Role of interface potential barrier, Auger recombination and temporal coherence in In$_{0.5}$Ga$_{0.5}$As/GaAs quantum dot-based p-i-n light emitting diodes

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Abstract
In this work, we investigate the mechanisms that control the electroluminescence from p-i-n heterostructures containing self-assembled In$_{0.5}$Ga$_{0.5}$As quantum dots embedded inside a GaAs/Al$_{0.3}$Ga$_{0.7}$As quantum well as a function of temperature and applied bias. Our results reveal that the carrier dynamics at the interface between the quantum dot and the quantum well play a crucial role in the electroluminescence emission. At low temperatures, two distinct emission bands are observed. Initially at low bias current, we observe broad emissions from the quantum wells and wetting layers. Another dominant and sharp emission at lower energy arises from the quantum dots, but only at higher bias currents. We discuss how a potential barrier between the quantum dots and quantum well can control the density of injected carriers undergoing optical recombination. We have also investigated the role of carrier capture and escape, quantum-confined Stark effect and band-filling effects in the electroluminescence emission. In addition, we demonstrate how measurements of temporal coherence of individual spectral peaks, can detect the presence of Auger recombination in quantum dots under high injection currents. Interestingly, a significant increase in the temporal coherence of quantum dot emissions is observed, which could be due to a decrease in Auger recombination with increasing temperature.

Keywords: quantum dots, electroluminescence, coherence, Auger recombination

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

The quantum dot (QD) laser is a device of great interest in optoelectronics because of its expected energy efficiency [1], temperature stability and spectral sharpness, which can be better than existing quantum well (QW) lasers [2]. Three-dimensional spatial confinement and atom-like sharp density of state in QDs are the reasons for its low lasing threshold and narrow emission spectra [3–5]. Through improvements in material engineering, growth techniques and device level structural modification, QD lasers are becoming more efficient and applicable to various technologies [6–8]. One such modification for extra confinement of carrier is the embedding of QDs within a quantum well (QD-QW) system [9, 10]. Such step-by-step like band structure improves the carrier confinement inside the QDs, and as a result, improves the light emission [11–13]. However, internal potential barriers can be formed at the interface of such heterostructures, which can significantly affect the carrier transport and electroluminescence (EL) inside a QD-QW. Also, the energy levels of QDs, which depend on size and mole fractions of alloy materials, determine the extent of thermal escape and the capture of carriers from QDs and luminescence quenching [10, 14]. The physics of excitonic recombination [15], non-radiative defects [16], thermal escape and re-capture [17], Auger recombination (AR) [18], etc, were previously explored to explain the outcome of these QD lasers. Numerous electrical and optical investigations were also reported showing how these can affect QD emission. However, there is still barely any consensus on the interpretation of these findings. Specifically, the role of interface potential and its effect on EL spectra and temporal coherence are rarely discussed in the literature. Therefore, detailed investigations of all these aforementioned factors can be utilized to overcome some of the generic problems with QD laser diodes, such as the inability of high-power emissions, efficiency droop [19], etc.

In this paper, we present an investigation on the optoelectrical properties, as a function of applied bias and temperature, of an In0.5Ga0.5As/GaAs/Al0.3Ga0.7As QD-QW p-i-n heterostructure. We use two similar samples, with and without distributed Bragg reflector (DBR) stacks. Most of these studies are carried out on the latter sample without any DBR, and the first sample is used only for comparison purposes. Detailed descriptions of both samples and experimental setups are given in section 2. We observe two distinct EL peaks at ~8.8 K: one from QDs and the other from QWs and wetting layers combined. In the low current density regime, the evolution of both peaks with increasing bias currents is analysed. We discuss how the potential barrier formed at the interface of QDs and QW can play an important role. Dependence of the bias current and temperature of EL spectra are discussed in detail in section 3 for the sample without DBR and these are compared with the other sample. Also, in the same section, the temporal coherence of the EL of the sample without DBR is analysed in the high current density regime using a Michelson interferometer. Thereby, we explain how AR affects optical coherence of the EL from the In0.5Ga0.5As QDs in the high bias current regime. Surprisingly, the temporal coherence of QD emission increases with increasing temperature.

