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High-Performance Three-Layer 1.3-μm InAs–GaAs Quantum-Dot Lasers With Very Low Continuous-Wave Room-Temperature Threshold Currents

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***Abstract*—The combination of high-growth-temperature GaAs spacer layers and high-reflectivity (HR)-coated facets has been utilized to obtain low threshold currents and threshold current densities for 1.3-μm multilayer InAs–GaAs quantum-dot lasers. A very low continuous-wave (CW) room-temperature threshold current of 1.5 mA and a threshold current density of 18.8 A/cm^2 are achieved for a three-layer device with a 1-mm HR/HR cavity. For a 2-mm cavity, the CW threshold current density is as low as 17 A/cm^2 for an HR/HR device. An output power as high as 100 mW is obtained for a device with HR/cleaved facets.**

***Index Terms*—Epitaxial growth, quantum dots (QDs), semiconductor diodes, semiconductor lasers.**

RECENTLY, there has been significant progress in the development of 1.3-μm InAs–GaAs quantum dot (QD) lasers [1]. In particular, extremely low room-temperature (RT) threshold current densities $J_{\rm th}$ have been demonstrated for single-layer InAs–GaAs QD lasers operating near 1.3 μm. $J_{\rm th}$ values of 32.5 A/cm^2 [2] and 19 A/cm^2 [3] under continuous-wave (CW) operation have been reported for single-layer QD devices with as-cleaved and high-reflectivity (HR)-coated facets, respectively. However, the limited QD density in these single-layer devices requires the use of HR-coated facets [3] or very long cavity lengths (9.2 mm in [2]). In addition, their output power is also limited by the low QD density [3], with lasing switching from the ground state to the first excited state at high temperature and/or at high drive current, due to gain saturation of the ground-state transition [2]. To increase the effective QD density and, hence, provide additional gain, multilayer QD structures are required. However, unless the growth is carefully optimized, the structural and optical properties of the QDs in the second and subsequent layers are likely to be degraded [4], [5]. To obtain high-quality 1.3-μm-emitting multilayer structures, it has been found necessary to use relatively thick ($\gtrsim$40 nm) GaAs spacer layers [4] and to deposit these spacer layers at a relatively high temperature, referred to as a high growth temperature spacer layer (HGTSL) [5], [6]. Recently, we demonstrated that the use of an HGTSL, in which the initial 15-nm GaAs spacer layer is grown at the same temperature as the QDs but the final 35 nm is grown at an elevated temperature, significantly improves the performance of 1.3-μm multilayer InAs–GaAs QD lasers [6]. The HGTSL serves to reduce surface roughness, which in turn suppresses the formation of dislocated dots in the second and subsequent dot layers, resulting in improved interlayer dot uniformity [5]. By using HGTSLs, the RT $J_{\rm th}$ decreased by a factor of $\sim$5, and ground-state lasing up to 105 °C in as-cleaved devices was achieved [5], [6].

In the present letter, we demonstrate that the combination of HGTSLs and HR facet coatings results in an extremely low CW RT threshold current $(I_{\rm th})$ of 1.5 mA and a record low CW RT $J_{\rm th}$ of 17 A/cm^2 for 1.3-μm-emitting devices containing three QD layers. In addition, power in excess of 100 mW is obtained for a device with HR/cleaved facets.

The 1.3-μm-emitting InAs QD material was grown in a VG Semicon V90H solid-source MBE system on 3-in Si-doped GaAs (100) substrates. The laser active region consisted of three InAs–InGaAs dot-in-a-well (DWELL) structures [7], separated by 70-nm GaAs spacer layers. Each DWELL structure consisted of 3.0 monolayers of InAs grown on 2 nm of $\rm In_{0.15}Ga_{0.85}As$ and covered by 6 nm of $\rm In_{0.15}Ga_{0.85}As$. These dot and well parameters have been shown to optimize the optical properties and density of the InAs QDs [8]. Following the DWELL layers, the initial 15 nm of GaAs was deposited at 510 °C, after which the temperature was increased to 580 °C for the remaining 55 nm. This spacer layer growth is referred to as the HGTSL step [5], [6]. The active region was grown at the center of an undoped 150-nm GaAs–AlGaAs waveguide with n-type lower and p-type upper cladding layers consisting of 1.5-μm $\rm Al_{0.4}Ga_{0.6}As$ deposited at 620 °C. A 300-nm p$^+$-GaAs contact layer completed the growth. Atomic force microscopy (AFM) measurements were performed on uncapped reference samples in which the growth was halted after the formation of the QDs. A typical AFM image is shown in the inset of Fig. 1,

