation (7). It can be seen that at a high pump level of above around 1100 mA, the slope efficiency starts to drop. This could be due to increasing the self head, even though the device is under pulse operation, or due to gain saturation at high pumped level or increasing homogenous broadening. We start from this point to apply the ABC model in the InAsP QD laser.

Figure 2. Output optical power versus pumped forward current in InAsP QD laser at room temperature under pulse mode operation, inset is the optical emission of the laser.
It is now possible to find $\Delta p$ and $\Delta I$ above the threshold current (220 mA) of the laser, to measure the ($\Delta p/\Delta I$) and EQE at each level of pumped current. Hence, it became possible to find the EQEmax. To find the normalized optical power ($P=P_{\text{out}}/P_{\text{max}}$), the EQE is plotted against output optical power in Figure 3. Pmax is found to be near 373 mW and EQEmax is approximately 34%. To find Q-factor in equation (3), we plot EQEmax/ EQE ratio against $p^{1/2} + p^{-1/2}$ after normalizing the optical power; as shown in Figure 4. Q was calculated from the linear fitting line in Figure 4 and is found to be 0.7 ±0.03.

Figure 3. EQE against output optical power in InAsP QD laser at room temperature

Figure 4. (EQEmax / EQE) ratio against the normalized optical power $p^{1/2} + p^{-1/2}$ in the QD laser
Furthermore, to calculate the radiative recombination time, the calibrated spontaneous emission spectra were found at different pumped currents for the multi-section device by means of equation 8. Figure 5 represents the spontaneous emission spectra in real units for InAsP QD. The area under the curve provides the radiative recombination rate. By multiplying this rate by the electron charge yielding the radiative current density \( J \), \( t_{\text{spon}} \) can be calculated via equation 9. Additionally, to find SHR recombination coefficient \( A \), we plot the differential carrier lifetime (i.e. radiative recombination time) against the corresponding normalized power in the form shown in Figure 6. By fitting experimental data in Figure 6 in equation 4, it is found that \( A \) is approximately \( 2.03 \times 10^{9} \) sec\(^{-1}\).

![Figure 5. Spontaneous emission spectra in real unit for InAsP QD at different pumped currents](image)

We used equation (5) and equation (6) to calculate Radiative and Auger recombination coefficients \( B \) and \( C \). To find the \( I_{\text{max}} \), which is the value of the laser current caused by the maximum EQE, we plot in Figure 7 EQE versus driven current. It is found that the \( I_{\text{max}} \) is roughly 950 mA.
Figure 6. The differential recombination lifetime against normalized optical power

Figure 7. EQE against driven current in InAsP QD laser at room temperature
It is now possible to calculate the radiative coefficient \( B \) and Auger recombination coefficient \( C \) because all of the operators in equation 5 and equation 6 are now known. We yield the radiative coefficient \( B \) at around \( 2.89 \times 10^{-14} \text{ cm}^3\text{ sec}^{-1} \) and Auger recombination coefficient \( C \) at approximately \( 8 \times 10^{-37} \text{ cm}^6\text{ sec}^{-1} \). Now, if we invoke the relation \( Q = \frac{B}{(A C)^{1/2}} \) to calculate \( Q \), we get \( Q = 0.7 \), which is consistent with the result from Figure 4. Finally, the model has been applied successfully to the InAsP QD laser.

5. Conclusion
The ABC recombination model was applied for the first time to the InAsP quantum dot laser. Shockley-Read-Hall, Radiative and Auger recombination coefficients were determined. The results show that the Shockley-Read-Hall (\( A \)) is \( 2.03 \times 10^9 \text{ sec}^{-1} \). Radiative coefficient (\( B \)) is \( 2.28 \times 10^{-14} \text{ cm}^3\text{ sec}^{-1} \) and the Auger recombination (\( C \)) is around \( 8 \times 10^{-37} \text{ cm}^6\text{ sec}^{-1} \). Moreover, the measurement method is feasible which can be used to determine the losses mechanism. We believe that the ABC model with further adjustment could be an appropriate model to calculate important loss coefficients (Shockley-Read-Hall, Radiative and Auger recombination coefficients) that currently require complicated experimental setups.

Acknowledgments
We thank prof. Peter M. Smonwton from Cardiff University for designing the sample, Dr Andrey B. Krysa form University of Sheffield for growing the sample and Dr Richard Beanland from University of Warwick for the TEM image.

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