2. Samples and experimental methods

The two samples investigated here were grown by molecular beam epitaxy (MBE) on semi-insulating GaAs (100) substrates. Sample A is a p-i-n heterostructure with QDs embedded within a QW. A buffer layer of 500 nm of n-type GaAs (6 × 10^{18} cm^{-3}) was grown on the substrate at 600 °C, which serves as a n-type bottom electrical contact for the sample. It is followed by 800 Å of Al0.3Ga0.7As and six layers of the QD-QW system. The centre of the QD-QW structure, which was grown at 450 °C, consisted of 100 Å of Al0.3Ga0.7As, 51 Å of GaAs, 11 Å In0.3Ga0.7As and 51 Å of GaAs. This way In0.3Ga0.7As QDs were grown inside ~100 Å GaAs/Al0.3Ga0.7As layer. This was followed by an 800 Å Al0.3Ga0.7As layer. Finally, the structure was capped with 1.3 μm of highly doped p-type Al0.6Ga0.4As/GaAs (6 × 10^{18} cm^{-3}) for top electrical contact. Ring-shaped mesas of diameter ~40 μm and area of ~5 × 10^{-4} cm^2 were made with gold for both optical and electrical access from the top. For sample B, the three key differences over sample A are: (i) there are three layers in the QD-QW system instead of six (as in sample A), (ii) the 800 Å Al0.3Ga0.7As layers above and below the QD-QW layers are replaced by an 1100 Å Al0.3Ga0.7As layer and (iii) 20 repetitions of Al0.3Ga0.7As layer (18 Å) and GaAs (10 Å) were deposited at 600 °C on either side of this active structure which works as a DBR cavity.

Samples are kept within a customized copper sample holder inside an ARS CS204-DMX-20 closed cycle cryostat for temperature dependent measurements. The electrical bias is applied using an Agilent E4980A LCR meter in DC mode. EL spectra are measured with a CCS200 spectrometer (Thorlabs). The spectral bandwidth of the spectrometer is kept at <2 nm (@633 nm) unless specified otherwise. EL was measured under forward bias levels above which the device capacitance (30 mV, 1 kHz) goes to negative [20, 21]. The λ^2 correction was incorporated in all of the EL spectra presented here. We want to further clarify that the bias current range for spectral studies in section 3.1 is from 0.11 mA to 2.2 mA.

Measurement of temporal coherence is carried out using a piezo controlled Michelson interferometer. Light coming from the samples is first focused on a 50:50 beam splitter. The distance between the mirrors and beam splitter is used to create a temporal lag (τ) between the two split beams. These temporally separated beams are then superimposed to create an interference pattern whose visibility determines the magnitude of temporal coherence, e.g. the magnitude of the first order correlation function g^{(1)}(τ). One of the interferometer arms is controlled by a piezo controller with a minimum spatial resolution of 20 nm, and the other arm is controlled by a stepper motor with a resolution of 10 μm. The positions of the mirrors are optimized to be at equal lengths from the beam splitter to measure the autocorrelation function g^{(1)}(τ = 0). Output of the interferometer is fed to an Acton Research SP255i monochromator with a full spectral bandwidth of 2.1
9.6 nm to separate the interference patterns arising out of two different spectral regions. Interference patterns are finally recorded with a Thorlabs BC106N-VIS/M CCD camera. For the coherence studies, we have used bias currents from 1 mA to 15 mA.

