Ground-state lasing of stacked InAs/GaAs quantum dots with GaP strain-compensation layers grown by metal organic chemical vapor deposition

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We report the device characteristics of stacked InAs/GaAs quantum dots (QDs) with GaP strain-compensation (SC) layers grown by metal organic chemical vapor deposition. By inserting GaP SC layers within the stacked structures, decrease in the density of QDs by stacking QDs can be suppressed due to reduction of overall compressive strain within the stacked QDs. We demonstrate ground-state lasing at 1.265 μm of six layers of InAs/GaAs QDs with GaP SC layers. The threshold current density is as low as 108 A/cm^2. We also assess the internal loss and maximum modal gain of fabricated QD lasers by using a segmented contact method. The internal loss is as low as 5 cm^{-1}, and the maximum modal gain of the ground state of the stacked QDs is approximately 10 cm^{-1}.
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Research in the fabrication of quantum dot (QD) lasers has been recently exploited for metro/access optical-fiber communication systems with low threshold current densities (J_{th}), low-chirp operation, high-speed modulation, and high J_{th} temperature stability owing to their unique properties of zero-dimensional systems.[1] Above all, QD lasers grown by metal organic chemical vapor deposition (MOCVD) have attracted practical interest in terms of the application to distributed feedback lasers or optically integrated devices that require regrowth or selective area growth. Several groups have so far reported QD lasers grown by MOCVD.[2–7] Lasing near 1.3 μm has been obtained from five layers of InAs/InGaP QDs clad by an InGaP layer,[4] and from the first excited states of five layers of InAs/GaAs QDs clad by low-temperature-grown AlGaAs layer at 1.28 μm.[6] However, the accumulation of the overall compressive strain by stacking In(Ga)As/GaAs QDs can cause threading dislocations and increased internal loss due to scattering introduced by surface undulations of the interface between the active and *p*-cladding layers. The accumulated strain fields also cause a reduced QD density due to seeding effects of the progressively larger stacked QDs.

One of the ways to overcome these problems is to insert a tensile layer within the stacked structure to compensate the overall compressive strain. Two methods for compensating the overall strain of stacked QDs have been reported. One approach is to use GaNAs strain compensation (SC) as the capping layer of InAs QDs,[8] and another is to insert Ga(In)P SC layers within the stacked structure.[7,9–11] We have already investigated the effect of SC in stacked InAs QDs,[10,11] and demonstrated the lasing at 1.25 μm from three layers of high-density InAs QDs with GaP SC layers with the threshold current of 550 A/cm^2.[7]

In this letter, we demonstrate ground-state lasing from a six-stack InAs/GaAs QDs with high uniformity containing GaP SC layers grown by MOCVD. By inserting the GaP SC layers, the overall compressive strain can be reduced, and thus the reduction of dot density by stacking QDs can be suppressed. The dot density of the fourth layer of stacked QDs increases from 1.1×10^{10}/cm^2 to 2.0×10^{10}/cm^2 by optimizing the growth conditions of GaP SC layers. The threshold current density is 108 A/cm^2, the lasing wavelength is 1.265 μm, and we confirm that the ground state of stacked InAs/GaAs QDs contributes to the lasing, compared with the results of the electroluminescence (EL) spectra.

