1. English Abstract

A series of highly strained InGaAs quantum wells (QWs) with GaAs barriers emitting at wavelength longer than 1.2 \( \mu \text{m} \) are grown on GaAs substrates by metalorganic chemical vapor deposition (MOCVD). The optimized windows of the V/III ratio of the InGaAs layer and the growth rate of the barrier are first investigated on these highly strained QWs. By an appropriate choice of the growth conditions, we extend the room temperature photoluminescence (PL) wavelength of InGaAs QWs to 1245 nm, which corresponds to an indium content of 42\%. A GaAs-based InGaAs vertical-cavity surface-emitting laser (VCSEL) at an emission wavelength of 1.28 \( \mu \text{m} \) with a large detuning of 90 nm has been realized by the use of highly strained InGaAs QWs.

3. Introduction

Even if the metalorganic chemical vapor deposition (MOCVD) growth of InGaAs is used for several devices, such as light emitters, photodetectors, and transistors, the influences of the parameters on highly strained InGaAs have not been clarified to date. The understanding and control of these technologies are important for device applications, as highly strained InGaAs VCSEL is a promising candidate for long-wavelength, low-cost source fiber-optical communication systems [1-2]. To grow a highly strained InGaAs QWs with a thickness greater than critical thickness, misfit dislocations have to be suppressed and growth mode transition from two-dimensional to three-dimensional (Stranski-Krastanov) growth modes [3-6] should be delayed. The formation of abrupt interfaces between InGaAs and GaAs is inherently
limited by the surface accumulation of In atoms during growth. Thermal nonequilibrium conditions, such as a low growth temperature, may be effective in decreasing the indium surface migration length, reducing indium surface segregation, and thus increasing the critical thickness, [7-8] to realize such a highly strained material. Simultaneously, a high V/III ratio should be adopted to maintain the crystal quality. However, few investigations on V/III ratio have been carried out for such highly strained QWs because of the difficulty of epitaxy. During epitaxial growth, indium atoms tend to move to the upper layer and thermally desorb from the surface. [9] Thus, we believe that the growth rate of the cap layer plays a key role in determining the quality of multiple highly strained InGaAs QWs. In this study, we have systematically investigated the influences of both the V/III ratio of the InGaAs layer and growth rate of the GaAs barrier on photoluminescence (PL). Using the results of this investigation, VCSEL structures were grown and processed.

4. Structure and Device Process

InGaAs double QWs consisted of two InGaAs QWs sandwiched between GaAs spacer layers and separated by a GaAs barrier layer. No growth interruption was introduced before and after growing the QWs. All the samples were grown by varying V/III ratio, \([\text{tributylarsine (TBAs) + AsH}_3]/[\text{triethylgallium (TEGa) + TMIn}],\) to investigate the effect of V/III ratio on optical qualities.

5. Results and Discussions

For the samples emitting at 1215 nm, the correlation between PL results and V/III ratio is shown in Fig. 1. All the growth parameters were kept constant, except for the TBA/III ratio, which was changed from 50.02 to 60.52 by changing the TBA flow rate while maintaining a fixed AsH3/III ratio of 90.33. We adopted a growth temperature of 520°C and a growth rate of 0.8 Å/sec. The nominal thickness of the QWs was adjusted for all the samples to 75 Å and the In content was 39%. As shown in Fig. 1, the PL intensity increases with TBA/III ratio, exhibits a peak, which occurs for a TBA/III ratio of 58.36, and then substantially decreases. This is due to an enhanced incorporation rate of In molecules under an increased surface coverage of As molecules. Mobile In molecules on the growing surface have a shorter lifetime before being incorporated into the bulk phase. Note that the migration length of source molecules on epitaxial surfaces decreases with increasing V/III ratio [9-10], thus, TBA/III ratio is increased to prevent the system from reaching thermodynamical equilibrium. As a result, for increasing TBA/III ratio up to 58.36 (V/III ratio = 148.69), PL intensity benefits from nonequilibrium conditions.
Simultaneously, the Full-Width Half-Maximum (FWHM) decreases slightly from 34.5 to 32.7 nm. This can be interpreted as the improvement of abrupt heterointerfaces. When TBA/III ratio increases from 58.36 to 62.52, PL intensity is degraded considerably and FWHM is extended to 35. This is because excess arsenic on the surface acts to block attachment sites for incoming In and Ga precursors, and to prevent the atoms from moving and depositing at exact sites. This results in the formation of vacancies of group-III atoms during the growth of highly strained QWs. Additionally, this excessive TBA/III ratio makes In surface accumulation pronounced, which leads to InAs-rich clusters near the surface that then give rise to a severe compositional grading and a higher In incorporation into the GaAs barrier.