3. Experimental results

3.1. Bias dependence of electroluminescence from QD and QW-WL

Figure 1 shows the EL spectra measured at ~8.8 K with varying levels of forward bias. Decreasing values of forward bias voltages and corresponding bias currents are indicated in figures 1(a)–(c), respectively. We clearly see two distinct bands: one around 1.33 eV due to the EL from the In_{0.5}Ga_{0.5}As QDs, and another around 1.47 eV due to the GaAs/Al_{0.3}Ga_{0.7}As QW and In_{0.5}Ga_{0.5}As wetting layer. From now on, we will refer to the emission at 1.47 eV as QW-WL emission as it also has the contributions from QD wetting layers. It is evident from figure 1(c) that at low bias currents, the emission of the QW-WL peak is more prominent than the actual In_{0.5}Ga_{0.5}As QD peak. It can be seen from the contour diagram in figure 1(d) that even the emission of QW-WL starts before the QD emission. The QD peak begins to show up only after a bias current of ~0.33 mA. This implies that after the initial injection of carriers, the first major radiative recombination occurs inside the QW-WL, not at the QDs. However, at higher bias currents, the intensity of these QD peaks increases substantially compared to the QW-WL peaks.

To understand the above-mentioned observations, we present a schematic of the QD-QW heterostructure sample and its potential landscape in figures 2(a) and (b), respectively. The grey shadow over the QDs in figure 2(a) and the inset in figure 2(b) indicates the presence of a potential barrier at the GaAs/Al_{0.3}Ga_{0.7}As interface. Quantized energy levels (blue) of QWs within the potential barrier at the interface of QDs and the QW are shown in the inset. The potential barrier at the GaAs/Al_{0.3}Ga_{0.7}As interface and wetting layers are omitted from this schematic band diagram for simplicity.
regions of the In$_{0.5}$Ga$_{0.5}$As conduction band at the interface. Clearly, such a depletion potential barrier at the interface between GaAs and In$_{0.5}$Ga$_{0.5}$As can affect carrier injection from the QW to the QDs. Injected electrons confined by this potential barrier can get trapped within the QW; these then recombine with available holes inside this region and emit light. As a result, at low bias currents, as shown in figure 1(c), the QW-WL emission is greater in intensity than the QDs. This is because the QW-WL emission is reducing under increasing forward bias currents. However, as the forward bias current increases, electrons can eventually cross into the QDs, and EL from the QDs increases gradually, as shown in figures 1(a) and (b). A similar study based on such a potential barrier at the interface of a heterostructure is reported by Popescu et al [9] and Mu et al [22] in an InAs/In$_{0.15}$Ga$_{0.85}$As/GaAs QD-QW system. Popescu et al had speculated that it can act as an additional activation energy for photoluminescence other than thermal activation energy for carrier escape. Although, both authors have considered the presence of potential barriers in both conduction and valence bands due to compositionally induced strain, here we mostly focus on the effect of the potential barrier in the conduction band only.

The reported conduction band offset of In$_{0.32}$Ga$_{0.68}$As/GaAs is $\Delta E_c^{QD}$ ~ 0.43 eV at 4.2 K [25], while GaAs/Al$_{0.32}$Ga$_{0.68}$As is $\Delta E_c^{QW}$ ~ 0.25 eV [26–28]. It is worth noting that the magnitude of the band offset determines the amount of charge transferred at the interface, and hence the height of the interface potential barrier. Here, we have ignored the interface potential barrier, if any, between GaAs/Al$_{0.32}$Ga$_{0.68}$As because we did not observe any emission from Al$_{0.32}$Ga$_{0.68}$As at these currents. However, at even higher bias currents > 5 mA used for the coherence studies in section 3.3, a small emission peak is observed from Al$_{0.32}$Ga$_{0.68}$As at 1.85 eV. Around 60% of the energy difference between the band gaps of Al$_{0.32}$Ga$_{0.68}$As and GaAs agrees with the reported value of $\Delta E_c^{QW}$. However, it is interesting to note from figure 1 that the difference in the emission energy between In$_{0.5}$Ga$_{0.5}$As QDs and the QW-WL is only ~140 meV at ~8.8 K indicating that the ground state energy levels of QDs are quite elevated because of the high gallium content and small sizes of the QDs. The difference between the ground state conduction band energy level of the QDs and the top of the QD-QW potential barrier is referred to as $E_{loc}$ [29] in this report, as shown in figure 2(b).
of the QCSE and band-filling effects [32]. It is possible that the QCSE is more important at lower injection currents and band-filling effects can be dominant at higher injection currents. For injection currents above 1 mA, one may also expect enhancement of ARs [33–35] within In_{0.5}Al_{0.5}As QDs, as will be discussed later in section 3.3. Such an increasing presence of Auger-like non-radiative processes at higher bias currents can also broaden the FWHM, as reported here.

