Enhanced thermal stability of laser diodes with shape-engineered quantum dot medium

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Optical properties of the quantum dots (QDs) were optimized by shape engineering through the adjustment of the thickness of the GaAs overlayer prior to an additional heating step leading to QD truncation. QDs with a 6-nm-thick overlayer with the subsequent heating step were found to have the highest photoluminescence intensity at room temperature and the lowest luminescence bandwidth, 29 meV. 1.22 μm edge-emitting laser with a triple-layer truncated QD gain medium demonstrated room temperature threshold current density, 56 A/cm^2, and saturated modal gain, 16 cm^{-1}. An extremely high characteristic temperature for lasing threshold, $T_0 = 380$ K up to 55 °C, and a maximum ground state lasing temperature of 219 °C were measured for these laser diodes.
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Growing interest in InAs quantum dot (QD) laser medium is mainly due to superior performance parameters of laser diodes (both predicted[1] and partially achieved)[2,3] and the possibility to fabricate long-wavelength lasers on GaAs. However, an InAs/GaAs QD medium still has relatively poor thermal stability and low gain as compared to quantum wells, the latter preventing QDs to be employed in vertical cavity surface emitting lasers with epitaxial distributed Bragg reflectors. Ground state QD laser diodes with the highest thermal stability reported so far have demonstrated an operation temperature up to 167 °C and a characteristic temperature for threshold current of 160 K.[4] The structures used employed modulation p-type doping to increase occupancy of the QD valence states, but this was accompanied by a significant increase of intrinsic losses.

There are relatively few studies focused on the effect of the QD capping layer[5–9] and on the development of QD overgrowth procedures,[10,11] which are responsible for QD shape. Theoretical studies of correlation between QD size, shape, and electronic structure, such as ground and excited state energies are available[12,13] and might be used to improve QD properties. For example, it is anticipated that the QD gain should increase significantly with the shape modification to a more symmetrical than typical pyramidal shape.[14] It was proven experimentally that a QD laser with a large ground-to-first-excited-state energy separation demonstrated improved thermal stability.[15] All these facts stimulate the research on effective methods of QD shape management.

As was proposed by Wasilewsky *et al.*,[10] the optical properties of InAs QDs can be significantly altered by fast heating (flashing) of partially overgrown dots. In this letter, we developed an InAs QD overgrowth procedure with an additional AlAs capping layer and modified truncation. As a result, a laser diode with a truncated QD medium demonstrated a superior temperature stability close or even better than quantum well lasers, making the shape-engineered QD medium a true competitor to QWs.

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The InAs QDs were grown in the EPI MOD GEN II molecular beam epitaxy system. Details of the growth procedure and layout of the heterostructures are described elsewhere.[16] The self-assembled InAs QDs were embedded into $(AlAs)_{2\,ML}/(GaAs)_{8\,ML}$ (ML denotes monolayer) short-period superlattice (SPSL) barriers with a 25-ML-thick GaAs overlayer on top of the QDs. At first, a 2.3 ML InAs QD layer was deposited at 0.05 ML/s growth rate at 460 °C onto the GaAs surface and capped with 2 ML AlAs. The second step involved the overgrowth of QDs by GaAs and/or SPSL with various thicknesses, $d_{OL} = 4$–16 nm. The third step included growth interruption and substrate heating up to 580 °C for QD truncation. This step resulted in a modification of the QD shape by removing In from the top of the InAs pyramids. The growth procedure for nontruncated samples did not contain the third step, and those QDs were overgrown without interruption. The forth and final step was the overgrowth of the QDs by GaAs and/or SPSL. This growth procedure provides the QD ensemble with relatively high QD density of 4×10^{10} cm^{-2} as reported earlier.[16]

The laser diode structures were grown on n-type GaAs substrates. 1-μm-thick n- and p-type $Al_{0.7}Ga_{0.3}As$ cladding layers were grown before and after an undoped 400 nm SPSL waveguide with the QD active layers in the middle. The laser active medium contained triple QD stack with 30 nm of SPSL barrier between the QD sheets.

