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p-doped 1.3 μm InAs/GaAs quantum-dot laser with a low threshold current density and high differential efficiency

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A modification of the thickness of the low-growth-temperature component of the GaAs spacer layers in multilayer 1.3 μm InAs/GaAs quantum-dot (QD) lasers has been used to significantly improve device performance. For a *p*-doped seven-layer device, a reduction in the thickness of this component from 15 to 2 nm results in a reduced reverse bias leakage current and an increase in the intensity of the spontaneous emission. In addition, a significant reduction of the threshold current density and an increase of the external differential efficiency at room temperature are obtained. These improvements indicate a reduced defect density, most probably a combination of the selective elimination of a very low density of dislocated dots and a smaller number of defects in the thinner low-growth-temperature component of the GaAs spacer layer. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2336998]

p-type modulation doped 1.3 μm In(Ga)As/GaAs quantum-dot (QD) lasers have attracted considerable recent attention, a result of their highly temperature stable threshold current density J_{th} around room temperature (RT).[1] For example, a temperature-independent J_{th}, i.e., a characteristic temperature $T_0=\infty$, has been demonstrated for a 1.3 μm InAs/GaAs QD laser between 5 and 75 °C.[2] However, *p*-type modulation doping of the QDs has the undesired side effects of increasing the absolute value of J_{th} and decreasing the differential efficiency η_d.[1,2]

Recently, we have investigated the effects of the growth temperature used for the GaAs spacer layers (SPLs), placed between the QD layers, on the performance of 1.3 μm multilayer InAs/GaAs QD lasers. It was found that the incorporation of a high-growth-temperature spacer layer (HGTSL) inhibits dislocation formation, resulting in a dramatically improved device performance.[3] With this approach, an extremely low RT continuous-wave J_{th} of 17 A/cm^2 has been achieved for a three-layer QD device.[4] In the present work, the HGTSL technique is used to improve the performance of *p*-type modulation doped multilayer 1.3 μm InAs/GaAs QD lasers. By engineering the thickness of the low-growth-temperature (LGT) component of the GaAs SPL, which is deposited at the same temperature (510 °C) as the InAs QDs, a very low RT J_{th} of 33 A/cm^2 and a high η_d are achieved for a seven-layer QD laser device.

The InAs/GaAs QD laser structures were grown by molecular beam epitaxy on Si-doped GaAs (100) substrates. Each dot layer consisted of 3 ML of InAs grown on 2 nm $In_{0.15}Ga_{0.85}As$ and covered with 6 nm $In_{0.15}Ga_{0.85}As$ to give a dot-in-a-well (DWELL) structure.[5,6] All of the DWELL materials were deposited at a temperature of 510 °C. Laser devices consisted of seven DWELLs separated by 50 nm GaAs SPLs. The active region was grown at the center of an undoped 150 nm GaAs/AlGaAs waveguide with 1.5 μm $Al_{0.4}Ga_{0.6}As$ *n*-type lower and *p*-type upper cladding layers. A 300 nm p^+-GaAs contact layer completed the growth. *p*-type modulation doping of the QDs was provided by a Be doped layer of width of 6 nm placed 9 nm before each DWELL. The doped region was grown at 510 °C and gives a doping level of 12 acceptors per dot. Two structures were grown to study the effect of different thicknesses of LGT GaAs SPL. For sample A, following each DWELL, the initial 15 nm of the GaAs SPL was deposited at the same temperature as used for the DWELL at 510 °C. This is referred to as the LGT component of the SPL. Following this, the temperature was increased to 580 °C for the next 20 nm of the SPL. This increased temperature growth is referred to as the HGTSL.[3] Next the growth temperature was reduced back to 510 °C for the remaining 15 nm of the SPL, including the doped region, and the next DWELL. For sample B, the thickness of the LGT component of the GaAs SPL was reduced to 2 nm, with the high temperature component increased to 33 nm to maintain a constant total SPL thickness. The wafers were fabricated into uncoated-facet ridge laser devices, with a ridge width of 15 μm, and optical access mesas for spontaneous emission measurements and current-voltage characterization. Laser device characteristics were measured in pulsed mode using 10 μs pulses with a 0.1% duty cycle.

