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Microphotoluminescence investigation of InAs quantum dot active region in 1.3 μm vertical cavity surface emitting laser structure

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Microphotoluminescence ($\mu\text{-PL}$) investigation has been performed at room temperature on InAs quantum dot (QD) vertical cavity surface emitting laser (VCSEL) structure in order to characterize the QD epitaxial structure which was designed for 1.3 μm wave band emission. Actual and precise QD emission spectra including distinct ground state (GS) and excited state (ES) transition peaks are obtained by an edge-excitation and edge-emission (EEEE) $\mu\text{-PL}$ configuration. Conventional photoluminescence methods for QD-VCSELs structure analysis are compared and discussed, which indicate the EEEE $\mu\text{-PL}$ is a useful tool to determine the optical features of the QD active region in an as-grown VCSEL structure. Some experimental results have been compared with simulation results obtained with the aid of the plane-wave admittance method. After adjustment of epitaxial growth according to EEEE $\mu\text{-PL}$ measurement results, QD-VCSEL structure wafer with QD GS transition wavelength of 1300 nm and lasing wavelength of 1301 nm was obtained. © 2010 American Institute of Physics. [doi:10.1063/1.3490236]

I. INTRODUCTION

InAs quantum dot (QD) vertical cavity surface emitting lasers (VCSELs) emitting at 1.3 μm region are very promising for light source applications in low-cost access network, free-space optical communications, all-optical signal processing, etc., owing to low-threshold current, low power consumption, high thermal stability, and simple fabrication process^{1–5} compared with InP-based or GaAs-based quantum well (QW)-VCSELs.

It is well known that effective lasing and excellent characteristics of QD-VCSELs occur when the QD emission coincides with cavity mode formed by resonances of the inner cavity and maximum reflectivity of distributed Bragg reflector (DBR) mirrors. In addition, the optical features of QD materials in an as-grown VCSEL structure are also important for fundamental principle study.⁶ It is noteworthy that the QD characteristics may be discrepant between various whole epitaxial structures (e.g., QD-VCSEL structure and QD edge emitting laser (EEL) structure) even if the epitaxial parameters of QD parts in these structures are entirely the same. Accordingly, it is necessary to develop a rapid and direct method to specialize in precise QD emission spectrum on a QD-VCSEL structure wafer.

However, generally it is difficult to obtain the fine and direct spectra of the QD active region without any influence of DBRs in a QD-VCSEL structure. In order to know the QD emission spectra, we may fabricate an EEL using the QD-VCSEL structure wafer, and measure its electroluminescence (EL) spectra, and then determine the QD transition peak roughly. But this approach is not instant and precise for col-

lecting the optical features of QD materials. EELs with different cavity length may produce different EL spectra. Recently, differential surface photovoltage spectroscopy (DSPS), which is based on the measurement of the change in photovoltaic response of semiconductors as a function of the wavelength of the incident illumination, was used to investigate QW emission on a QW-VCSEL structure as a nondestructive characterization technique.^{7,8} However, compared to DSPS, PL spectra investigations are more convenient and direct because of relatively simple setup as well as easy data processing. The surface-excitation and edge-emission PL made the determination of the QW luminescence wavelength in a QW-VCSEL structure possible although interference effects still existed and luminescence intensity was very weak.⁹

Microphotoluminescence ($\mu\text{-PL}$) has been widely used for the investigation of submicron or nanoscale materials.^{10–13} $\mu\text{-PL}$ investigation on the cleaved facet of QW infrared photodetector (QWIP) has been reported and it has been proven to be an effective way in extracting QW signal and characterizing QWIP material structure.¹⁴ In this work, we developed an edge-excitation and edge-emission (EEEE) $\mu\text{-PL}$ technique to determine the precise QD luminescence spectra at room temperature (RT) within an as-grown QD-VCSEL structure. The conventional surface incident PL investigation for QD-VCSEL samples with different process such as removing top DBR mirrors are demonstrated as comparison and reference. Some experimental results have been compared with simulation results obtained with the aid of the plane-wave admittance method. After adjustment of epitaxial growth based on the feedback of EEEE $\mu\text{-PL}$ measurement results, QD-VCSEL structure wafer with QD ground state (GS) transition wavelength of 1300 nm and devices' lasing wavelength of 1301 nm was obtained.

