Carrier hopping in InAs/Al\textsubscript{y}Ga\textsubscript{1−y}As quantum dot heterostructures: effects on optical and laser properties

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Abstract

The optical properties of InAs/Al\textsubscript{y}Ga\textsubscript{1−y}As self-assembled quantum dots are studied as a function of temperature from 10 K to room temperature. The temperature dependence of carrier hopping between dots is discussed in terms of the depth of the dot confinement potential and the dispersion in dot size and composition. We show that carrier hopping between dots influences both the electrical and optical properties of laser devices having dots as active medium. © 2000 Published by Elsevier Science B.V. All rights reserved.

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The effect of temperature, $T$, on the optical properties of self-assembled quantum dots (QDs) is of great importance for their use in devices working at room temperature. Various papers have discussed the temperature dependence of the photoluminescence (PL) properties of QDs in InAs/GaAs [1–8], In\textsubscript{y}Ga\textsubscript{1−y}As/GaAs [9–11], Al\textsubscript{x}In\textsubscript{1−x}As/Al\textsubscript{y}Ga\textsubscript{1−y}As [10] and ZnSe/ZnS heterostructures [12]. Common features are observed in the temperature dependence of the PL associated with the QDs. For example, there is a minimum in the luminescence line width at $T \sim 100$ K and, with increasing $T$, a faster red-shift of the PL peak position with respect to that expected from the temperature dependence of the bulk band gap of the dot material [1–8,10,12].

This paper reports a study of carrier transfer phenomena induced by temperature as observed in the PL properties of InAs/Al\textsubscript{y}Ga\textsubscript{1−y}As ($y=0–0.8$) self-assembled QDs. The high quality of the samples investigated allows us to study these processes from $T = 10$ K to room temperature, $T = 300$ K, in QD structures having different carrier-confining potential barriers, $V_0$. Increasing $T$ leads to a carrier thermal redistribution between dots. This is discussed in terms of $V_0$ and the intrinsic disorder of the dot ensemble by means of an analogy with carrier relaxation in disordered quantum wells (QW) [13,14]. An analysis of the electroluminescence spectra of lasers having QDs...
The energy difference, $V_{\text{room temperature}}$ for InAs, is the peak position, $h\nu$, for InAs dots embedded in different Al content ($y$) matrices (full circles). The continuous line is the (AlGa)As band gap dependence on $y$ at the same temperature.

Fig. 1 shows the dependence of the photoluminescence (PL) peak position, $h\nu$, on Al concentration at room temperature for InAs/(AlGa)As QDs (set A). The energy difference, $V_0$, between the dot levels and the barrier band gap is shown in the same figure. As a consequence of the large value of $V_0$, the dots embedded in the Al$_y$Ga$_{1-y}$As matrices with $y \geq 0.3$ have a high thermal stability. In fact, the PL intensity falls by only a factor three as $T$ increases from 10 K to room temperature [1]. Furthermore, a clear luminescence signal persists up to 500 K for the dots embedded in the GaAs/Al$_{0.3}$Ga$_{0.7}$As QW (set B) and in the (AlGa)As matrices having $y \geq 0.3$ [15].

The analysis of the PL line shape with varying temperature provides an insight into the mechanisms governing the carrier thermal redistribution between dots [1–12]. In particular, the variation of $h\nu$ with $T$ deviates from that expected from the band-gap variation of the dot material (InAs). With increasing $T$, enhanced carrier relaxation between dots results in an increasing difference between the observed PL peak and its expected position, calculated from the $T$ dependence of the InAs band gap. We define this offset as the “Stokes shift”, $S$, of the dot luminescence and we estimate experimentally that $S(T) = \Delta(h\nu_{\text{QD}}) - \Delta(h\nu_{\text{bulk}})$, where $\Delta(h\nu_{\text{QD}})$ is the thermal shift of the dot PL peak position measured with respect to $T = 10$ K and $\Delta(h\nu_{\text{bulk}})$ is the corresponding thermal variation of the dot material band gap, also relative to its value at 10 K.