Lasing spectra recorded at 100 °C for 3 mm long cavity devices are shown in the inset of Fig. 1. Lasing occurs via the ground state at wavelengths of 1.35 and 1.29 μm for samples A and B, respectively. The difference in wavelength indicates that the size of the QDs is decreased when the thickness of the LGT GaAs SPL is reduced in sample B. The

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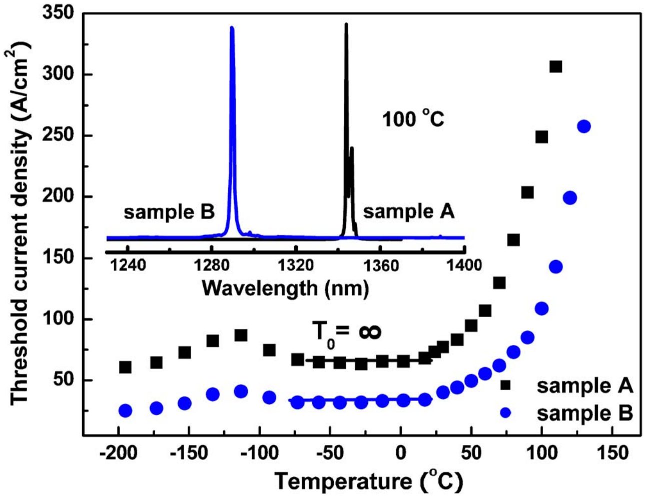

FIG. 1. (Color online) Temperature variation of the threshold current density for seven-layer *p*-doped QD laser devices with a LGT GaAs spacer layer thicknesses of 15 nm (sample A) and 2 nm (sample B). The cavity lengths are 3 mm. The inset shows lasing spectra at 100 °C.

main part of Fig. 1 compares the temperature dependence of J_{th}. The J_{th} values of sample B are very low and are significantly smaller than those of sample A for all temperatures. At RT and 100 °C, J_{th} for sample B is 33 and 108 A/cm^2, respectively. In contrast, values for sample A are 65 and 248 A/cm^2, respectively. Of particular note is that the RT J_{th} for sample B is significantly lower than the values previously reported for *p*-doped 1.3 μm QD lasers.[1,2] For both devices, the *p*-type modulation doping of the QDs results in a temperature-independent $J_{th}(T_0=\infty)$ over the temperature range of −75 to 20 °C.

The reduction of the thickness of the LGT component of GaAs SPL also results in a dramatic improvement in the RT value of η_d from 26% to 62% for a device with 3 mm cavity length. A value of 85% is obtained for sample B and a 2 mm cavity length device. These values are significantly better than previously reported values for *p*-doped 1.3 μm QD lasers,[1] and are comparable to values obtained for multilayer undoped 1.3 μm InAs/GaAs QD lasers, for example, 84% and 88% for five- and ten-QD-layer devices, respectively.[7]

In order to further understand the effects of reducing the thickness of the LGT GaAs SPL on the laser characteristics shown in Fig. 1, the optical and electronic properties of the two devices were studied in detail. Spontaneous electroluminescence (EL) spectra at RT and for different injection currents are compared in Fig. 2. The full widths at half maximum for the two samples are essentially identical at about 26 meV, indicating that reducing the thickness of the LGT component of the SPL does not affect the size distribution of the QDs. The RT emission occurs at 1.31 and 1.28 μm for samples A and B, respectively. The EL intensity of sample B is a factor of 4.3 and 1.7 more intense than that of sample A for injection currents of 0.1 and 1 mA, respectively. This behavior is consistent with a higher density of nonradiative centers in sample A, with these centers becoming saturated at high injection currents.[3,8] In addition, RT current-voltage measurements, as shown in Fig. 3, indicate a reverse bias leakage current for sample B which is approximately one order of magnitude lower than that of sample A over the bias range of 2 to 22 V. This difference suggests that defects causing the nonradiative centers in sample A also act as current leakage paths.[3]

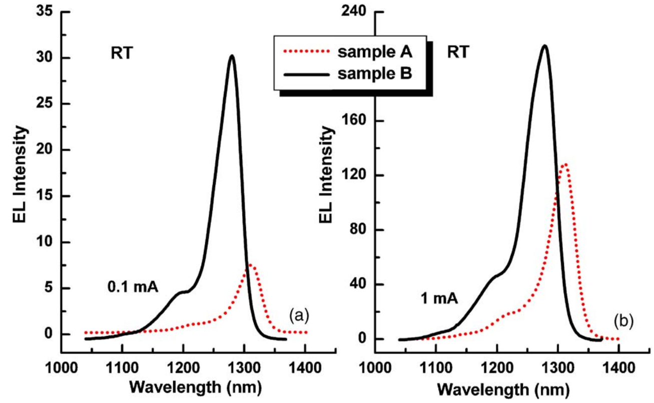

FIG. 2. (Color online) Room-temperature spontaneous electroluminescence spectra of samples A and B.

Cross-sectional transmission electron microscopy (TEM) images of the two samples were recorded to compare the structural properties of the QDs. These images reveal that the dot density is similar for both samples but that the height of the dots in sample B is smaller, consistent with the shorter wavelength lasing and spontaneous emission for this sample (Figs. 1 and 2). A TEM image of sample B is shown in the inset of Fig. 3. No defective dots are observed in a number of similar TEM images recorded for both samples, consistent with a very low density of defective dots which, if present, are below the level detectable by the present technique.