Transmission electron microscopy (TEM) cross-sectional imaging of QD samples was carried out using a 200 keV JEOL-2010FEG microscope. Photoluminescence (PL) spectra of the QDs were excited using an Ar^+ laser (514 nm) and detected by a cooled Ge p-i-n photodiode. Simple gain-guided lasers with 50–200 μm wide stripe contacts and cavity lengths up to 8.5 mm were fabricated. No coatings were applied to the cleaved facets.

Figure 1 shows TEM micrographs of a triple-layer QD structure grown according to the procedure outlined before. The images were taken in dark-field two-beam conditions with diffraction vector (002), providing a strong chemical contrast in zinc blende crystal structures. AlAs layers appear brighter than GaAs in the images, and InAs is darker due to

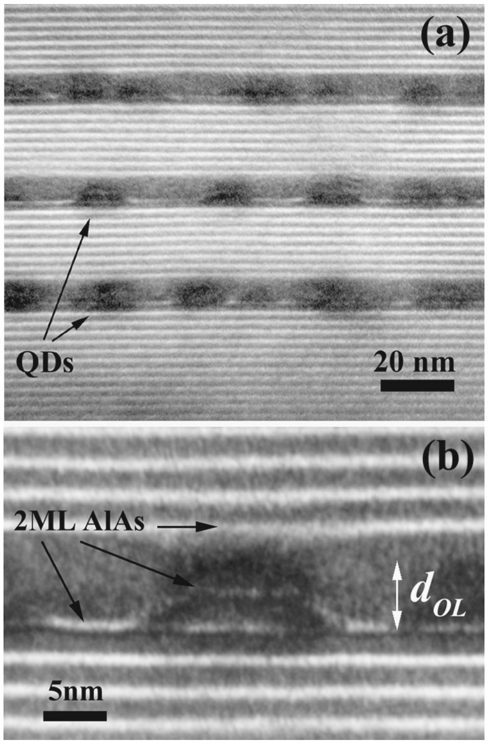

FIG. 1. Dark-field ($g=002$) TEM micrographs of a triple-layer quantum dot structure: (a) QDs in GaAs quantum wells imbedded into short-period superlattice and (b) magnified image of a single QD showing 2-ML-thick AlAs capping layer on top of the QD.

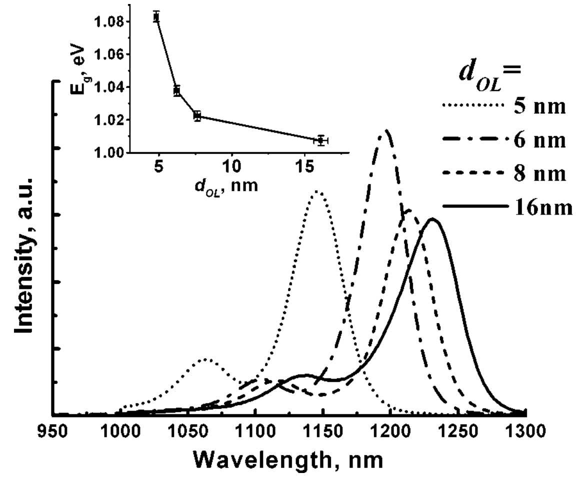

FIG. 2. Room temperature PL spectra of 2.3 ML InAs truncated QDs as a function of d_{OL}, i.e., the overlayer thickness prior to the truncation step. Inset: PL ground state transition energy of QDs vs d_{OL}. Δ_{exc} equals 89–93 meV in the samples with $d_{OL}=5-8$ nm, and is 82 meV in the sample with $d_{OL}=16$ nm.

strong high-angle scattering. Just after formation of the QDs, they have been capped by a 2-ML-thick AlAs layer, which is visible between the dots, and also on top of the QDs [Fig. 1(b)]. The employed growth procedure results in a truncated pyramidal shape of QDs with a flat top entirely covered by a 2-ML-thick AlAs layer even though the partially overgrown dots were subjected to the heating step. It is important to note that a thin InAs wetting layer is clearly visible as a darker band between the QDs and is not entirely dissolved by AlAs capping as concluded in Ref. 8.