Figures 4(a) and (b) show the variation in spectrally integrated EL (Int. EL) of individual peaks with respect to bias current and bias voltage. The Int. EL of both the QD peak and the QW-WL peak increase with bias current but the rate of increase in the Int. EL of the QDs (Int. EL_{QD}) is greater than that of the QW-WL. An explanation for this behaviour has been discussed already in previous paragraphs in terms of the interface potential barrier, as shown in figure 2(b), and how it quantitatively affects the carrier injections and radiative recombinations from both the QDs and QW-WL. Also, in the inset of figure 4(a), we have plotted the difference ‘Int. EL_{QW-WL} − Int. EL_{QD}’ (black) and the ratio ‘Int. EL_{QW-WL}/Int. EL_{QD}’ (blue) to clearly indicate such variation in QW-WL and QD integrated intensities in accordance with our above explanations.

Increasing bias voltages lead to changes in both the effective potential (V_{eff}) and the interface potential barrier between the QW and QDs. In figure 4(b), we fit Int. EL_{QD} versus bias voltage to understand how the applied voltage can affect the potential barrier and band alignment at the interface. Here, Int. EL_{QD} is fitted with a stretched exponential function with respect to the bias voltage. The reason for this empirical fit is given in the following discussion. As such, any simple relationship between current and voltage in a diode is given by the Shockley diode model [36] and expressed by equation (3)

\[ I(V, T) = I_0 \left[ \exp \left( \frac{eV}{k_B T} \right) - 1 \right]. \] (3)

In the differential form, equation (3) can be written as,

\[ \frac{dI}{dV} \propto (I + I_0). \] (4)

The reverse saturation current \( I_0 \) can be mostly ignored because we are only working in forward bias and \( I_0 \) being a constant does not affect the proportionality relation in equation (4). The total sum of Int. EL from the QD and QW-WL \( \Sigma(EL) = \text{Int. EL}_{QD} + \text{Int. EL}_{QW-WL} \) increases linearly with the bias current \( I \), as shown in the inset of figure 4(b). This indicates that \( \Sigma(EL) \) is approximately proportional to the bias current \( I \) in the forward bias when any QD-based light emitting device is operational. Therefore, assuming that the external quantum efficiency of such a sample is also independent of the bias current, we replace \( I \) with the total Int. EL \( \Sigma(EL) \) in equation (4) as,

\[ \frac{d\Sigma(EL)}{dV} \propto \Sigma(EL). \] (5)

If a similar relation is needed for Int. EL_{QD}, i.e. \( \frac{d(EL_{QD})}{dV} \), then we also have to consider the contributions of Int. EL_{QW-WL} towards Int. EL_{QD}. The emission coming from the QW-WL has a major dependence on the interface potential barrier, which controls the level of carrier injection to the QDs. Nevertheless, we do not know the exact relation between the potential barrier and QW-WL emission. However, we understand that the potential barrier should change with the bias voltage, which affects the QW-WL emission. Hence, to get the above differential relation for QDs only, we need to introduce another term for such additional dependences on bias voltage. Such empirical dependence on bias voltage, which is in accordance with our data, can be given below as,

\[ \frac{d(EL_{QD})}{dV} \propto (EL_{QD})/V^n. \] (6)

Putting the constant of proportionality in equation (6) as \( \alpha \) gives,

\[ \frac{d(EL_{QD})}{dV} = \alpha EL_{QD}/V^n. \] (7)