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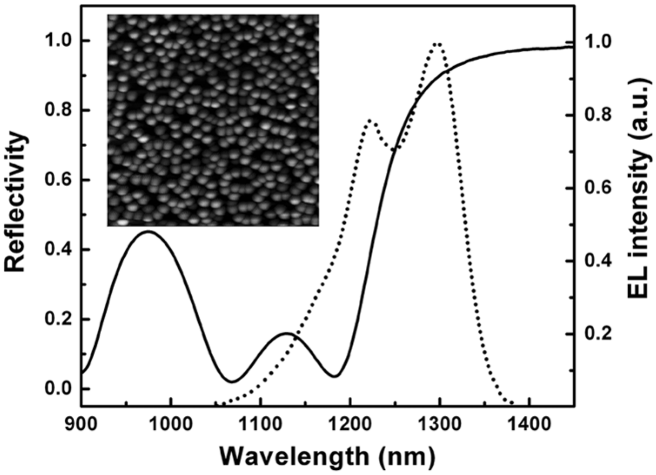

Fig. 1. Reflectivity of the Si–SiO$_2$ multilayer HR coatings and an RT EL spectrum of the laser structure. The inset shows a 1 × 1 μm AFM image of an uncapped reference sample.

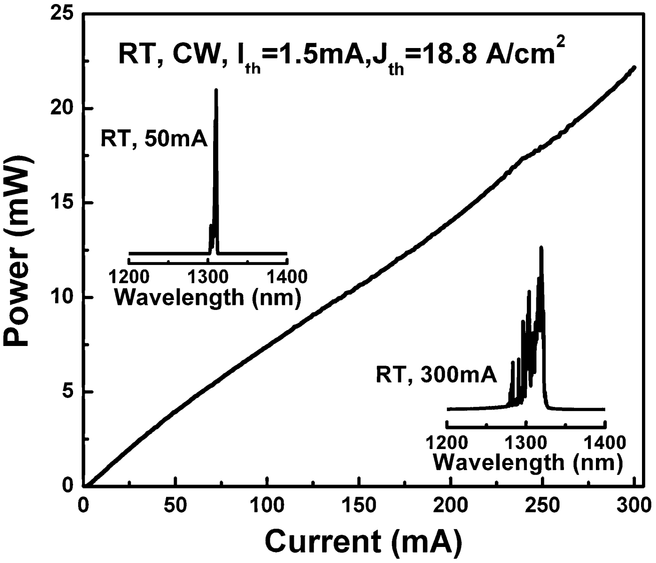

Fig. 2. Light versus current characteristic for RT CW operation of a 1 mm × 8 μm device with HR-coated facets. The insets show the lasing spectra with drive currents of 50 and 300 mA at RT.

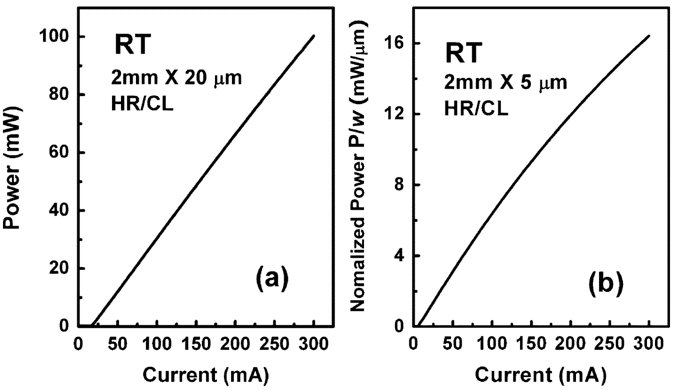

Fig. 3. (a) Light versus current characteristic for RT CW operation of a 2 mm × 20 μm device with an HR coating applied to the rear facet only (HR/CL). (b) Power normalized by device width for RT CW operation of a 2 mm × 5 μm HR/CL device.

