Effect of gain saturation and nonradiative recombination on the thermal characteristics of InAs/GaAs 1.3 μm quantum dot lasers

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Gain saturation increases the radiative component, J_{rad} , of the threshold current density, J_{th} , and its contribution to the thermal sensitivity of J_{th} in short cavity or low QD density devices. However, the main cause of their thermal sensitivity is a strong non-radiative recombination.

In spite of the fact that InAs quantum dot (QD) lasers have low threshold current densities, J_{th} [1], the thermal sensitivity of the devices continues to be a significant problem. This limits the commercial use of these lasers. Different mechanisms of re-emission of carriers into the optical confinement layers activated by increasing temperature and their subsequent radiative or nonradiative recombination in the OCL as well as effect of gain saturation, which causes an increase of the threshold current with temperature have been discussed in the literature as possible causes of this behaviour [2, 3]. A significant improvement in the thermal stability of J_{th} has been achieved using p-type doping of the QD active region to avoid gain saturation [4] albeit at the expense of a higher J_{th} . In our previous work it was shown that the thermal sensitivity of J_{th} in quantum dots is caused mainly by nonradiative recombination processes, which depend on the band gap of the dots and their energy level distribution. The results showed the likely importance that Auger recombination can have in 1.3 μm QD lasers [2, 3]. In this paper using a set of 1.3 μm InAs QD lasers with different cavity lengths and different QD densities we investigated the effects of gain saturation and non-radiative recombination on the thermal sensitivity of J_{th} .

The lasers studied were 5, 10, 15, and 20 μm wide ridge dot-in-a-well structures with five stacked layers of InAs QDs within $\text{Ga}_{0.85}\text{In}_{0.15}\text{As}$ quantum wells separated by 50 nm GaAs barriers. The active region was embedded between 2 μm $\text{Al}_{0.4}\text{Ga}_{0.60}\text{As}$ cladding layers in a 200 nm GaAs waveguide. The facets were as-cleaved and the cavity

lengths were 2, 3, and 5 mm. The lasing line corresponded to the ground state emission at all temperatures with a wavelength of $\lambda=1.31 \mu\text{m}$ at room temperature (lasing from the excited state was observed in some of the shorter cavity devices above 320-340 K). Lasers with longer cavity lengths showed the lowest threshold current densities of 30-50 A/cm^2 at $T=295 \text{ K}$, which is close to the record low values for 1.3 μm QD lasers [1, 2].

Using the measured integrated spontaneous emission rate at J_{th} , which is proportional to the radiative recombination rate, we studied the temperature variation of the radiative part of total threshold current density, J_{rad} . These direct measurements allow us to estimate the relative contributions of radiative and non-radiative processes to J_{th} at different temperatures.

Fig. 1 shows the temperature dependence of the pulsed threshold current density, J_{th} , and its radiative component, J_{rad} , measured for the devices with different cavity lengths of 2 mm and 5 mm. The decrease in J_{th} with increasing temperature below 180 K is often observed in QD lasers and is attributed to the enhanced carrier transport between dots with increasing temperature, which allows carriers to contribute more effectively to the lasing process [3]. Above 200 K, J_{th} increases strongly whilst J_{rad} remains almost temperature insensitive in the 5 mm-device as originally predicted by Arakawa et al. [5], demonstrating that the strong increase of J_{th} is caused by non-radiative processes. An increase of J_{rad} in the shorter cavity device and the higher thermal sensitivity of J_{th} in this device can be explained by the fact that QD lasers are much

Fig. 1. Threshold current density, J_{th} , and its radiative component, J_{rad} , versus temperature for the devices with different cavity lengths ($L_c=2$ mm and 5 mm).

more prone to gain saturation. Due to the shorter cavity length of the 2 mm device, the mirror loss is more than double that of the 5 mm device. Therefore in order to compensate for the gain reduction due to increasing homogeneous broadening at higher temperatures a higher carrier concentration is required to achieve threshold, especially in the lasers with increased mirror losses. This effect with increasing temperature can lead to an increase of J_{rad} (and J_{th}) and sometimes to a transition from lasing from the ground state to lasing from an excited state, which was observed in the 2 mm-devices above 340 K.

The characteristic temperatures (T_0) corresponding to both J_{th} and J_{rad} for the devices with different cavity lengths over the temperature intervals $T=280-330$ K and $T=330-360$ K are summarized in Table 1. An interesting fact is that the T_0 -values for both J_{th} and J_{rad} decrease with decreasing cavity length demonstrating the increased importance of gain saturation in the shorter devices. The increased T_0 of the 2 mm device above $T=330$ K is caused by a switch of the lasing emission to the first excited state. However, as one can see from the Table 1 and Figure 1 the T_0 of J_{th} is also much smaller than that of J_{rad} showing that the origin of the thermal sensitivity of J_{th} is non-radiative recombination. Assuming that below 200 K nonradiative recombination is negligible (this is supported by the fact that J_{rad} closely follows

J_{th} in this temperature range), we estimated the maximum fraction of J_{rad} at room temperature. We find that J_{rad} is at most 37%, 27%, and 22% in the 5 mm, 3 mm, and 2 mm devices, respectively. Room temperature high hydrostatic pressure studies of J_{th} and J_{rad} of these devices further suggests that Auger recombination is the dominant non-radiative recombination process around room temperature.

Table 1. Characteristic temperatures of J_{th} and J_{rad} for the devices with different cavity length, L_c

Set of QD lasers processed identically	T=280-330 K		T=330-360 K	
	$T_0(J_{th})$	$T_0(J_{rad})$	$T_0(J_{th})$	$T_0(J_{rad})$
$L_c=5$ mm	80 K	∞	52 K	118 K
$L_c=3$ mm	40 K	120 K	30 K	44 K
$L_c=2$ mm	36 K	90 K	60 K	188 K

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