Finally, solving the differential equation (7), we get the stretched exponential form of that empirical dependence as,

\[ EL_{QD} = A \cdot \exp \left( \frac{-\alpha}{mV^n} \right). \] (8)
Here, \( A \) is the constant of integration and \( m = (n + 1) \). We believe that \( \alpha \) has inverse temperature dependence. Since the curve fitting is carried out at a constant temperature (~8.8 K) and only the bias is varied, the exact temperature dependence cannot be extracted from this relationship. The estimates obtained from the curve fitting of equation (8) are \( A = 1482 \pm 72 \) a.u., \( \alpha = 365 \pm 28 \) a.u. and \( m = 5.6 \pm 0.1 \), respectively. Such stretched exponential dependence may be indicative of the presence of energy dispersive and bias dependent rate processes within the heterostructure.

For further understanding of the effective role of the potential barrier at the In\(_{0.5}\)Ga\(_{0.5}\)As/GaAs interface in confining the carriers undergoing radiative recombination in either QDs or in the QW-WL, we fit a log–log plot of Int. EL versus bias current of the QDs and QW-WL at ~8.8 K, as shown in figure 4(c). The power law exponent for Int. EL\(_{\text{QD}}\) is found to be 1.73 ± 0.02. For Int. EL\(_{\text{QW-WL}}\), this exponent is 0.78 ± 0.02. This exponent value around unity is possibly connected to the presence of excitonic recombinations in the QW-WL layers. Clearly, more carriers are being effectively recombined inside the QDs compared to the QW-WL. We have already explained that the Int. EL\(_{\text{QD}}\) depends upon the bias current that incorporates the effect of the potential barrier. After a particular applied bias, the carrier jumps into the QD from the QW after crossing that barrier and carrier transport in the QDs increases exponentially. The exponent value ~2 in the QDs indicates that EL intensity is increasing in QDs faster than that in QWs with increasing bias current. Usually, such a large exponent points to bi-molecular recombination of free electrons and holes. However, all charge carriers inside these QDs are quantum-confined from all three spatial directions. Therefore, we tend to attribute this higher exponent value (~2) to the symptomatic presence of trions or biexcitons related to radiative recombination in QDs [37]. Such evidence of the presence of trions or biexcitons may also point towards the likelihood of non-radiative AR of these excitonic complexes [34], and how it is broadening the EL peaks in figure 3(b) at higher bias currents. Further details of these understandings will be discussed again in section 3.3.
probability of electron–hole recombinations. Moreover, the QD ground state also provides the lowest energy for the system of injected carriers. In the QW-WL, carriers escape to the Al$_{0.3}$Ga$_{0.7}$As barrier layer and are swept away from the active region to become irrelevant for EL in this spectral range. Therefore, even after receiving some escaped carriers from QDs, non-radiative recombination and thermal escape can collectively dominate over radiative recombinations leading to significant emission quenching in the QW-WL. As a result, the QW-WL peak is nearly non-existent above 200 K.

The peak energy of QDs is also red shifted with increasing temperatures. Variation in QD peak energy is fitted with three models, namely Varshni [38], Vina et al [39] and Passler [40], as shown in figure 6. The fitted parameters are given in table 1. Previously, it was shown that the behaviour of the peak energy of QDs with respect to temperature is sigmoidal [10, 17]. In some of these previous studies, the measured peak energy actually red shifts more than that predicted using Varshni fitting after a particular temperature. This effect was attributed to redistribution of the charge carriers among QDs, where charge carriers get transferred into bigger QDs with lower emission energy. However, in our case, no such sigmoidal variation of peak energy is observed with increasing temperature. This is possible if there are no effective channels of carrier redistribution between the QDs, either through the wetting layer or the QW, even though the thermal escape of carriers from QDs is possible at higher temperatures.