InAs QDs emitting at 1.3 μm are close to the critical limit for the nucleation of dislocations[9] and it is possible that some defective dots may be present. Previously an *in situ* defect-reduction technique has been developed to selectively eliminate dislocated dots by annealing InAs QDs capped with a very thin layer.[7,10–12] To further investigate the possible formation of precapped defective dots in the present structures, large area atomic force microscopy (AFM) scans were recorded for uncapped QDs. The resultant images [Fig. 4(a)] reveal two types of dots: (i) relatively large, irregular shaped dots with a very low density $\sim 1\times 10^6$ cm^{-2}, and (ii) small, regular shaped dots with a high density

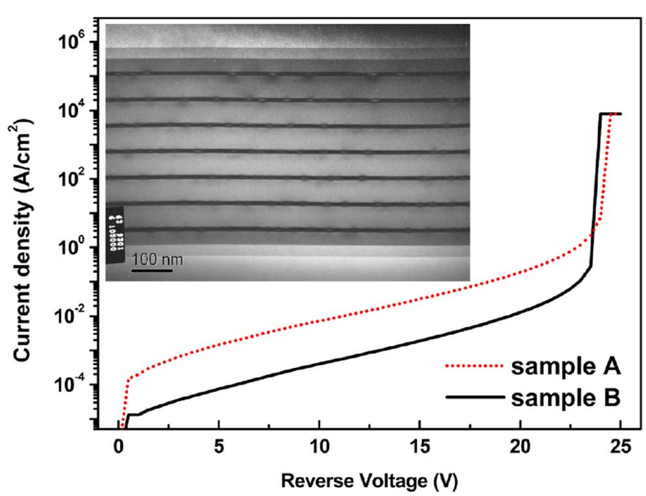

FIG. 3. (Color online) Room-temperature reverse bias current-voltage characteristics for samples A and B. The inset shows a cross-sectional TEM image of sample B.

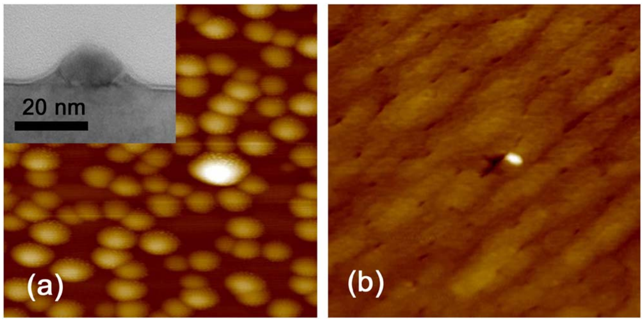

FIG. 4. (Color online) (a) 500×500 nm^2 AFM image of uncapped QDs. (b) 500×500 nm^2 AFM image of InAs dots capped with 6 nm of InGaAs followed by 2 nm of GaAs. The inset to (a) shows a cross-sectional TEM image of a large InAs island with dislocations formed near the edges.

$\sim 4 \times 10^{10}$ cm^{-2}. Large irregular shaped QDs have been observed previously in similar structures.[9] Cross-sectional TEM images of the type of large dots indicate the presence of dislocations around their edges, as shown in the inset of Fig. 4(a). In contrast, the smaller QDs are found to be coherent.

AFM images were also recorded for InAs QDs capped with 6 nm of InGaAs and 2 nm of LGT GaAs, identical to that used in sample B before the HGTSL is deposited. A typical AFM image is shown in Fig. 4(b) and exhibits a high density of small holes and a very low density of islands. These holes and islands represent the evolution of the coherent and defective InAs QDs during overgrowth by the thin cap layers.[13–15] When the growth temperature is increased to 580 °C for the HGTSL, In atoms within the defective QDs may be fully evaporated because they are only partly covered,[10,11] while the covered coherent dots are retained. This would result in the selective removal of the large defective QDs. In sample A the thicker LGT GaAs cap is likely to also cover the defective dots, preventing their removal during initial growth of the HGTSL.

The selective removal of a low density of defective dots may result in the improved device performance observed for sample B (see Fig. 1).[7,12] Although at high temperatures where interdot carrier transport is possible, a low density of defective dots can significantly affect device performance, at low temperatures where carriers remain in the dot into which they are initially captured, a low density of defective dots would appear to have less effect. Therefore, the significantly reduced J_{th} at low temperature (<200 K) could not be understood just by reducing the density of defected islands. It is possible that the growth temperature used for the LGT GaAs SPL, which is significantly below the optimum value, may introduce additional defects,[6] which would be present with a larger number in sample A which has a thicker LGT SPL. In addition, it has been shown that defective QDs can act as photon scattering centers, resulting in an increased value for the internal loss α_i.[16]

In conclusion, we have studied the effects of reducing the thickness of the LGT component of the GaAs SPL in multilayer 1.3 μm *p*-doped QD lasers. The threshold current density is reduced, and the external differential efficiency increased when the thickness of LGT GaAs layer is decreased from 15 to 2 nm. It is possible that further modifications to the growth approach of GaAs SPLs may result in additional improvements to the device performance.

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