Recombination and Loss Mechanisms in Low-Threshold InAs–GaAs 1.3-μm Quantum-Dot Lasers

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***Abstract*—We show that even in quantum-dot (QD) lasers with very low threshold current densities ($J_{\rm th} = 40$–50 A/cm^2 at 300 K), the temperature sensitivity of the threshold current arises from nonradiative recombination that comprises $\sim$60% to 70% of $J_{\rm th}$ at 300 K, whereas the radiative part of $J_{\rm th}$ is almost temperature insensitive. The influence of the nonradiative recombination mechanism decreases with increasing hydrostatic pressure and increasing band gap, which leads to a decrease of the threshold current. We also studied, for the first time, the band gap dependence of the radiative part of $J_{\rm th}$, which in contrast increases strongly with increasing band gap. These results suggest that Auger recombination is an important intrinsic recombination mechanism for 1.3-μm lasers, even in a very low threshold QD device, and that it is responsible for the temperature sensitivity of the threshold current.**

***Index Terms*—Characteristic temperature, hydrostatic high pressure, InAs, quantum dot (QD), recombination mechanisms, semiconductor laser, threshold current.**

I. Introduction

THERE is a major effort to develop InAs-based quantum-dot (QD) lasers with better performance than existing quantum-well (QW) lasers. More than 20 years ago, the first theoretical prediction showed that using three-dimensional confined structures with an atomic-like discrete density of states in the active region of semiconductor laser should allow the development of low threshold current density devices with very high thermal stability [1], [2]. Since then, a lot of work has been undertaken to create such lasers and to study their unique properties [3]–[25]. However, despite the growth of very good self-assembled layers of QDs, the longer wavelength lasers required for optical communications remain temperature sensitive at higher temperatures. Fig. 1 summarizes the performance of the best InAs–GaAs-based QD lasers [4]–[19], where we have plotted the characteristic temperature, T_0, of the threshold current density, $J_{\rm th}, (T_0 = J_{\rm th}(dJ_{\rm th}/dT)^{-1})$ in the temperature range $T = 290$–300 K versus $J_{\rm th}$ at room temperature. The results for $\sim$1.3- and $\sim$1-μm lasers are shown in Fig. 1 with solid and open circles, respectively. The interesting trend observable in Fig. 1 is that the higher T_0 values are achievable only at higher $J_{\rm th}$ values.

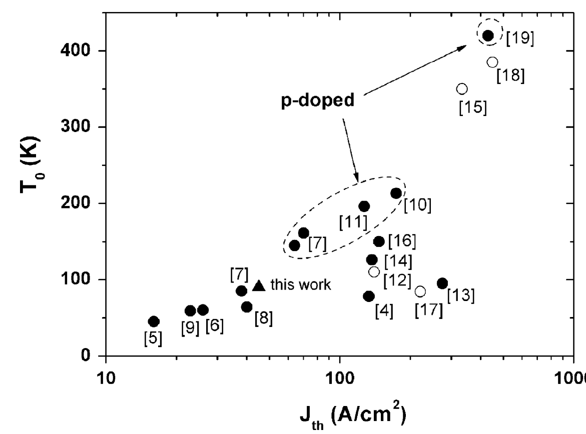

Fig. 1. Characteristic temperature, T_0, in the temperature range $T =$ 290–300 K of InAs–GaAs QD lasers with emission wavelengths of $\sim$1.3 μm (solid circles) and $\sim$1 μm (open circles) as a function of room temperature threshold current density.

To explain the temperature sensitivity of the QD lasers, several different mechanisms have been proposed in the literature. Reemission of carriers into the optical confinement layers (OCLs) activated by increasing temperature and their subsequent radiative or nonradiative recombination in the OCL was proposed [20], [21]. Indeed, Matthews *et al.* showed that the temperature sensitivity of short wavelength ($\lambda \sim 1\mu$m) QD lasers is caused by gain saturation due to the presence of a high density of states in the wetting layer. The available gain decreases with increasing temperature and at room temperature only achieves $\sim$30% of its maximum [22]. Experimentally, it has also been shown that to decrease the temperature sensitivity of $J_{\rm th}$, the shape of the QDs should be engineered to maximize the energy separation between the ground electron and hole states and their respective excited states [23]. Finally, a significant improvement of T_0 has been reached using p-type doping of the QD active region to avoid gain saturation. This increased the characteristic temperature up to $T_0 = 213$ K [10] and to $T_0 = 420$ K [19] around room temperature, and enabled modulation at 10 Mb/s up to 70 °C, albeit at the expense of higher $J_{\rm th}$ values. However, above 60 °C, T_0 decreased to only $T_0 = 70$ K [19]. More recently, a theoretical approach has been proposed assuming combined statistics for free carriers

Manuscript received November 15, 2004; revised June 20, 2005. This work was supported by EPSRC.