In figures 7(a) and (b), the Int. EL$_{\text{QD}}$ and Int. EL$_{\text{QW-WL}}$ are plotted as a function of the inverse of the sample temperature (1/T), respectively, and fitted using the Arrhenius equation (9) of EL quenching with only a single activation energy. The effective free energy barrier is given by:

$$I(T) = \frac{I_0}{1 + A \cdot \exp \left(-\frac{E_a}{k_B T} \right)}$$

(9)

where $k_B$ is the Boltzmann constant, $I_0$ is the integrated EL at 8.8 K, $E_a$ is the activation energy, and $A$ is a pre-exponential factor. $E_a$ and $A$ are fitting parameters and are given in table 2. Although, the activation energies required for EL quenching from QDs and QW-WL are well below the respective potential energy barriers, $E_{\text{loc}}$ and $\Delta E_{\text{QW}}$, the thermal escape of charge carriers is still possible. This is because of the existence of thermodynamically non-zero probability of carrier escape, i.e. $\exp \left(-\frac{E_{\text{loc}}}{k_B T} \right)$ from such potential wells. A model is given in figure 7(c) indicating all such carrier dynamics. These can be both radiative and non-radiative recombinations inside the QD and the QW. Here, we assume that these fitted activation energies for both peaks are not only just thermal activation energies for carrier escape from QDs and QWs, but these also include the combined effects of activation of thermal escape as well as non-radiative recombinations through defects.

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**Table 1.** Fitted parameters of the Varshni, Vina et al and Passler models for the peak energy of QDs.

| Models          | Varshni   | Passler   | Vina et al |
|-----------------|-----------|-----------|------------|
| $E(0)$ (eV)     | 1.338     | 1.338     | $a = 1.361 \pm 0.003$ eV |
| $10^{-4} \alpha$ (eV K$^{-1}$) | 3.0 ± 0.5 | 2.4 ± 0.2 | $b = 0.023 \pm 0.004$ eV |
| $\beta$ or $\theta$ (K) | $\beta = 230 \pm 87$ | $\theta = 205 \pm 47$ | $\theta = 300 \pm 36$ |

**Figure 7.** Integrated EL of (a) QDs and (b) QW-WL are plotted with respect to the inverse of temperature in K$^{-1}$, respectively. The plots are fitted with an Arrhenius formula of luminescence quenching with single activation energy. (c) A schematic diagram of radiative and non-radiative transitions in In$_{0.5}$Ga$_{0.5}$As/GaAs QDs and GaAs/Al$_{0.3}$Ga$_{0.7}$As QWs. R and R$'$, and NR and NR$'$ are the radiative recombination and non-radiative recombination of QDs and QWs, respectively. Downward arrows indicate the carrier capture while upward arrows show the thermal escape (TE). TE$_1$ shows the escape for the carrier from the In$_{0.5}$Ga$_{0.5}$As QD to GaAs, and TE$_2$ is the carrier escape from the GaAs QW to the Al$_{0.3}$Ga$_{0.7}$As barrier layer. The grey line between the QDs and the QW represents the presence of an interface potential barrier restricting the carriers from entering the QDs at low injection currents.

**Table 2.** Fitted values of the Arrhenius equation (9) for QDs and the QW-WL, respectively.

| For QDs         | For the QW-WL |
|-----------------|---------------|
| $E_a = 21 \pm 4$ meV | $E_a = 52 \pm 10$ meV |
| $A = 25 \pm 14$  | $A = 201 \pm 192$  |
3.3. Bias and temperature effects on optical coherence

In the previous sections, we reported EL from sample A under bias currents from 0.11 mA to 2.2 mA. Here, we will present measurements of temporal coherence of EL of QDs and the QW-WL at even higher biases up to 15 mA. For these, we have used basic Michelson interferometry to measure the first order autocorrelation function $g^{(1)}(\tau = 0)$, as described in section 2. The modulus of $g^{(1)}(\tau = 0)$ can be directly calculated from the visibility of the interference pattern generated by the Michelson interferometer [41] using equation (10). In figures 8(a) and (b), $g^{(1)}(\tau = 0)$ of spectrally separated EL emissions from QDs and the QW-WL at different bias currents and temperatures are shown, respectively.

$$|g^{(1)}(\tau = 0)| = \text{visibility} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}.$$ (10)