Optical properties of the self-assembled QDs were characterized at room temperature at excitation intensity, 70 W/cm^2. PL studies were employed to design a QD ensemble with better efficiency at high excitation levels, narrow PL band, and larger ground-to-first-excited-state energy separation (Δ_{exc}). Total overlayer thickness prior to the truncation step, d_{OL}, is found to affect significantly the electronic spectrum of the QDs as shown in Fig. 2. The sample with $d_{OL}=16$ nm can be considered as nontruncated because the overlayer is significantly thicker than the average height of QDs.[16] The ground state transition energy dependence on d_{OL} is plotted in the inset of Fig. 2. This dependence is strong at low thickness, $d_{OL}<7$ nm, below the height of the dots, and saturates at larger thicknesses.

As theoretically estimated by Kim *et al.*,[12] the ground state energy is mainly determined by QD volume, but Δ_{exc} depends strongly on the QD lateral size. Therefore, the observed change in the QD ground state energy is due to the truncated pyramidal shape of the QDs as shown in Fig. 1, which results in the reduction of the QD volume at small d_{OL}. It is quite remarkable that the truncated QDs with $d_{OL}=6$ nm have shown almost 30% higher PL peak intensity and the lowest PL full width at half maximum (FWHM), 29 meV. PL band narrowing may be explained by stabilization of the QD volume when the overlayer thickness (6 nm) matches the average height of the InAs QDs and excess InAs is removed from the larger dots. The highest PL intensity of this sample may indicate either an increased overlap integral of the electron and hole wave functions due to QD shape change[14] or reduced evaporation of the excitations from the dots to the barrier or wetting layer. It is worth noting that the Δ_{exc} and, therefore, QD lateral size[12] are not affected significantly by the d_{OL} thickness. High Δ_{exc} values (up to 108 meV) have been obtained recently using the InAlAs capping layer[9] and are reported to be due to a stronger blueshift effect of potential barrier height on the first-excited-state energy than the ground-state energy. These results indicate a possible path to further enhancement of the QD thermal stability.

The developed triple-layer QD shape-engineered structure with $d_{OL}=6$ nm was tested in laser diodes, and compared with a nontruncated QD medium (Table I). Electroluminescence measurements were carried out under pulsed excitation with 1 μs pulse width and 0.5% duty cycle. Both lasers demonstrated a similar ground state threshold current density, J_{th}, for the longest, 5–9 mm, cavities with cleaved

TABLE I. Parameters of laser diodes with truncated and nontruncated QD media.

QD Laser diode	Lasing wavelength (μm)	Minimum threshold current density (A/cm^2)	Minimum cavity length (mm)	Saturated modal gain (cm^{-1})	Maximum lasing temperature (°C)	T_0 at room temperature (K)
Truncated	1.22	56	0.87	16	219	380
Nontruncated	1.23	78	1.73	9	130	85

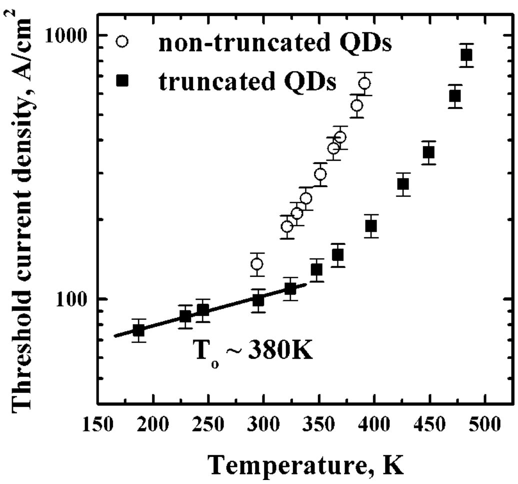

FIG. 3. Temperature dependence of the threshold current density for non-truncated QD 6.8×0.2 mm^2 laser diode (open circles), and truncated QD 5.15×0.2 mm^2 laser diode (solid squares) with $T_0\sim380$ K between 187 and 324 K.