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Digital Object Identifier 10.1109/JSTQE.2005.853847

and excitons, which explains the experimental observations in undoped and p-doped lasers in terms of radiative recombination only [24]. However, in our previous work, it was shown that the thermal sensitivity of $J_{\rm th}$ in QDs is due to nonradiative recombination processes, which depend on the band gap of the dots and their energy level distribution. The results highlighted the likely importance that Auger recombination can have in 1.3-μm QD lasers [25].

In this paper, we extend the study to 1.3-μm QD lasers with very low threshold current densities (Fig. 1) close to record values and also show for the first time how the radiative current density at threshold varies with lasing wavelength brought about by the application of hydrostatic pressure. These high-pressure results confirm the existence of significant nonradiative recombination with the characteristics expected for Auger processes.

II. Experiment

The 1.3-μm QD lasers studied were 10- or 20-μm-wide ridge dot-in-a-well structures with five stacked layers of InAs QDs within $Ga_{0.85}In_{0.15}As$ QWs separated by 50-nm GaAs barriers [26]. The active region was embedded between 2-μm $Al_{0.4}Ga_{0.60}As$ cladding layers in a 200-nm GaAs waveguide. The facets were as-cleaved, and the cavity length was 3 mm. Both unamplified spontaneous emission L from a window milled in the substrate contact and the emission from the laser facet were investigated as functions of the injected current at different temperatures. A detailed description of this technique was given elsewhere [25]. Using the value of the integrated spontaneous emission at the threshold current, which is proportional to the radiative recombination rate, we were able to measure the temperature variation of the radiative part of total threshold current density, $J_{\rm rad}$. These direct measurements allow us to estimate the relative contribution of radiative and nonradiative processes to $J_{\rm th}$ at different temperatures. The lasers were investigated in continuous wave (CW) mode and in a pulsed regime. The pulse duration and repetition rate were 500 ns and 10 kHz, respectively.

As an additional tool to study recombination and the loss mechanisms responsible for laser performance, we used high hydrostatic pressure. This has been previously used to investigate QW lasers [27], as well as in our previous study of 980-nm and 1.3-μm QD lasers [25]. Applying high pressure allows the energy $E_{\rm las}$ of the emitted photons to be varied, while keeping the basic properties of the band structure relatively unchanged. Various recombination mechanisms depend on $E_{\rm las}$ in different ways. For example, the radiative recombination contribution to the laser threshold current ideally increases with pressure as $E_{\rm las}^2$ in QW lasers [27], whereas the Auger recombination coefficient decreases [27], [28]. In conjunction with other techniques, these variations allow one to determine the relative importance of these recombination mechanisms. Measurements of the hydrostatic pressure dependence of $J_{\rm th}$, and the lasing photon energy $E_{\rm las}$, were carried out at room temperature using a piston and cylinder apparatus capable of generating pressures up to 1.5 GPa [25]. Using a specially designed holder with a laser clip, we studied for the first time the pressure dependence of the spontaneous emission from the QDs to determine the pressure variation of the radiative part of the threshold current density, $J_{\rm rad}$. To avoid internal heating, the high pressure measurements were carried out in the pulsed regime.