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FIG. 1. SEM image of cross section with active region schematic illustration of the 1.3 μm emission InAs QD-VCSEL epitaxial structure.

II. EXPERIMENTAL

The InAs QD-VCSEL epitaxial wafers were prepared by molecular-beam epitaxy on n^+ -GaAs substrates. The epitaxial structure consists of QD's active region sandwiched in between top and bottom DBR mirrors. DBR part consists of 24 pairs of p-doped top $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ /GaAs DBR mirror and 33.5 pairs of n-doped bottom $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ /GaAs DBR mirror. Graded interfaces and modulation doping were used to reduce the DBR resistance. The 3λ , intercavity comprises 17 layers of InAs QDs which include five groups QDs and two separated QD sheet layers. Each group of QDs consists of three sheets of QD and was situated around the antinode position of standing wave. The QDs are grown directly on GaAs and capped by an 8 nm-thick $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ layer. A 5 nm-thick undoped GaAs layer is grown after the InGaAs cap layer, followed by a 5 nm-thick p-doped GaAs layer. Carbon and silicon are used for p-type and n-type dopant, respectively, for the whole structure. An AlAs thin layer embedded in p-DBR adjacent to the active region is used for selective oxidation. Scanning electron microscopy (SEM) image of cross section with an active region schematic illustration of the 1.3 μm emission InAs QD-VCSEL epitaxial structure is shown in Fig. 1.

The μ -PL measurements were carried out at RT. An argon laser with a wavelength of 514 nm was used for excitation. The excitation beam was focused onto a spot with a diameter of about 2–3 μm . The actual thickness of 3λ , intercavity is slightly more than 1 μm . It is not necessary to reduce the size of excitation spot to the intercavity size because luminescence wavelength from top and bottom DBRs is far from that of the QD active region. But it should be noted that the excitation spot cannot overstep the range of DBRs, or else the PL signal from impurities in the heavy doped GaAs substrate may interfere with the real QD signal. The excitation power intensity was adjusted using different neutral density filters controlled by a computer. The emission spectra in PL measurements collected through the same microscope objective were detected by InGaAs array detectors for spectral analysis or dispersed into a charge coupled device camera for imaging. The EEEE μ -PL configuration is shown schematically in Fig. 2(a). Before EEEE μ -PL measurements, the QD-VCSELs sample was cut into the size of

(a)

(b)

FIG. 2. (Color online) (a) Schematic illustration of μ -PL measurement from edge excitation and edge emission, (b) illustration of wafer orientation and the positions of point A, B, and C.

a few millimeters by a few millimeters, and stood on edge as shown in Fig. 2(a). The QD-VCSELs sample can be still used for the conventional device fabrication process³ after μ -PL measurements. Based on this point, this method can be regarded as a nondestructive testing. We selected three positions {point A, point B, and point C, from the top to the bottom along the [011] direction, see Fig. 2(b)} on the QD-VCSEL wafer for EEEE μ -PL investigation. We also carried out conventional surface-excitation and surface-emission PL investigation as well as EEEE PL investigation with large-area (the excitation spot oversteps DBRs and expands to the substrate) for the identical samples as comparison.