Fig. 2 shows the value of $S$ at room temperature, $S_{\text{RT}}$, as a function of the dot luminescence line width measured at 10 K, $W_{10K}$. Note that due to the randomness of the carrier capture process into the dots at low $T$, $W_{10K}$ reflects the distribution of all dot states. Data for a number of self-assembled QD systems grown under different conditions/laboratories and with a different degree of disorder are shown in Fig. 2. The inset shows the PL spectra recorded at low and room temperature for an InAs/Al$_{0.15}$Ga$_{0.85}$As QD sample, along with the definition of the parameters $W$ and $\Delta(h\nu_{\text{QD}})$ used in the main figure. $S_{\text{RT}}$ and $W_{10K}$ are proportional. We find empirically that $S_{\text{RT}} = \alpha W_{10K}$, where $\alpha = 0.44$ (see the straight line in Fig. 1). This indicates that greater the size- and compositional-disorder of the dot ensemble (larger $W$), the larger is the number of states toward which the carriers may diffuse, thus resulting in an increasing value of $S$ with $W$. In the limit of a distribution of identical dots, carrier diffusion would result in no shift of the PL peak position with a zero $S$ at all temperatures. The same kind of proportionality between the Stokes shift and the absorption line width was observed in disordered quantum wells and modelled by assuming carrier relaxation into local energy minima having a Gaussian energy distribution [13].
Fig. 2. Room temperature Stokes shift, $S_{\text{RT}}$, of the QD luminescence energy versus dot PL linewidth measured at 10 K, $W_{10K}$. The line $S_{\text{RT}} = aW_{10K}$ ($a = 0.44$) is an empirical fit to all data. Open triangles: InAs/(AlGa)As QDs grown under different conditions; Full diamond: Ref. [8]; Full triangle: Ref. [11]; Full square: Ref. [19]; Full circle: Ref. [20]. Inset: PL spectra recorded at low (dotted line) and room temperature (continuous line) for InAs dots in an Al$_{0.15}$Ga$_{0.85}$As matrix.

The analogy between disordered two-dimensional systems and self-assembled QDs can be further strengthened. The low-temperature ($T < 100$ K) line width of the dot luminescence, $W$, reflects the width of the energy distribution of the dots and the magnitude of $S$ indicates the ability of carriers to diffuse from smaller towards larger dots. The decrease of $W$ and the increase of $S$ with increasing temperature have been predicted theoretically in disordered QW in which the inhomogeneous potential, due to monolayer fluctuations and alloy disorder, localises carriers [14]. With increasing $T$, excitons can overcome shallow energy minima by thermal activation and diffuse into deeper states. The same picture can be applied to the present study except that in this case the carriers are more strongly localised. Because the energy scale of the potential fluctuations in conventional quantum wells ($\sim 1$ meV) is much less than for self-assembled dots ($\sim 100$ meV), the temperatures at which carrier hopping becomes important are much higher for QDs.

Carrier redistribution between dots is also responsible for some of the characteristic properties of laser devices based on QDs. Fig. 3 shows the temperature dependence of the threshold current density, $J_{\text{th}}$, (right axis, full circles) and of the laser spectra line width (left axis, hollow squares), $\Gamma$, for a laser having InAs QDs embedded in a GaAs QW as the active medium (set B). A clear narrowing of the mode distribution can be observed with increasing $T$: the insets of Fig. 3 show the above threshold ($J = 1.1 J_{\text{th}}$) electroluminescence spectra recorded at $T = 30$ K and 290 K [$J(T) = 1.1 J_{\text{th}}(T)$].
width recorded below threshold has a minimum at the same temperature at which $J_0$ reaches its lowest value. The presence of a minimum in the luminescence line width has been discussed in terms of carrier hopping [1] and in this contest well relates to the effect of carrier redistribution on the QD laser properties.

In conclusion, we studied the PL properties of InAs/Al$_y$Ga$_{1-y}$As self-assembled QDs as a function of temperature. The high quality of the samples allowed us to study carrier relaxation phenomena up to room temperature in QD structures having different carrier confining potential barriers. We observe evidence for carrier hopping between dots similar to the behaviour seen and predicted in highly disordered quantum wells [13,14]. The effect of carrier hopping has been also investigated in QD lasers, where it determines a narrowing of the multi-mode emission of the lasers and the dependence of the threshold current density on temperature.

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References