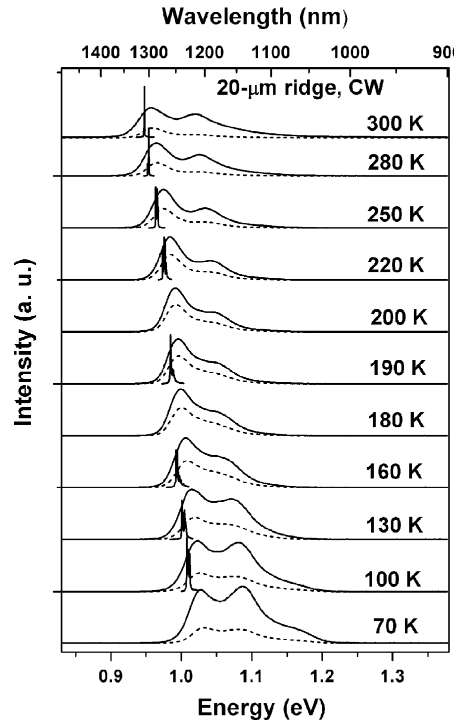

Fig. 2. CW spontaneous emission spectra at $J_{\rm th}$ (solid lines) and at constant current density of 8 A/cm^2 (or 8 A cm^{-2}), which is below $J_{\rm th}$ over this temperature range (dashed lines), and the lasing spectra just above $J_{\rm th}$ for the 20-μm ridge device as a function of temperature.

III. Experimental Results and Discussion

Due to optimized growth [26] and the decreased inhomogeneity of the dots, the lasing occured over a relatively narrow spectral region over the full temperature range investigated (5 meV at 100 K and 1 meV at 295 K). A detailed study of the emission spectra and mode structure of InAs–GaAs self-assembled QD lasers has been presented in [29]. The lasing line corresponded to the ground state emission at all temperatures with a wavelength of $\lambda = 1.31$ μm at room temperature, which matches very well the zero dispersion region of standard silica single-mode fiber.

Spontaneous emission spectra obtained both at lasing threshold and at a constant current density of 8 A/cm^2, which is always below $J_{\rm th}$, together with facet emission spectra just above $J_{\rm th}$ at different temperatures, are shown in Fig. 2.

The temperature dependence of the spontaneous emission spectra is similar to that previously observed in 1.3-μm QD lasers and discussed in detail elsewhere [25], [30]. The influence of the inhomogeneity of the dots was strong at temperatures below $T = 180$–200 K and led to the unusual behavior of the spontaneous emission spectra, where emission from the higher energy emission peaks decreased with increasing temperature. We observed several emission peaks in the spectra at low temperature. Their positions at $T = 70$ K were about 1.033, 1.082, and 1.165 eV. Taking into account that these bands were observable in the spectra even at very low current, we ascribed them to the ground state emission of dots with different particular sizes. However, with increasing current, the emission from the excited state of the bigger dots may also make a contribution that overlaps the ground state emission bands of the smaller dots. For instance, it was shown earlier that the energy separation between the ground state emission of big QDs and small QDs in InAs "dot-in-a-well" structures with 2.0–2.5 ml of InAs can be approximately the same as the difference between the ground and first excited state of the large dots [31].

As the temperature is lowered below 200 K, thermal reemission and transport between the dots is reduced, and the laser must be pumped harder to get the required carrier concentration in the ground state of the larger dots. The increased J_{th} leads to an increased emission from the ground state of smaller dots and also from the excited state of bigger dots.

The spontaneous emission spectra at constant current showed that the emission of the smaller dots, which was observable at low temperature, almost vanished with increasing temperature from $T = 70$ to $T = 200$ K, whereas the emission intensity from the ground state of the bigger dots increased by almost by a factor of 2. Therefore, the total integrated emission intensity remained almost constant, showing that there was no significant change in emission efficiency over this temperature range. This implies that nonradiative emission is likely to be small up to $T = 200$ K.

The temperature behavior of spontaneous emission spectra is also explained by the fact that with increasing temperature the coupling between the dots improves significantly and carriers recombine radiatively in the bigger dots, leading to the observed narrowing of the spontaneous emission spectra and to a decrease of J_{th} (discussed later). Above $T = 200$ K, as the threshold current increased, an increased emission from the excited state of the bigger dots was observed. Nevertheless, transitions from the smaller dots also may contribute to the spontaneous emission spectra, especially under higher injected current when lower energy states are filled.

Due to the increased emission from the excited state above 200 K, the integrated spontaneous emission at the threshold current remained almost constant with temperature as will be discussed later. However, a decrease of the total emission intensity at constant current took place above ~200 K, demonstrating a decrease of the internal radiative efficiency. We also observed some emission from the wetting layer in the spontaneous emission spectra at threshold at 300 K, albeit very small (the integrated area of this region was about 0.7% of the total integrated emission). Therefore, we conclude that the decrease of radiative efficiency must be caused by nonradiative recombination of carriers within the dots.