mirrors: about 110 A/cm^2 for nontruncated QDs and about 90 A/cm^2 for truncated QDs. Minimum J_{th} (shown in the Table I) was measured in four-facet cleaved 400×400 μm^2 lasers. The saturated gain values were estimated from the minimum cavity lengths for lasing using intrinsic losses of 1.8 cm^{-1} that were measured in the case of the QW laser diodes with the same layer compositions and waveguide thickness, 0.4 μm. Increased material gain of the truncated QD medium agrees with the enhanced PL intensity of these QDs outlined earlier.

Thermal quenching curves of the threshold current density for truncated and nontruncated QD lasers are plotted in Fig. 3. The maximum operating temperature of truncated QD lasers was found to decrease with the cavity length, L, and reached 219, 210, and 197 °C for $L=7.5$, 5.15, and 2.9 mm, respectively, that significantly exceeded the highest reported value for InAs QD lasers.[4] The main reason for the higher thermal stability of truncated QD lasers is a higher saturated modal gain. The truncated QD laser has demonstrated extremely high thermal stability with a characteristic temperature for threshold current, $T_0=380$ K from -100 up to $+55$ °C. This value is the highest reported value for QD lasers.

Figure 4 shows power-current curves and lasing spectra of a truncated QD laser at different temperatures. Thermal shift of the laser wavelength is close to linear 0.41 nm/K in a wide temperature range [Fig. 4(a)]. Power-current characteristics [Fig. 4(b)] show a noticeable decrease of the differential efficiency only above 136 °C, and the laser has a reasonably steep lasing slope even at 200 °C.

In summary, we have developed a method for QD shape engineering via the overgrowth procedure. The triple-layer QD edge-emitting laser diode was fabricated using the truncated QD gain medium and showed 1.22 μm lasing with extremely high characteristic temperature, $T_0=380$ K in the 180–330 K interval was measured for this laser.

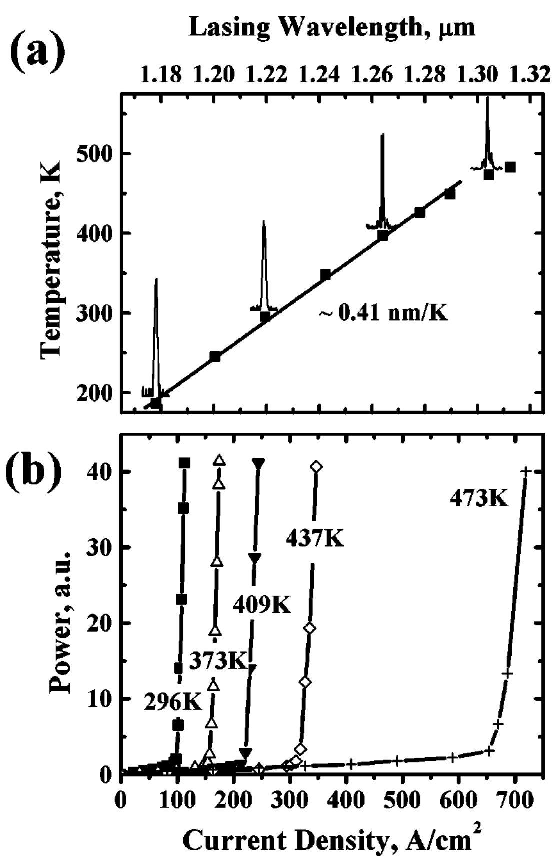

FIG. 4. Truncated QD laser characteristics as a function of temperature: (a) ground state lasing wavelength and corresponding spectra and (b) power-current characteristics at pulse excitation for 5.15×0.2 mm^2 laser diode.

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