III. RESULTS AND DISCUSSION

For point A, the top position of the structure wafer (near the orientation flat or the major flat), the conventional surface-excitation and surface-emission PL investigation for the sample with the top DBR mirrors partly removed was carried out at RT (Fig. 3). Figure 3 also shows the surface-excitation and surface-emission PL of the as-grown QD-VCSEL sample for reference. QD peak modulated by top and bottom DBRs appears at around 1250 nm which is obviously far from the actual QD GS transition peak from active region according to previous experience for laser devices. An inconspicuous excited state (ES) transition peak envelop can be seen between 1150 and 1200 nm. Several tiny peaks marked with DBR modulation in Fig. 3 correspond to the “edge of stop band” of the optical reflectance spectrum or

FIG. 3. (Color online) Conventional surface-excitation and surface-emission PL investigation for QD-VCSEL sample (point A): as-grown and partly removing top DBR mirrors.

the resonance peaks of the residual inner cavity. It has been found from our simulation results obtained with the aid of the vectorial plane-wave admittance method,¹⁵ that the position of the edge of stop band peak corresponds very exactly with a sudden decrease in the VCSEL mirror reflectivity spectrum. That is to say, we cannot obtain the actual QD emission spectra from conventional surface-excitation and surface-emission PL method because of the influence of top and bottom DBRs.

For point B, the mid position of the structure wafer, the conventional surface-excitation and surface-emission PL measurements under different excitation power for the reference samples with incompletely removing top DBR mirrors and with fully removing top DBR mirrors were implemented at RT (Figs. 4 and 5). The QD GS transition peaks can be determined by multiple-peaks curve fit through Gaussian function. QD GS transition peaks change from 1278 to 1273 nm under different excitation intensities for the sample with incompletely removed top DBRs, however, QD GS transition peaks fixed at 1272 nm under different excitation intensities for the sample whose top DBRs were completely removed. For both cases, distinct DBR modulation (tiny fluctuation) can be seen on the PL spectra. Therefore, bottom DBRs modulation is still existent even if we fully remove the top DBRs and then eliminate the excitation intensity-dependent peak shift in conventional surface-excitation and surface-emission PL measurement. Accordingly, although QD peaks may be determined approximately, the results are still not the actual QD emission spectra. Besides, another drawback of above mentioned approach of fully removing top DBRs is that the epitaxial structure should be damaged. The fully etching of top DBR without destroying the QD region is also difficult to be realized and time-consuming.

Figure 6 shows the EEEE PL spectra with excitation spot size of $\sim 50 \mu\text{m}$ for QD-VCSEL sample at point A. Because the size of excitation spot is far larger than the thickness of epitaxial layers, a large proportional of laser spot is on the GaAs substrate. In the meanwhile, the PL signal from impurities in the heavy doped GaAs substrate is too strong to be

FIG. 4. (Color online) Conventional surface-excitation and surface-emission PL investigation for QD-VCSEL sample (point B) by incompletely removing top DBR mirrors under different excitation intensity (a) with linear Y coordinate axis, (b) with logarithmic Y coordinate axis.

neglected and the luminescence ranging from 1000 to 1400 nm just covers the QD emission region. Accordingly, a wide spectrum can be obtained for the combination of QD region and GaAs substrate in Fig. 6(a). The coarse QD spectrum [shown in Fig. 6(b)] could be obtained by filtering the spectrum from GaAs substrate. The large-area EEEE PL spectrum with signal subtraction method may determine QD peak roughly but the result is not precise. The GS transition peak is visible at about 1261 nm as shown in Fig. 6(b).

For obtaining the precise QD emission spectrum, EEEE μ -PL investigation was employed for QD-VCSEL samples at point A, B, and C. In Fig. 7, distinct GS and ES transition peaks can be seen from EEEE μ -PL measurements. For point A, the QD GS transition peak is about 1262 nm. First ES transition peak wavelength is about 1181 nm which is 81 nm shorter than GS peak. Because the resonance cavity mode position is 1285 nm as shown at Fig. 3. The 23 nm detuning makes the QD-VCSEL structure difficult to lase after device fabrication process. The GS transition peak is about 1271 nm for point B which is very close to the conventional measurement result of 1272 nm by completely removing top DBR mirrors in Fig. 5. No DBRs modulation trace or excitation intensity-dependent peak shift has been