The integrated spontaneous emission L from the window versus current at different temperatures is shown in Fig. 3 by the dashed lines. The peak intensity of the ground state emission as a function of injected current, normalized to the value of L at the threshold current at each temperature, is plotted with solid lines. The integrated spontaneous emission pins better at higher temperatures. The pinning of the ground state emission is more

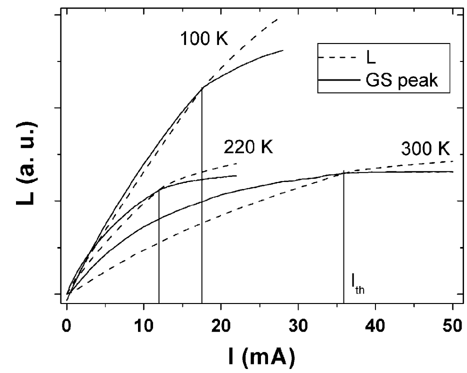

Fig. 3. Integrated spontaneous emission (dashed lines) and maximum intensity of the ground state peak (solid line) as a function of injected current at $T =$ 100 K, 220 K, and 300 K. The solid lines show the threshold current at each temperature.

complete than that of the total spontaneous emission at all temperatures. Above 250 K, the ground state spontaneous emission pins almost ideally, whereas the total spontaneous emission remains unpinned. This demonstrates that it is the emission from the excited states that leads to the poor pinning observed for the total integrated emission at high temperatures. In contrast, at low temperatures, the inhomogeneous carrier distribution results in a lack of pinning for both the total and ground state spontaneous emission. The fact that at all temperatures the total spontaneous emission pins less well than the ground state emission of the larger dots where lasing is occurring shows that thermalization to this ground state is being impeded. This could be due to localization of carriers in the smaller dots and/or due to phonon-bottleneck effects within the larger dots.

It is interesting to note that the integrated spontaneous emission just below threshold is proportional to the injected current at low temperature, indicating that the dominant recombination process is radiative. However, the dependence of L versus I becomes sublinear with increasing temperature, which shows that the dominant current path has a stronger n dependence than the radiative current. This is consistent with the onset of nonradiative Auger recombination, as has previously been observed in QW lasers [32].

Lasers with different ridge widths showed almost the same CW threshold current density of 40–50 A/cm^2 at $T = 295$ K, which is close to the record low values for 1.3-μm QD lasers [33]. Fig. 4 shows the temperature dependence of the threshold current density, J_{th}, and its radiative component, J_{rad}, measured in both the CW and pulse regimes. The characteristic temperatures of J_{th} measured between 270 K and 300 K were $T_0 = 50$–K and $T_0 = 83$ K for CW and pulsed modes, respectively. The faster increase of the threshold current and its radiative component for the CW regime above 270 K is caused by internal heating. Because the nonradiative component of the threshold current is decreasing very quickly with decreasing temperature from room temperature down to 200 K, the radiative current was normalized assuming at J_{th} it is totally radiative below 150 K. This assumption is supported by the close fit between the observed variations of J_{rad} and J_{th} below 150 K. Because J_{rad} cannot be larger than J_{th} at low temperature, this

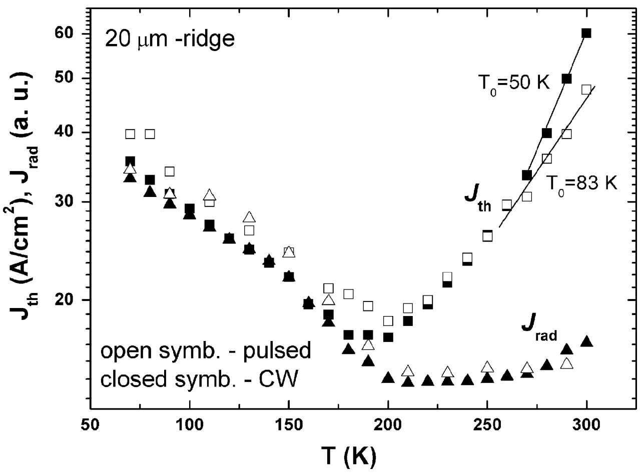

Fig. 4. Threshold current density and its radiative component versus temperature for the 20-μm ridge device for CW and pulsed measurements.