All samples are grown by low-pressure MOCVD using trimethylindium, trimethylgallium, trimethylaluminum, tertiarybutylphosphine (TBP), and arsine (AsH_3) as the source materials at a total pressure of 60 Torr. Disilane and carbontetrachloride are used as the *n*- and *p*-type doping materials. The QD laser structure is grown on a (100) *n*-GaAs substrate followed by a 1.46 μm *n*-$Al_{0.3}Ga_{0.7}As$ cladding layer, an active layer, a 1.46 μm *p*-$Al_{0.3}Ga_{0.7}As$ cladding layer, and a 400 nm p^+-GaAs contact layer. The growth temperatures of *n*- and *p*-cladding layers are 700 and 560 °C, respectively. The active layer consists of six layers of InAs QDs with GaP SC layers. Each QD layer is grown at 520 °C on 5 ML (monolayer) $In_{0.15}Ga_{0.85}As$ buffer and covered with 25 ML $In_{0.15}Ga_{0.85}As$ cap. The growth rate of InAs QDs is 0.075 ML/s, and the nominal thickness of InAs is approximately 2.6 ML. The density of the first layer of InAs QDs is determined to be 1.9×10^{10}/cm^2 by using atomic force microscope (AFM), as shown in Fig. 1(a). In the growth of stacked QDs, an *indium-flushing* method[12] is used to improve surface morphology and quality of GaAs capping layer.[5,6,11] An indium-flushing step is accomplished by annealing the surface for 300 s under the AsH_3 flow after QD layer is covered with 4 nm GaAs cap. Then, a GaP SC layer is grown on the GaAs cap. After the growth of GaP SC layers, the wafer temperature is increased to 540 °C and the surface of GaP is annealed for 180 s under the TBP flow to improve the interlayer dot uniformity for QDs grown in GaAs.[13,14] After surface annealing, another 14 nm GaAs cap is grown at 540 °C. Then, the wafer temperature decreases to 520 °C, and the next QD layer is grown.

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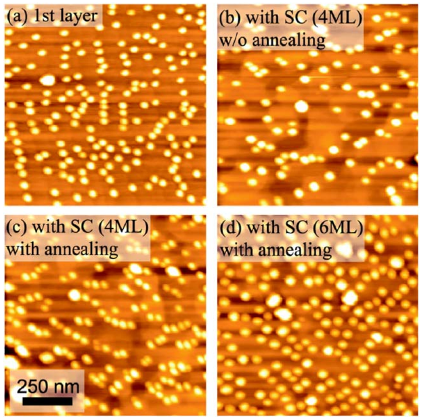

FIG. 1. (Color online) AFM images of uncapped surface of (a) single layer (dot density: $1.9\times10^{10}/\mathrm{cm}^2$), and fourth layer of stacked InAs QDs (b) containing a 4 ML GaP SC layer without surface annealing ($1.1\times10^{10}/\mathrm{cm}^2$), (c) containing a 4 ML GaP SC layer with surface annealing ($1.4\times10^{10}/\mathrm{cm}^2$), and (d) containing a 6 ML GaP SC layer with surface annealing ($2.0\times10^{10}/\mathrm{cm}^2$).

Figures 1(b) and 1(c) show AFM images of uncapped surface of the fourth layer of stacked QDs containing GaP SC layers without and with surface annealing, respectively. The density of the fourth layer of InAs QDs increases by applying the surface annealing step. Moreover, by increasing the thickness of a GaP SC layer, the density of the fourth layer of stacked QDs becomes almost the same as that of single-stack QDs, despite the fact that the size of the fourth layer of QDs is larger than that of the first layer, as shown in Fig. 1(d). These results are due to the improvement of surface morphology by applying the surface annealing and the accumulation of strain compensation by increasing the thickness of GaP SC layer.

The cross-sectional transmission electron microscope (TEM) image of six-stack InAs QDs with 27 nm spacing containing GaP SC layers, in Fig. 2, shows the six-stack QD active along with the GaP SC layers. The image suggests that

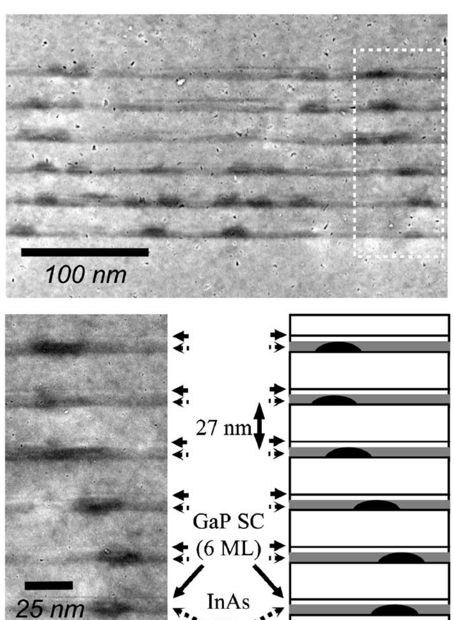

FIG. 2. Cross-sectional TEM images and a schematic illustration of six layers of InAs QDs embedded in $In_{0.15}Ga_{0.85}As$ layer with 27 nm spacing containing 6 ML GaP SC layers.

