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High gain 1.55 μm diode lasers based on InAs quantum dot like active regions

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InP diode lasers with InAs quantum dot (QD) like active regions emitting at 1.55 μm have been fabricated. The QDs were grown in an As_2 mode, which reduces the degree of elongation of the nanospecies yielding nearly circular shapes. Lasers with four to six dot layers show low absorption $\alpha_i < 10\ cm^{-1}$ and high modal gain Γg_0 of $10\ cm^{-1}$ per QD layer (QDL) and above. The high gain values are compatible with an inhomogeneous linewidth that is much narrower than in quantum dash material, which is the common nanoscale gain material in the InP system. © *2011 American Institute of Physics*. [doi:10.1063/1.3590727]

InAs nanostructures based on self-organized growth are of great interest for basic as well as application-driven research. However, the self-organized nucleation of InAs on InP substrates is still not well understood. Thus, depending on the growth technique and recipe quantum dashes, wires, and dots have been reported.[1–3] This variety of nanospecies is thought to mainly stem from the lower lattice-mismatch of the InAs/InP system, which is roughly half the value of the InAs/GaAs system. Anisotropic effects on the surface, e.g., group III migration have therefore a considerably large impact on the nucleation of the structures.

Quantum dots (QDs) are favorable for diode lasers as the improved height/diameter aspect provides a deeper confinement of the charge carriers as compared to quantum dashes.[4,5] This renders the lasers more robust against thermal escape of charge carriers (improved characteristic temperature T_0) and leads to a symmetric gain function enabling almost chirp-free direct modulation.[5–7] Therefore, lasers based on InAs QDs are ideal candidates for high speed optical telecommunication in the 1.55 μm band. We recently reported on a growth process that stimulates the growth of QD like islands on InP(100) substrates by growing in an As_2 environment.[8] The process improved the homogeneity of the self-organized structures, which was observable by a reduced inhomogeneous linewidth broadening as compared to As_4-grown (quantum dash) structures. This letter deals with diode lasers in which such a tailored QD like material is used as active region.

All lasers presented in this letter are grown by means of all solid-source molecular beam epitaxy (MBE). N-doped InP(100) wafers were used as substrate. The epitaxial structure consists of 200 nm waveguide layers composed of $In_{0.528}Al_{0.238}Ga_{0.234}As$ in which the InAs QD layers (QDLs) are embedded. The cladding is formed by a 200 nm $In_{0.523}Al_{0.477}As$ layer, 200 nm InP buffer layer and the InP substrate on the n-side while 200 nm thick $In_{0.523}Al_{0.477}As$ and 1.7 μm InP layers are deposited for the p-cladding, respectively. A highly p-doped 200 nm thick $In_{.532}Ga_{.468}As$ layer serves as p-contact. Figure 1 contains a sketch of the conduction band edge of the laser structure.

All layers are lattice-matched to the InP substrate. Si and Be were used as dopant sources. The active QDLs consist of 4.5 monolayers InAs grown at 480 °C and are separated by 20 nm $In_{0.528}Al_{0.238}Ga_{0.234}As$ layers. As_2 and P_2 species were used throughout the whole growth process. Broad area (BA) lasers with 100 μm stripe widths were fabricated and characterized in pulsed mode using 500 ns pulses at a duty cycle of 0.03% and an ambient temperature of 20 °C. The facets were left as cleaved. Figure 2(a) depicts the output power versus drive current of a laser having 6 QDLs as active region. As can be seen in the inset of Fig. 2(b), a 0.8 mm long laser emits at 1565 nm. The emission shifts to longer wavelengths with increasing cavity length. A 1.0 mm long device emits at 1572 nm. The internal characteristics extracted from length-dependent threshold current density characteristics [shown in Fig. 2(b)] reveal a low internal absorption coefficient of $\alpha_i < 8\ cm^{-1}$. The modal gain was measured to be $60\ cm^{-1}$, which corresponds to $10\ cm^{-1}$ per dot layer. Total output powers of more than 440 mW (limited by the available drive current) were measured for a 0.6 mm long device.