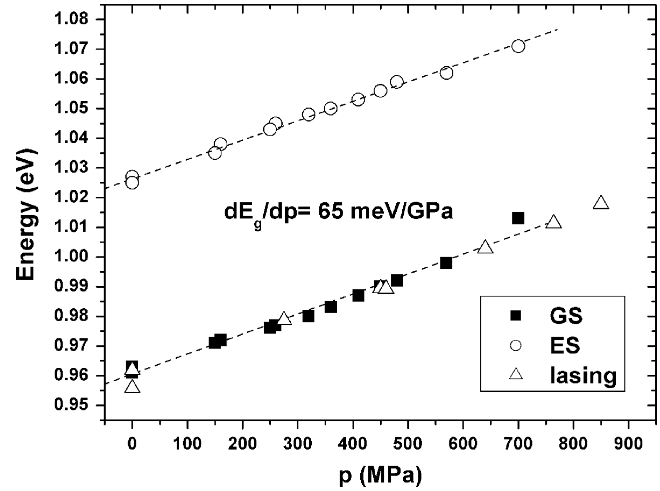

Fig. 5. The ground state and excited state spontaneous emission peaks, and lasing emission photon energy as a function of hydrostatic pressure.

assumption sets an upper limit to the value of $J_{\rm rad}$, even at high temperature. The decrease in $J_{\rm th}$ 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 as described previously, which allows carriers to contribute more effectively to the lasing process [25]. Above 200 K, $J_{\rm th}$ increases strongly, whereas $J_{\rm rad}$ remains almost temperature insensitive as originally predicted by Arakawa and Sakaki [1]. A small increase of $J_{\rm rad}$ can be explained by the fact that QD lasers are much more prone to gain saturation. It was shown earlier that the increasing effect of gain saturation with increasing temperature can lead to an increase of $J_{\rm rad}$ and sometimes to a transition from lasing from the ground state to lasing from an excited state [34].

From the $J_{\rm th}$ and $J_{\rm rad}$ data shown in Fig. 4, we see that at room temperature $J_{\rm rad}$ accounts for only $\sim$30% to 40% of $J_{\rm th}$ in these lasers. Therefore, the temperature sensitivity of the lasers must be due to a nonradiative recombination process.

For the first time, we measured both the threshold current density, $J_{\rm th}$, and its radiative part, $J_{\rm rad}$, as a function of hydrostatic pressure. This allowed us to vary the band gap of the structure at constant temperature, which gives additional information for the analysis of recombination and loss processes. The pressure dependencies of the ground state and excited state transitions and lasing photon energy, $E_{\rm las}$, are shown in Fig. 5. The lasing line and spontaneous emission peaks increase linearly with pressure with the same gradient of $dE/dP \sim 65$ meV/GPa. It was calculated earlier that the ground state and the continuum states (wetting layer states) have the same pressure variation [25]. Therefore, if there is some recombination process due to carrier escape into the wetting layer, it will not change with pressure.

The pressure dependencies of the normalized threshold current, $J_{\rm th}(P)/J_{\rm th}(0)$, and of the radiative current, $J_{\rm rad}(P)/J_{\rm rad}(0)$, for the 10-$\mu$m ridge laser are given in Fig. 6. $J_{\rm rad}$ was normalized to 30% of $J_{\rm th}$ at room temperature as we estimated from Fig. 4. The threshold current decreases with pressure by about 8% to $P = 1$ GPa. However, the radiative current, measured as the integrated spontaneous emission at $J_{\rm th}$,