from which a QD density of 4.3×10^{10} cm^{-2} is obtained. This relatively high dot density for 1.3-μm-emitting InAs–GaAs QDs is a result of the InGaAs strained buffer layer, which is present in the DWELL structure [8].

Shallow ridge waveguide lasers were fabricated by a SiCl$_4$ inductively coupled plasma technique, with etching below the p-doped AlGaAs cladding layer. HR facet coatings, consisting of multilayer Si–SiO$_2$, were applied to either both facets or only one facet. Cavity lengths of 1 and 2 mm were studied in the present work. The HR coating reflectivity and the RT electroluminescence (EL) spectrum of the laser are shown in Fig. 1. The reflectivity at 1.3 μm, corresponding to the QD ground-state emission, is ~90%, but falls to ~40% at 1.22 μm, corresponding to the first-excited-state emission. This reduced reflectivity at the first-excited-state transition is designed to increase the relative loss of this transition in comparison to that of the ground state, and hence, to suppress laser switching from the ground to first excited state with increasing drive current [9]. The lasers were characterized under CW conditions.

Fig. 2 shows the RT lasing characteristics of a 1-mm-long by 8-μm-wide device, with HR coatings applied to both facets. EL spectra of the device for drive currents of 50 and 300 mA are shown in the inset. The EL spectra indicate that at RT lasing occurs via the ground state around 1.31 μm with drive current up to 300 mA, which is about 200 times greater than $I_{\rm th}$ [9]. $I_{\rm th}$ has a very low value of 1.5 mA, which corresponds to a $J_{\rm th}$ of 18.8 A/cm^2. A maximum output power of ~22 mW (for both facets) is obtained for a current of 300 mA. To the best of our knowledge, the $I_{\rm th}$ of 1.5 mA is the lowest reported CW RT value for a ridge-waveguide QD laser. Lower RT CW $I_{\rm th}$ values of 1.2 [3] and 1.25 mA [10] have been only reported for narrower oxide-confined QD lasers with HR facet coatings. However, the maximum output powers achieved for these devices were very low, with values of 290 [3] and 350 μW [10]. The RT threshold current density can be reduced further by increasing the cavity length to 2 mm. For the present structure, an RT CW $J_{\rm th}$ of 17 A/cm^2 is obtained for a 2 mm × 8 μm device with HR coating applied to both facets. To the best of our knowledge, this is the lowest reported RT CW $J_{\rm th}$ for a QD laser or for any 1.3-μm-emitting laser. This extremely low $J_{\rm th}$ is a consequence of the use of the HGTSL step [6], which enhances the optical efficiency by preventing the formation of defective QDs in multilayer structures [5], and also reduces the internal loss (α_i) via the elimination of scattering centers [11].

The output powers are dramatically increased for devices with an HR coating applied to only one facet. Fig. 3(a) shows the RT CW output power as a function of current for a 2 mm × 20 μm device, with an HR coating applied only to the rear facet. The output power exceeds 100 mW for a current of 300 mA, with no evidence of power saturation and no lasing switching from the ground state to the first excited state at this current. The differential quantum efficiency is ~38%, and the RT $J_{\rm th}$ is 41 A/cm^2. For a better comparison of the output power of the present devices with previously reported values for QD lasers operating near 1.3 μm [1], the output power is normalized by dividing by the laser width (w). A maximum normalized power ($P_{\rm max}/w$) of 16.4 mW/μm is obtained for a 2 mm × 5 μm device at a drive current of 300 mA, as shown in Fig. 3(b). Both the maximum output power and maximum