A large difference between the transparency and threshold current densities is observed. This may be attributed to the large band gap of the InAlAs cladding acting as a blocking layer for the charge carriers, which may cause an additional carrier loss. This is consistent with the relatively low internal quantum efficiency (31%) exhibited by the laser, which has to be improved. A quantum well (QW) laser with three unstrained InGaAs QWs of 7 nm thickness was grown for comparison. While having a similar efficiency, the laser shows an absorption of $12\ cm^{-1}$. This effect can be explained by the reduced active volume and hence a lower confinement factor, of the QD lasers. Extrapolating from this argument, the absorption can be further lowered by using fewer QDLs. Hence, lasers with five and four layers were consequently grown. The evaluation is summarized in Table I.

FIG. 1. Sketch of the conduction band edge of the lasers.

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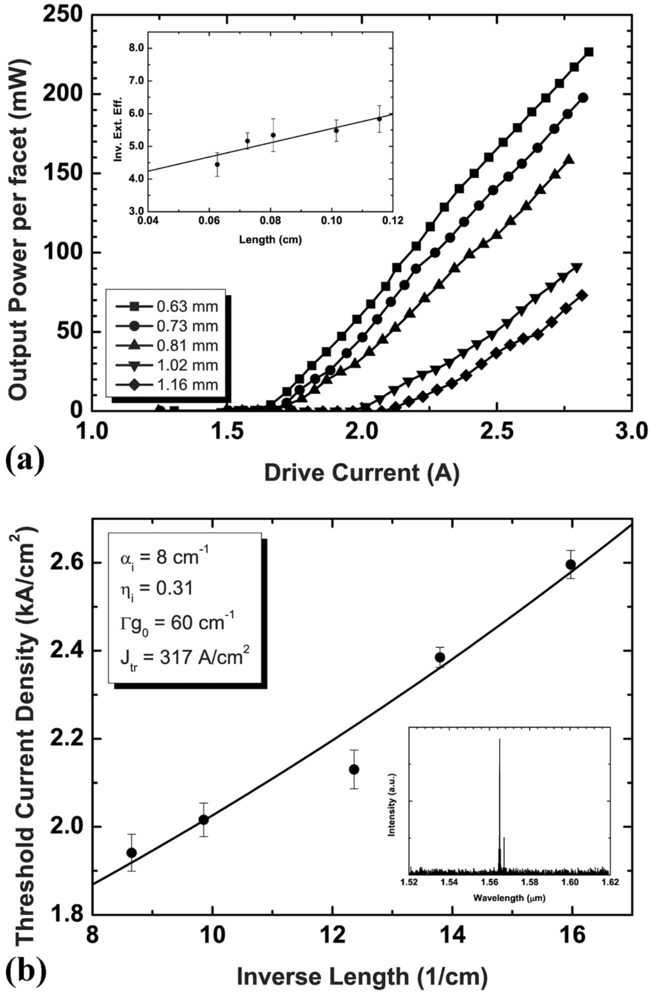

FIG. 2. (a) Plot of the output power vs drive current. The inset depicts the reciprocal external efficiency vs cavity length providing internal absorption and efficiency. (b) Length-dependent threshold current density for a laser with 6 QDLs. The inset in (b) shows the emission spectrum of a 0.8 mm long cavity being centered at 1565 nm. An absorption smaller than 10 cm^{-1} in combination with a high modal gain of 10 cm^{-1} per QDL were extracted. Note that output powers are given per facet.