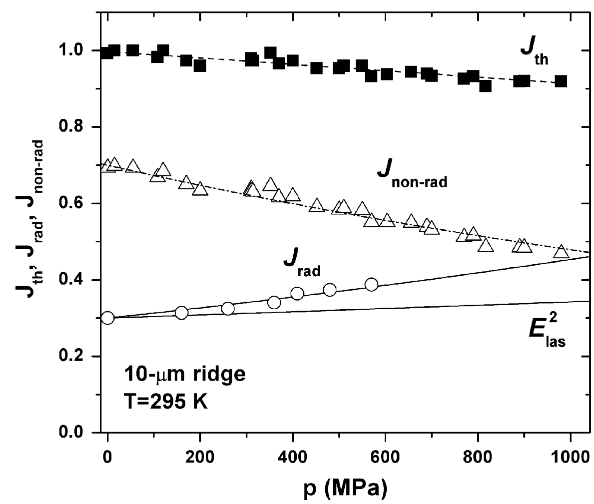

Fig. 6. Pressure dependencies of the threshold current density $J_{\rm th}(p)/J_{\rm th}(0)$ (squares) and of its radiative $J_{\rm rad}$ (circles) and nonradiative $J_{\rm non-rad}$ (triangles) components. $J_{\rm rad}$ was normalized to 30% of $J_{\rm th}$ at atmospheric pressure and fitted as a function of the band gap. The solid line is a fit of $J_{\rm rad}$, which gives $J_{\rm rad} \sim E_{\rm las}^6$ over this pressure range. The other solid line shows the ideal variation of $J_{\rm rad}$ for a QW laser with the same gradient $dE_{\rm las}/dP$, where it is proportional to the square of the lasing photon energy $[E_{\rm las}(p)/E_{\rm las}(0)]^2$. The dashed-dotted line is a fit of the difference $(J_{\rm th}–J_{\rm rad})$ due to Auger recombination, where $J_{\rm Aug} \sim E_{\rm las}^{-5.5}$.

strongly increases with increasing pressure. At $P = 0.6$ GPa, it is $\sim$30% larger than $J_{\rm rad}$ at atmospheric pressure. This indicates that the dominant recombination mechanism in these low-threshold devices is a nonradiative recombination process, which is strongly decreasing with increasing pressure. The presence of a significant nonradiative mechanism is consistent with the temperature dependence of the threshold current as discussed previously. Although the exact functional form of the variation of $J_{\rm rad}$ is unclear at present, from an empirical fit of $J_{\rm rad}$ as a power dependence of the band gap or lasing photon energy, $E_{\rm las}$, we find that $J_{\rm rad}$ increases approximately as $E_{\rm las}^6$ over this pressure range; thus, we can estimate the band gap dependence of the nonradiative component, $J_{\text{non-rad}}$, of the threshold current density. $J_{\rm non\text{-}rad}$ is also shown in Fig. 6 as a difference between $J_{\rm th}$ and $J_{\rm rad}$. The decrease of $J_{\rm non-rad}$ with pressure is consistent with a decrease in Auger recombination with increasing band gap as seen in QW lasers [27], [28].

It is interesting to note that $J_{\rm rad}$ increases with pressure much faster in QD lasers than predicted for the QW lasers, where $J_{\rm rad} \propto E_{\rm las}^2$ [27]. This is a complex subject that requires more detailed investigation that is outside the scope of this paper, where we take the increase in $J_{\rm rad}$ with pressure as an experimental fact.

The present results, in which pressure is used to increase the effective band gap of the QD laser, indicate that Auger recombination becomes weaker as the band gap is increased, and hence will be relatively insignificant in 980-nm devices, whereas the radiative current increases, and will be hence much larger in shorter wavelength devices. This latter effect may explain the higher $J_{\rm th}$ values generally obtained for 980-nm QD lasers (Fig. 1), despite the low Auger contribution to $J_{\rm th}$ at these wavelengths.

IV. Conclusion

We used spontaneous and stimulated emission measurements as a function of temperature and high hydrostatic pressure to analyze the recombination processes in low-threshold current density 1.3-μm QD lasers. The results show that the radiative component of the threshold current density, $J_{\rm rad}$, is relatively temperature insensitive around room temperature (RT), as originally suggested by Arakawa and Sakaki [1]. However, the temperature sensitivity of these lasers is caused by strong nonradiative recombination, which accounts for $\sim$60% to 70% of $J_{\rm th}$ at RT. The temperature and pressure dependence of this nonradiative process suggest that it is due to Auger recombination, which is very important in long wavelength QD lasers. The study of the band gap dependence of the radiative part of $J_{\rm th}$ showed that the strong increase in the radiative current density with decreasing wavelength also explains the higher current densities observed in 980-nm QD lasers, even though Auger recombination processes appear to be small at these wavelengths.

Acknowledgment

The authors gratefully acknowledge Dr. A. D. Andreev for helpful discussions.

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