Here, $I_{\text{max}}$ and $I_{\text{min}}$ are the maxima and minima of the fringes in the recorded Michelson interference pattern. In figure 8(a), we see that $g^{(1)}(\tau = 0)$ of QDs decreases with increasing bias current while for the QW-WL, it is increasing. The decrease in $g^{(1)}(\tau = 0)$ in QDs is likely due to AR within these QDs at such high bias currents. AR is a non-radiative process usually significant at high carrier densities and in low band gap materials. AR is effective in suppressing luminescence and reducing temporal coherence at higher injection currents for QD EL. From figure 4(c), it is clear that the integrated EL of QD already begins to saturate above bias currents of ~1 mA. EL spectra at such higher bias currents are not shown. Interestingly, the presence of the Auger process can be confirmed here mainly on the basis of the observed differences in temporal coherence of QD EL and QW-WL EL. This is because, contrary to QDs, QW EL is not affected by AR, mainly because of the following reasons. First, the QW recombinations only occur from remaining carriers in the QW-WL, whose densities are comparatively smaller than that of the QDs. This can be understood from the EL of QDs and the QW-WL shown in figure 4(a) where the EL of QDs exceeds the EL of the QW-WL at around 2 mA. Secondly, QWs have a higher band gap than QDs [34, 42–44]. Thirdly, QWs have less spatial confinement than QDs, which also keeps the carrier density below the threshold for any significant Auger process. Therefore, the temporal coherence of QW-WL EL still increases with increasing bias currents in the absence of any significant AR process within the QW-WL.

Auger is a three-particle scattering process where either two electrons and one hole or two holes and one electron ($e^-e^-h^+$ or $h^+h^+e^-$) get involved to recombine non-radiatively. The recombination energy of $e^-h^+$, instead of getting emitted as photons, is provided to a third particle which transfers to higher available energy states resulting in a final overall non-radiative recombination process. During the AR process in QDs, the third charge carrier carrying the recombination energy can also undergo transfer from the QD to the QW levels. This type of non-radiative AR can destroy temporal phase correlation between emitted photons leading to a reduced $g^{(1)}(\tau = 0)$ in QDs. Also, we have already attributed the power law exponent of integrated EL with bias currents to the presence of trions or biexcitons in these QDs in section 3.1. This explanation agrees with the discussion provided by Kurzmann et al [34] for InAs/GaAs QD at 4.2 K, where they concluded that trions can effectively contribute to AR.

Observed variations in temporal coherence with temperature at a bias current of 15 mA are shown in figure 8(b). These indicate interesting comparisons between QD EL and QW-WL EL. With increasing temperature, the coherence of QDs increases despite the increase in thermal energy of the charge carriers and then it saturates. Due to small $E_{\text{loc}}$ in QDs, the charge carriers easily escape QDs with increasing temperatures. This can significantly lower the carrier density below the required AR threshold inside these QDs. As a result of this effective reduction of carrier density at higher temperatures, there can be a subsequent decrease in AR [45, 46] leading to an increase in the coherence of QD EL with increasing temperatures up to a certain level and near saturation. However, the $g^{(1)}(\tau = 0)$ for QW-WL emissions is not affected, as expected, due to the absence of any significant Auger process at higher temperatures. As a result, the optical coherence of QW-WL EL mostly decreases above 50 K with the usual increase in non-radiative recombinations with increasing temperatures.

Figure 8. The first order correlation function, $g^{(1)}(\tau = 0)$ is estimated for both the EL of QDs and EL of the QW-WL, respectively. These $g^{(1)}(\tau = 0)$ are plotted against bias currents at ~8.8 K in (a) and against temperatures at a fixed bias current of 15 mA in (b), respectively. All lines in (a) and (b) are a guide for the eyes only. AR is possibly weakening the optical coherence at such high currents. However, thermal escape of charge carriers from QDs results in reduced carrier density at higher temperatures. This suppresses AR, which shows up as an increase in temporal coherence of QD EL at higher temperatures.
QD-based light emitting devices. and temporal coherence of EL can be suitable for optimizing AR and the above-mentioned interplay between quenching sample A.

temperatures with a fixed bias current of ~2.2 mA. Here, the emissions from both QDs and QW-WL are much sharper in comparison with sample A.

