Coupled strained-layer InGaAs quantum-well improvement of an InAs quantum dot AlGaAs–GaAs–InGaAs–InAs heterostructure laser

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Data are presented showing that, besides the improvement in carrier collection, it is advantageous to locate strain-matching auxiliary InGaAs layers [quantum wells (QWs)] within tunneling distance of a single-quantum-dot (QD) layer of an AlGaAs–GaAs–InGaAs–InAs QD heterostructure laser to realize also smaller size QDs of greater density and uniformity. The QD density is changed from $2 \times 10^{10}/\text{cm}^2$ for a 50 Å GaAs coupling barrier (QW to QD) to $3 \times 10^{10}/\text{cm}^2$ for a 5 Å barrier. The improved QD density and uniformity, as well as improved carrier collection, make possible room-temperature continuous-wave (cw) QD + QW laser operation (a single InAs QD layer) at reasonable diode length ($\sim 1 \text{ mm}$), current density $586 \text{ A/cm}^2$, and wavelength 1057 nm. The cw 300 K coupled InAs QD and InGaAs QW AlGaAs–GaAs–InGaAs–InAs heterostructure lasers are grown by metalorganic chemical vapor deposition. © 2001 American Institute of Physics.

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If the quantum well (QW) laser\textsuperscript{1} is modified into a quantum dot (QD) laser,\textsuperscript{2} an improvement in operation is expected because of the change from the step density of states of a QW into the discrete states of QDs. In spite of a large body of work on QD lasers,\textsuperscript{2} many problems exist associated with the random size, form, and density of QDs, and the limitations of carrier collection and charge rearrangement among the QDs. In an attempt to deal with these problems, the QD laser has recently been modified into a QD + QW laser\textsuperscript{3} by coupling, via tunneling ($L_t < 100 \text{ Å}$),\textsuperscript{4} auxiliary QW layers to the QD layers. Note that the QD active layer is outside of the auxiliary QW, at variable spacing, not inside the QW ("locked") as in previous work.\textsuperscript{5,6} In the present paper we extend the initial QD + QW laser work on the difficult InAlP–InGaAs–InP visible-red system\textsuperscript{7} to the more tractable AlGaAs–GaAs–InGaAs–InAs system (infrared).

Strained InGaAs QWs are coupled to a layer of InAs QDs, and serve as auxiliary collection and charge rearrangement layers from which carriers tunnel into the QDs and recombine.\textsuperscript{3} The data of the present work show that the InGaAs QWs not only improve carrier collection in the InAs QDs, but the strain of the QWs helps improve, moreover, the QD form and density during crystal growth, reduces QD size, and grades (alleviates) the strain induced by the lattice mismatch between the InAs QDs and the GaAs barrier and confining layers of the waveguide (WG) region.

The crystals used in this work are grown in a modified EMCORE GS 3100 reactor by low-pressure metalorganic chemical vapor deposition (LP-MOCVD)\textsuperscript{7} on $n$-type (100) GaAs substrates tilted 2° toward [110]. SiH$_4$ and CCl$_4$ are used as $n$-type and $p$-type dopants, respectively. For the laser diodes tested here, the GaAs–InGaAs–InAs QD + QW active region is located between 1100 Å of GaAs waveguide region on top and on bottom. The WG region is sandwiched between $n$-type and $p$-type Al$_x$Ga$_{1-x}$As cladding layers. The composition and thickness of the Al$_x$Ga$_{1-x}$As cladding layers are the same as reported earlier.\textsuperscript{8} The InAs QDs are deposited in the temperature range 480–520 °C.

Laser diode fabrication is accomplished by first patterning 12 μm photoresist masking stripes on the crystal and shallow etching (H$_2$SO$_4$ : H$_2$O$_2$ : H$_2$O, 1:8:80, 20 s) down to a depth that exposes the $p$-type Al$_{0.85}$Ga$_{0.15}$As upper confining layer. The crystal is then oxidized for 67 min at 430 °C in a furnace supplied with N$_2$ + H$_2$O vapor.\textsuperscript{9} Oxidation downward and $\sim 0.2$ μm laterally into the shallow exposed edge of the Al$_{0.85}$Ga$_{0.15}$As upper confining layer provides $\sim 11.5$ μm aperture defining the current and the waveguide width. The sample is then lapped to $\sim 200$ μm and metallized with Au–Ge on the $n$-type side and with Ti–Au across the oxide on the $p$-type side. Diode samples are cleaved and probe tested with the $p$-type side clamped downward on a metal heat sink.