FIG. 5. (Color online) Conventional surface-excitation and surface-emission PL investigation for QD-VCSEL sample (point B) by completely removing top DBR mirrors under different excitation intensity (a) with linear Y coordinate axis, (b) with logarithmic Y coordinate axis.

observed for the EEEE μ -PL measurements. For point C, the GS transition peak is located at 1277 nm. QD PL peak intensity decreased remarkably with the increasing transition wavelength for the three samples on the assumption that the test conditions under different EEEE μ -PL measurements are similar (such as excitation spot size). The values of full

FIG. 7. (Color online) Comparison of EEEE μ -PL of point A, point B, and point C at RT.

width at half maximum for three PL spectra are similar and about 50 nm. Besides, the PL peaks are distinctly shifted from one another. Such shifting cannot be explained solely by temperature variations, because as high as about 30° temperature change would be responsible for such a shift. Therefore, at least partly, those displacements are a result of some structure nonhomogeneities. As we know, the QD size increase will lead to a slight redshift in QD transition wavelength. Whereas a modicum increase in In content in capping layer of InGaAs will also produce a redshift in QD transition wavelength. In this case, the epitaxial nonhomogeneity might lead to both sides of abovementioned effects which finally cause the QD GS transition wavelength distribution from 1262 to 1277 nm on a wafer, and it may has the nature of randomness. Because of the discrepancy of the QD gain as well as possible difference of defects density, the relatively short wavelength emission of QD is remarkably stronger than that of relatively long wavelength. Further study is needed to find the elaborate relation between growth conditions and QD transition wavelength as well as QD luminescence intensity by using EEEE μ -PL technique.

After the adjustment of QD emission wavelength as well as the QD homogeneity by modifying the epitaxial growth,

FIG. 6. (Color online) EEEE PL spectra with $\sim 50 \mu\text{m}$ excitation spot for the combination of QD region and GaAs substrate (black curve) as well as only GaAs substrate (red curve) (a); coarse QD spectrum obtained by subtraction of two curves (b).

FIG. 8. (Color online) (a) EEEE μ -PL of two different points of modified QD-VCSEL wafer at RT; (b) resonance cavity mode from surface PL spectrum of center part of as-grown wafer at RT; (c) lasing spectrum of QD-VCSEL device from the center part of the wafer at RT.

the 1300 nm QD GS transition wavelength was achieved from the optimized structure wafer, which almost coincides the cavity mode [Figs. 8(a) and 8(b)]. The discrepancy of QD peaks wavelength from the center part to the edge of the wafer is very small, which indicates ameliorative homogeneities. In this case, the PL intensity for different positions in Fig. 8(a) cannot be compared because of different measure batch. The continuous wave lasing wavelength of 1301 nm for QD-VCSEL device from the center part of the wafer was obtained at RT [Fig. 8(c)]. Redshift in a few nanometers from resonance cavity mode wavelength to QD-VCSEL's lasing wavelength is due to the temperature increase in QD active region during the device operation.

IV. CONCLUSIONS

μ -PL investigation has been performed on InAs quantum dot QD-VCSEL structure at RT. QD emission spectra

including distinct GS and ES transition peaks are obtained by EEEE μ -PL configuration. Conventional surface-excitation and surface-emission PL measurement for QD-VCSELs structure analysis was carried out. Although the conventional PL spectra of the sample with top DBR fully removed can provide the relatively acceptable optical features of QD in VCSEL structure, the influence of bottom DBR as well as destructive process makes it unfit to be used. Large-area EEEE PL is also not satisfying because of the luminescence influence from the GaAs substrate. From the comparison, EEEE μ -PL is a simple, more direct and desirable method for determining the subtle optical features of QD active region in an as-grown VCSEL structure.

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