The EL intensity of the QW-WL at temperatures higher than ~120 K is small enough to obtain any reasonable estimate of $g^{(1)}(\tau = 0)$.

To the best of our knowledge, there are no literature reports that have related coherence of EL with AR in QDs. Moreover, here we showed an interesting interplay between two effects: EL quenching and temporal coherence of EL due to the escape of charge carriers from QDs with increasing temperatures. On one hand, charge depopulation from QDs results in quenching of QD EL with increasing temperatures. On the other hand, due to reduced charge carrier density, the ongoing AR also reduces, which results in more coherent light emission at higher temperatures. In a way, spectrally selective measurements of temporal coherence could be considered as a useful method to sense the presence of AR. From the point of view of applications, this sensitivity of $g^{(1)}(\tau = 0)$ to detect AR and the above-mentioned interplay between quenching and temporal coherence of EL can be suitable for optimizing QD-based light emitting devices.

3.4. Experimental results on sample B with DBR

We also investigated sample B, which has a structure similar to a vertical cavity surface emitting laser (VCSEL) that include QDs in the active region and DBR stacks on both sides, under similar electrical biases and temperatures. Clearly, the EL peaks of QDs and the QW-WL are distinct and well separated in comparison to sample A, as shown in figures 9(a) and (b). The spectral evolution of peaks with increasing biases at low temperature (~10 K) is still the same as sample A, which indicates the presence of a potential barrier at the interface of QDs and the QW. Although the peak position of QDs in sample B is the same as for sample A, the emission peaks in sample B are narrower. The FWHM in sample A ranges from 42 meV to 48 meV, while in sample B, it saturates to a much smaller value ~30 meV. This can be explained by the presence of DBR stacks at both ends of the structure, which form an optical cavity. Therefore, we attribute the observed reduct in the emission broadening to the selective nature of a 1D photonic band gap within such DBR stacks. In sample B, we also observe that the peaks follow similar trends with temperature. However, the QW-WL peak almost disappears at 250 K instead of 200 K, as observed in sample A. Due to three layers of QD-QWs instead of six, as in sample A, there can be twice the amount of injected charge carrier densities in the active region of sample B. This could be the reason behind the non-vanishing of QW-WL EL, even at 250 K for sample B.

4. Conclusion

We conclude that the interface potential barrier between QDs and QWs has an important role in determining carrier dynamics inside an In$_{0.3}$Ga$_{0.7}$As/GaAs/Al$_{0.3}$Ga$_{0.7}$As QD-QW heterostructure. For device applications, in the low current regime, this barrier could play a more decisive role. We further found an empirical dependence of the EL of QDs on the applied bias voltage, which directly incorporates the effect of the same interface potential barrier. The temperature dependence of the EL spectra shows that thermal escape of injected charge carriers and their non-radiative recombinations are the main causes of EL quenching. We also performed temporal coherence measurements and argued that AR is a major source of the loss of coherence in QD emission at high carrier densities. With increasing temperatures, due to the escape of carriers from QDs, the charge density reduces resulting in reduced ARs at a fixed bias current. These reduced ARs then further enhance the first order temporal correlation of light emission. Therefore, depopulation of carriers from QDs results in lower EL, but with improved optical coherence at higher temperatures.

In fact, we even argued that measurement of temporal coherence of individual spectral peaks could be an important sensitive tool to detect the presence of ARs in QDs. All these results also indicate that by using proper materials and device engineering of potential barriers within such QD heterostructures, a dynamical balance can be found between the thermally activated loss of carriers, which do not recombine radiatively, and the fraction of injected carriers which produce EL. Therefore, this work demonstrated how such an interface potential barrier mediated charge transferred to and from QDs helps to maintain the crucial interplay between EL quenching and the temporal coherence of EL. Such optimisations will be important to control not only the strength, but also the coherence of EL resulting in efficient QD-based light emitting devices for lasing.

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