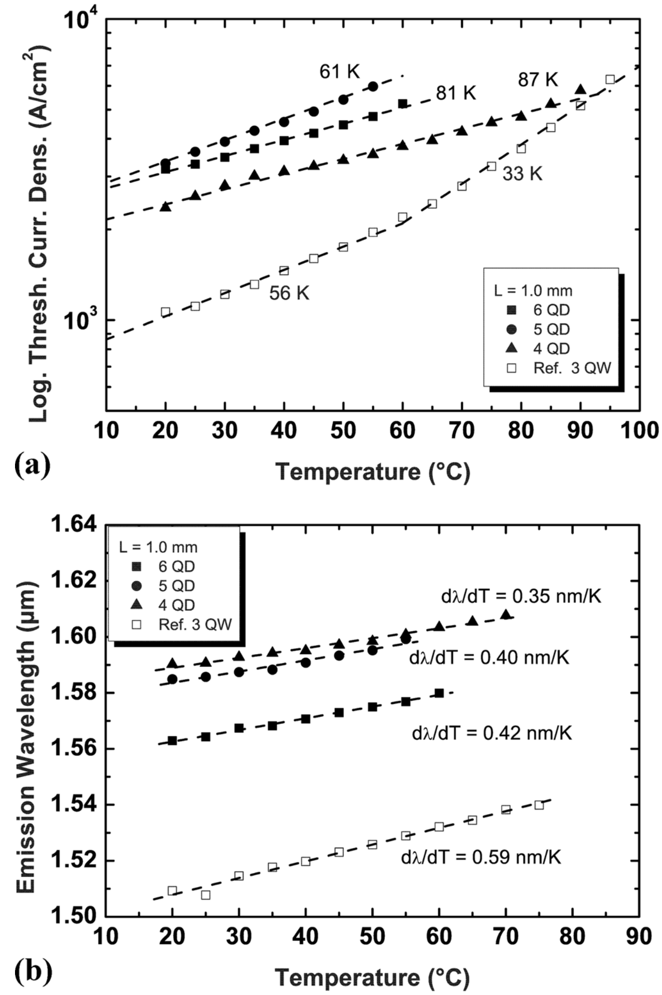

FIG. 3. Threshold current density (a) and emission wavelength (b) vs ambient temperature for the three QD lasers all having lengths of 1 mm. The dashed lines represent linear fits to the data. The inverse slope of the fits in (a) gives the characteristic temperature T_0. A constant T_0 value is observed over a broader temperature range for the QD lasers as compared to the reference QW laser.

As expected, transparency as well as threshold current density reduced significantly with a lower number of active layers. Even the laser with 6 QDLs shows a lower transparency current density than quantum dash lasers fabricated in this material system.[9] The high modal gain per dot layer of at least 10 cm^{-1} was reproduced in the 4 and 5 QDL lasers. This modal gain values are higher by at least a factor of 2 compared with quantum dash as well as QD gain media reported previously.[10–12] This indicates a higher level of homogeneity of the active ensembles leading to a higher spectral gain. Indeed, low-temperature photoluminescence of the present gain material reveals an inhomogeneous linewidth of only 33 meV. As reported earlier[8] such low linewidths are not achievable with typical quantum dash material. The use of As_2 has thus beneficial influence on the InAs dot nucleation, which in turn improves the laser performance.

TABLE I. Summary of the internal parameters of the grown QD BA lasers with 100 μm stripe width.

No. of QDL	J_{tr} (A/cm^2)	J_{tr}/QDL (A/cm^2)	η_i (%)	α_i (cm^{-1})	Γg_0 (cm^{-1})	Γg_0/QDL (cm^{-1})
6	317	53	31	8.0	60	10
5	248	50	24	10.6	75	15
4	155	39	26	4.0	41	10