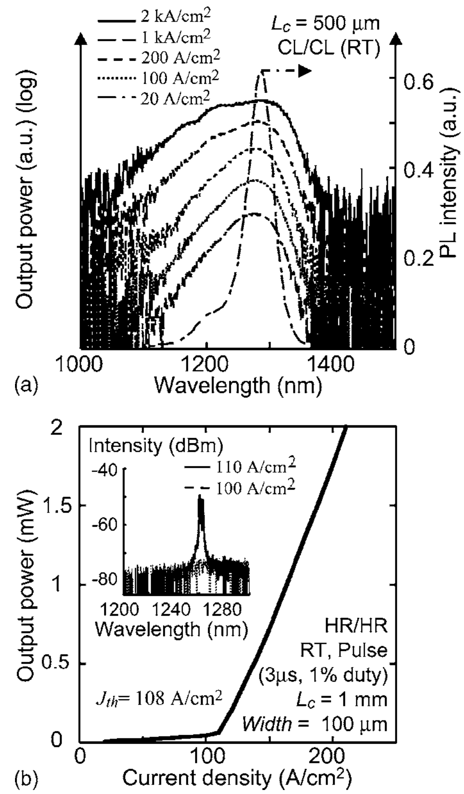

FIG. 3. (a) EL spectra of six-stack InAs QD lasers with GaP SC layers at various injected current densities ranging from $20\ \mathrm{A/cm}^2$ to $2\ \mathrm{kA/cm}^2$ and PL spectrum of their active layers. (b) *L-I* characteristics of the QD lasers under pulsed operation at RT. A threshold current density J_{th} is $108\ \mathrm{A/cm}^2$. Inset is the EL spectra of fabricated QD lasers just above and below the threshold current J_{th}.

the InAs QDs are not formed by columnar growth as might be expected from the very close QD spacing. Rather, each QD layer forms semi-independently of the underlying QDs. This lack of strain coupling between the QD layers allows the QD density to remain stable from layer to layer rather than decrease.

Broad area laser structures, 100 μm wide with varying cavity length, are fabricated for measurements of the device characteristics. First, we measure the spontaneous emission spectra of the QD lasers with cavity lengths of 500 μm that have as-cleaved facets on both sides at room temperature (RT). Figure 3(a) shows the EL spectra of the QD lasers at various injected current densities under pulsed conditions (1% duty cycle) ranging from $20\ \mathrm{A/cm}^2$ to $2\ \mathrm{kA/cm}^2$. We can observe separate peaks from the discrete set of the density of states at the peak wavelengths of 1.28, 1.22, and 1.16 μm at high injection current. The full width at half maximum of the PL spectrum is 33 meV. The intersubband energy spacing between the ground and excited states is 48 meV. Moreover, the EL peak of the QD lasers does not shift towards shorter wavelength by the effect of postgrowth annealing compared with the PL peak of the active region, as shown in Fig. 3(a).[6] We then study the output power-current (*L-I*) characteristics and lasing spectra of the laser structures with cavity lengths of 1 mm at RT. High-reflectivity coatings (reflectivities of 90% and 94%) are applied on both facets of the laser structures. Figure 3(b) shows *L-I* characteristics and EL spectra just below and above the threshold current under the same pulsed conditions. The threshold current density J_{th} is $108\ \mathrm{A/cm}^2$ and the lasing wavelength is 1.265 μm. We

