Carrier transfer in quantum-dot lasers

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In dense arrays of quantum dots, carrier transfer between dots affects the recombination kinetics, and thus the behavior of diode lasers and amplifiers that use such arrays.

Semiconductor quantum dots (QDs) are small single crystals embedded in a host matrix. They find numerous applications, for example, as the active-region material in semiconductor lasers and amplifiers. Nowadays QDs have left university labs and have even become part of commercial products. Modeling of QD-based devices helps to further optimize these innovative optoelectronic products.

A key parameter that describes semiconductor materials, including QDs, is the nonequilibrium carrier lifetime, \( \tau \), which is the characteristic time for a population of excess carriers to relax to a fraction \( \frac{1}{e} \) of its initial value. \( \tau \) is an important input parameter for device modeling, and accurate knowledge of its value is required for high-quality model results.

Several different techniques can measure \( \tau \). In direct-gap optoelectronic materials, such as III-V quantum wells or QDs, its value is typically around 1ns, and is conveniently determined from analysis of transient photoluminescence (PL). The PL decay time, \( t \), is then a rough measure of \( \tau \). For laser applications, dense QD ensembles, such as QD planes with a high areal density or even stacks of several QD planes on top of each other, are required to achieve sufficient overlap between the QDs and the optical field. In these dense ensembles, a distinct spectral dependence of the transient PL was found, as illustrated in Figure 1(a).

This PL spectrum can be viewed as a superposition of narrower lines originating from different-sized QDs. Thus the spectrum is a fingerprint of the specific QD ensemble. Since smaller QDs have energetically higher lying ground states, they emit at a shorter wavelength than larger QDs. The presence of two main features in Figure 1(a) indicates that there are two dominant QD sizes. Structural investigations confirmed this bimodal size distribution.

The specific shape of the \( \tau \) spectrum in Figure 1(b) is now qualitatively interpreted as follows. If the ‘genuine’ \( \tau \) value is tentatively considered constant for all QD sizes, the shorter PL decay time for smaller QDs (emitting at shorter wavelengths) is caused by the additional relaxation channel offered by inter-QD carrier transfer to larger QDs. In turn, the PL originating from the larger dots is delayed by the ‘refill’ process.

We systematically studied these effects for several different types of dense QD arrays. The time constant describing the efficiency of the inter-QD carrier transfer, \( \tau_t \), was found to be between 100ps and 3.5ns, as summarized in Table 1. The genuine \( \tau \) value describing the recombination behavior of noninteracting QDs was measured to 1.4–2.6ns. So it is clear that, in dense QD arrays, the parameter \( t \) is influenced, or even determined, by inter-QD carrier transfer.

QD device properties should be taken into account for experimental lifetime measurements in general, and also when \( t \) is used for device modeling and band-structure engineering. Our

![Figure 1](image-url)
Table 1. ‘Genuine’ lifetime and inter-QD transfer times in various dense QD systems. ML: Monolayer.

<table>
<thead>
<tr>
<th>Type of QD structure</th>
<th>Type of transfer</th>
<th>Genuine lifetime, $\tau$</th>
<th>Inter-QD transfer time, $\tau_t$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense QD array with bimodal size distribution</td>
<td>in-plane</td>
<td>2.6ns</td>
<td>3.5ns</td>
<td>1</td>
</tr>
<tr>
<td>Vertical stack of QD arrays</td>
<td>vertical</td>
<td>1.4ns</td>
<td>barrier thickness: 30 ML:280ps 40 ML:570ps 50 ML:1.3ns 50 ML:1.3ns 60 ML:2.6ns</td>
<td>2</td>
</tr>
<tr>
<td>Vertical stack of QD arrays in a p-i-n junction</td>
<td>vertical</td>
<td>2.0ns</td>
<td>100–600ps tunable by bias voltage</td>
<td>3</td>
</tr>
</tbody>
</table>

results help to make these properties more predictable for a wide range of applications.

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Jens W. Tomm received his diploma and PhD degree in physics from Humboldt University, Berlin, Germany. From 1993 to 1995 he was at Georgia Tech in Atlanta, GA. His main fields of interest are semiconductor optics and device physics. He is the author of more than 200 papers and a member of the German Physical Society.

References