Figure 3 depicts a comparison of the temperature behavior of all grown lasers. To overcome the limited drive current capabilities, lasers with 50 μm wide stripes and a cavity length of 1 mm were fabricated and used for the measurement of the characteristic temperature (T_0 parameter), although the cavity length is too short to obtain comparable low threshold current density values than a QW laser.[13] The maximum available drive current enabled the 6 QDL and 5 QDL lasers to only operate up to 55 °C and 60 °C, respectively. However, the 4 QDL laser could be measured up to 90 °C. The extracted characteristic temperature T_0 is 87 K, which is higher than that for QD lasers grown with InGaAsP barriers.[14] We mainly attribute this to the higher conduction band offset of the In(AlGa)As material system. Interestingly, the T_0 value stays at this level over the whole temperature range we used. The reference QW laser on the other hand has a lower threshold current density but showed the lowest thermal stability with a T_0 value of 56 K. It also suffers a severe breakdown in the regime above 60 °C. No such breakdown

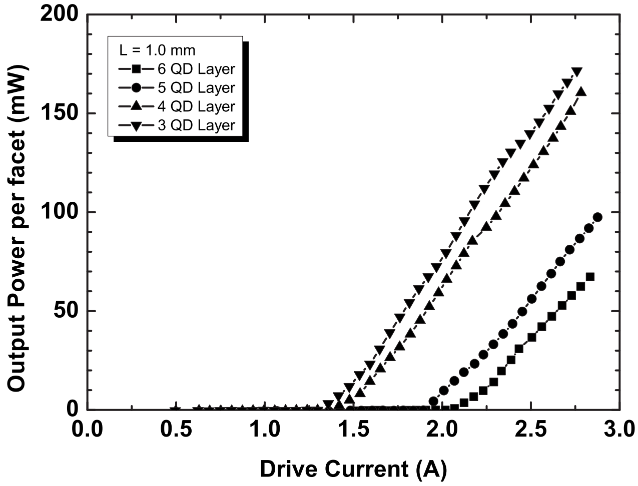

FIG. 4. Output power vs drive current characteristics for 1.0 mm long and 100 μm wide BA lasers having different numbers of QDLs.

was observed in any of the QD lasers. Due to the much higher T_0 value of the 4 QDL laser, the threshold current density at 90 °C is the same as for the QW laser.

The temperature behavior of the QD lasers is consistent with the improved charge confinement in the active material. QD lasers operating at shorter wavelengths also exhibited kink-free threshold current densities over a much broader temperature range than comparable QW lasers.[15] An explanation of this effect is not straight forward and is still under investigation.

The variation in the emission wavelength with increasing temperature $d\lambda/dT$ is shown in Fig. 3(b) for the various lasers. $d\lambda/dT$ is found to be lower in the QD lasers than in the reference QW laser. Nevertheless, values of 0.42 nm/K for the 6 QDL laser and 0.40 nm/K for the 5 QDL laser, respectively, are much higher than generally expected for QD lasers.[1] The lowest value was achieved with the 4 QDL laser (0.35 nm/K). Hence, the wavelength shift with temperature is dominated by the bandgap shrink of the active material. This indicates that under normal lasing conditions no significant saturation of the fundamental transition in the QD ensembles occurs. Higher order transitions that would induce a wavelength-stabilizing blueshift and thus lead to almost vanishing values of $d\lambda/dT$ seem to play a minor role under normal operation conditions.[16,17] Therefore, the temperature behavior is an indication for a high density of states at the lasing wavelength and is consistent with the observed high spectral gain. The high gain enabled even lasing with only 3 QDLs as can be seen in Fig. 4.

In summary, we have demonstrated 1.5 μm laser diodes with QD like active regions grown by MBE. The lasers combine a moderately low absorption and very high modal gain. We mainly attribute these results to the higher level of homogeneity of this type of active laser material that leads to a narrower inhomogeneous linewidth and higher spectral gain as compared to the more common quantum dash active regions. Although further improvement in the layer design are necessary to obtain higher quantum efficiency, this class of high gain QD material should allow to fully compete with basic QW laser performance, e.g., to enable short cavity and high speed active region designs with only a few QDLs but with additional dotlike features like low alpha factor and reduced temperature sensitivity in threshold and efficiency. Therefore, this laser material would be very appropriate for next generation low-cost high speed communication lasers.

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