We consider first the effect of growing an InGaAs QW and thus introducing strain into the system before the growth of the InAs QDs. Initially a GaAs buffer layer is grown on the GaAs substrate, and then a 70 Å In$_{0.17}$Ga$_{0.83}$As QW. The InGaAs QW layer is well below the critical thickness for dislocation formation.\textsuperscript{10} Next a GaAs barrier layer of thickness 50 or 5 Å is deposited before the growth of the InAs QDs. Figure 1 shows atomic force microscope (AFM) images of the two samples. The sample with the 50 Å GaAs barrier between the In$_{0.17}$Ga$_{0.83}$As QW and the InAs QDs [Fig. 1(a)] shows that the formation of the dots is random, and the GaAs surface between QDs is relatively flat. No effect of strain due to the In$_{0.17}$Ga$_{0.83}$As QW is evident in the image. In contrast, the sample with the 5 Å GaAs barrier between the InGaAs QW and the InAs QDs [Fig. 1(b)] shows the dots aligned diagonally and not just random. The effect of strain is evident also by the distinct ripple in the GaAs surface between rows of dots (ridges and valleys). In addition, the strain reduces the average height of the QDs. The height of the QDs in Fig. 1(b) is less than 15 nm, while...
The formation of dislocations owing to the large lattice mismatch of single-layer ground-state cw 300 K MOCVD QD lasers. In x continuous-wave on the strained GaAs barrier. Formation of aligned QDs, which is a property of QD growth density of QDs. The earlier results do not show, however, the show that an expanded crystal lattice produces a higher den-

There have been only a few reports of room-temperature continuous-wave (cw) 300 K operation of current-driven InxGa1-xAs QD lasers grown by MOCVD,12 and no reports of single-layer ground-state cw 300 K MOCVD QD lasers. The formation of dislocations owing to the large lattice mis-

FIG. 2. Schematic cross section of an AlGaAs–GaAs–InGaAs–InAs QD + QW laser active region with two auxiliary InGaAs WGs coupled via GaAs barrier layers to the bottom and top side of a single layer of InAs QDs. QW1 is a 70 Å In0.17Ga0.83As QW and QW2 is a 140 Å In0.2Ga0.8As QW. Both GaAs barrier layers (B1 and B2) have a thickness of 5 Å.

match between InAs QDs and GaAs confining layers is one of the major limitations. To overcome this problem in the present work a second strained In0.2Ga0.8As QW (QW2) is deposited on top of the InAs QD layer. A 5 Å GaAs barrier layer is employed between the QW and the QD layer. Figure 2 is a schematic diagram of the active layer showing the strain acting on the GaAs barrier layers owing to the InGaAs QWs. From the substrate upward, the active region is composed of a 70 Å In0.17Ga0.83As QW (QW1), a 5 Å GaAs barrier (B1), the QD layer, a second 5 Å GaAs barrier (B2), and a 140 Å top In0.2Ga0.8As QW (QW2). The second In0.2Ga0.8As QW (QW2) is deposited for the purpose of grading the lattice from the single InAs QD layer up to the smaller lattice size of the GaAs WG region. This configuration accommodates the strain caused by the large InAs–GaAs lattice mismatch and the pyramidal shape of the QDs, and helps prevent formation of defects. In addition, an extra InGaAs QW ensures adequate carrier collection and tunneling excitation of the InAs QDs, thus making possible laser operation of a single layer of QDs.

Figure 3 shows the QD + QW laser spectrum. The ~1-mm-long diode achieves room-temperature cw laser operation with a threshold current density of 586 A/cm² at a wavelength of 1057 nm. The small arrow indicates the location of the low intensity photoluminescence peak (997 nm) of the 140 Å quantum well (data not shown), and confirms that the laser operation occurs on a quantum dot state. Although the threshold current density is higher than that of the multiple-layer QD lasers of Ref. 12, the single layer QD lasers described here operate cw on the ground state with a diode length of only 1 mm. This cw 300 K QD laser operation is consistent with a low density of defects, a consequence of the strain relief afforded by the auxiliary InGaAs QWs, not...
to mention, of course, the more efficient collection and the tunneling transfer of carriers in an AlGaAs–GaAs–InGaAs–InAs QD+QW laser.

In summary, the results presented here show that, in addition to the increase in the number of carriers collected via tunneling from the QWs into the QDs, it is advantageous to place strained InGaAs QWs close to the single InAs QD layer of the AlGaAs–GaAs–InGaAs–InAs laser to improve the material properties, including specifically to realize smaller size QDs of greater uniformity and density. By using auxiliary quantum wells to improve carrier collection, as well as the QD density and size, we achieve room-temperature continuous-wave QD+QW laser operation at a reasonable diode length (~1 mm) and a threshold current density of 586 A/cm² at the wavelength of 1057 nm.

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