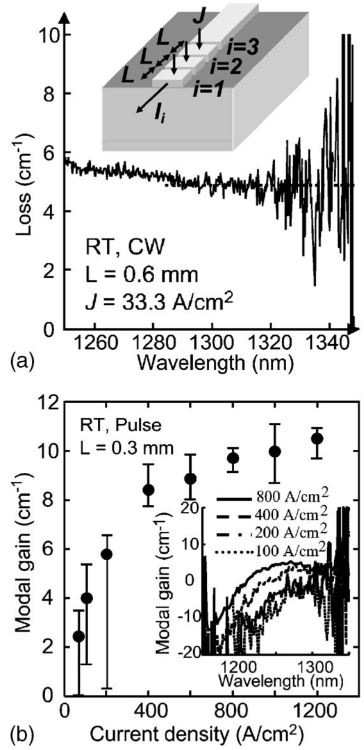

FIG. 4. (a) Modal absorption spectrum of fabricated QD lasers under an injected current density (J) of 33 A/cm^2. Inset is the schematic diagram of multisection device structure. (b) Modal gain of the ground and first excited states of stacked InAs QD lasers against injected current densities. Inset is the net gain spectra of the QD lasers at various injected current densities ranging from 100 to 800 A/cm^2.

believe that the lasing wavelength can be extended towards 1.3 μm by increasing the indium composition of InGaAs matrix.[15]

The internal loss and modal gain of the QD lasers are assessed by a segmented contact method using a single multisection device.[16,17] The wafers are processed into multisection devices which are electrically isolated following conventional broad area laser processing, as shown in the inset of Fig. 4(a). The width of the stripe is 50 μm. A final multisection device is composed of 0.3 or 0.6 mm long sections. The EL emission is detected from the cleaved facets of cavities by using optical spectrum analyzer. The net modal gain g and the modal absorption α are derived from the equations given as[17]

$$g = \frac{1}{L} \ln\left(\frac{I_3 - I_1}{I_2 - I_1} - 1\right), \quad (1)$$

$$\alpha = \frac{1}{L} \ln\left(\frac{I_2 - I_1}{I_{31} - I_1}\right), \quad (2)$$

where L is the cavity length, I_1, I_2, I_3, or I_{31} is the EL intensity when the sections 1; 1 and 2; 1, 2, and 3; or 1 and 3, respectively, shown in the inset of Fig. 4(a) are pumped with a current density J. The internal loss is determined to be approximately 5 cm^{-1} from the modal absorption spectrum derived from Eq. (1) below the band gap of the ground state of QDs as shown in Fig. 4(a). The low internal loss is likely due to the suppression of overall compressive strain by inserting GaP SC layers, resulting in the morphology improvement at the heterostructure interface. The net gain spectra are derived from Eq. (2) as shown in the inset of Fig. 4(b). We plot the modal gain characteristics of the ground states against injected current densities as shown in Fig. 4(b). By increasing the injected current density, the modal gain of the ground state at first increases but then is saturated. We can estimate that the maximum modal gain of the ground state of the QD lasers is approximately 10 cm^{-1}. It is possible to obtain higher modal gain by increasing the stacking numbers because we can form stacked QDs without degradation of the dot density caused by the accumulated strain field as stacking QDs by inserting SC layers within the stacked structure.

In summary, we demonstrate ground-state lasing of stacked InAs/GaAs QDs containing GaP SC layers grown by MOCVD. By inserting 6 ML GaP SC layers within the stacked structures, the decrease in the density of QDs due to stacking layers can be suppressed by the reduction of overall compressive strain within the stacked QDs. We obtain RT lasing at 1.265 μm from six-stack InAs QD lasers containing GaP SC layers with the threshold current densities of 108 A/cm^2. From the measurement of EL spectra of fabricated lasers, the observed lasing originates from the ground state of stacked InAs QDs. In addition, we assess the internal loss and modal gain of fabricated lasers by using segmented contact method. The maximum modal gain is approximately 10 cm^{-1}, and the internal loss is as low as 5 cm^{-1}, which is almost comparable to that of QD lasers by molecular beam epitaxy.

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