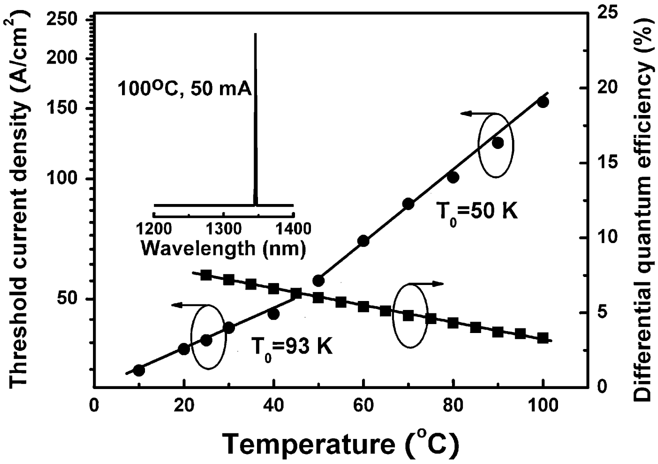

Fig. 4. Temperature dependence of the threshold current density and the differential quantum efficiency for CW operation of a 2 mm × 3 μm device with HR-coated facets. The inset shows the lasing spectrum at 100 °C.

normalized power obtained for the present devices are the highest reported to date for QD lasers operating above 1.3 μm at RT [1]. For comparison, the maximum power and normalized power for the low >1.3-μm QD lasers reported in [12] are 15 mW and 3 mW/μm, respectively. Although there have been a number of reports of very high power QD lasers, these are for broad area devices operating at wavelengths below 1.3 μm. For example, a maximum power of 2.7 W at a wavelength of 1.28 μm has been obtained for a 100-μm-width laser under CW operation, corresponding to a normalized power of 27 mW/μm [13].

The temperature dependences of the CW $J_{\rm th}$ and the differential quantum efficiency have been determined for a 2 mm × 3 μm device, with HR coating applied to both facets. Ground-state lasing is achieved up to 100 °C (the limit of our measurement system). The inset of Fig. 4 shows lasing occurring at 1.346 μm, at a temperature of 100 °C and a drive current of 50 mA. The main part of Fig. 4 shows the temperature dependence of the CW $J_{\rm th}$ and the differential quantum efficiency. The differential quantum efficiency has a linear dependence from 7.5 to 3.3% with increasing temperature from 25 °C to 100 °C. The characteristic temperature T_0 is 93 K over the range 10 °C–40 °C, decreasing to 50 K between 50 °C and 100 °C. It is found that the temperature stability of $J_{\rm th}$ is not significantly improved by the reduction of the nonradiative recombination centre density, achieved by the use of the HGTSLs [6], [1]. To improve the $J_{\rm th}$ stability of low-$J_{\rm th}$ multilayer QD lasers, ideally obtaining a temperature-independent $J_{\rm th}$ around and above RT [14], further growth modifications are required. For example, p-type modulation doping [12] and/or more DWELL layers [15] could be combined with the HGTSLs. Such studies will be reported in a future publication.

In summary, 1.3-μm-emitting InAs–GaAs QD laser devices consisting of three QD layers and combining the HGTSLs and HR-coated facets have been shown to exhibit excellent characteristics. A suitable choice of cavity dimensions and facet coatings yields devices which exhibit either an extremely low RT CW $I_{\rm th}$ of 1.5 mA, a record low RT CW $J_{\rm th}$ of 17 A/cm^2, CW ground-state lasing up to 100 °C with a T_0 of 93 K around RT, or an RT output power exceeding 100 mW. The combination of the HGTSLs, which optimize the structural and optical properties of the QDs, and HR-coated facets, which allow the device characteristics to be varied, allows the fabrication of high-performance multilayer 1.3-μm QD lasers with a number of characteristics suitable for telecommunications applications.

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