To study the effect of growth rate on the GaAs barrier, the TMGa flow rate of the barrier layer was varied from 5 to 7 sccm with a fixed TBA/III ratio of 58.36, which is the best ratio deduced from Fig. 1. Figure 2 shows the intensity and FWHM of the PL results for the 1215 nm QWs as a function of TMGa flow rate. It is clearly seen that the PL intensity increases when TMGa flow rate is changed from 5 to 6 sccm, when the barrier growth rate increases from 2.23 to 2.56 Å/s. This is caused by the increase in barrier growth rate that tends to promote thermal nonequilibrium conditions. A higher concentration of group-III species in the growing barrier layer reduces the influence of purging at the QW interface on indium atom migration. Thus, a better square-well structure can be obtained. When the growth rate exceeds 2.56 Å/s, PL intensity deteriorated and FWHM extended noticeably. The explanation of these experimental results is inhomogeneous indium taking place in the upper layer. A significant compositional broadening of the interface occurs, which is attributed to the formation of an In-enriched surface. Simultaneously, the growth rate going beyond the limit leads to a poorer barrier crystalline quality. Figure 3 shows a comparison of as-grown (nonannealed) characteristics of QWs with a fixed nominal well width of 75 Å and indium mole fractions of 39, 41, and 42%. As can be seen, the RT PL wavelength emission extends from 1215 to 1245 nm, which is the longest emission wavelength ever reported in a pseudomorphic InGaAs/GaAs material system without a strain-compensated layer structure grown by MOCVD. The PL intensity of our results remains competitive till the wavelength was extended to 1230 nm. These results demonstrate that the possible application of InGaAs with a very high In composition and a large thickness grown by MOCVD is very promising for improving device performances and providing flexibility in band-structure engineering.
A standard oxide-confined technology with aperture diameters of 15 μm was used for a InGaAs VCSEL. The simulated reflectance spectrum for the VCSEL with a Fabry-Perot dip wavelength of 1.28 μm is depicted in Fig. 4. The lower part also shows the RT photoluminescence spectra after the removal of several pairs of p-type Distributed Bragg Reflectors (DBRs) by wet etching. The multipeak spectra of the InGaAs QWs are induced from the mismatch between the stopband of the reflective spectrum and gain position. The peak emission wavelength reveals an approximately 25 nm blue shift during the growth of p-type DBRs with respect to that of the as-grown QWs. This significant blue shift may be due to the severe interdiffusion between highly strained QWs and the GaAs barrier. Light output characteristics for the InGaAs VCSEL emitting at 1.28 μm with a p-DBRs growth temperature of 670°C under CW operation are shown in Fig. 5. The corresponding threshold current is 13 mA. This relatively large threshold current is due to the large detuning between gain peak and cavity resonance as indicated in Fig. 4. The inset in Fig. 5 shows the emission spectrum at a driving current just above threshold at room temperature. The insufficient optical power may be attributed to a nonactivated CBr4 doping, presumably a result of the low growth temperature of 670°C, which leads to high-resistance p-DBRs; nevertheless, this result demonstrates it is possible to extend emission wavelength toward 1.3 μm by extensive detuning after optimizing.

6. Conclusion

In conclusion, we have demonstrated a double QW without N or Sb incorporation fabricated by MOCVD with an emission wavelength of 1.245 nm. The quality of such highly strained multiple InGaAs QWs deduced from PL intensity and FWHM as functions of V/III ratio and barrier growth rate were investigated. In spite of extensive detuning, we have demonstrated a CW-operation long-wavelength InGaAs VCSEL with an emission spectrum extending up to 1.28 μm by optimizing highly strained InGaAs active regions.
Reference:

Fig. 1. RT PL intensity and FWHM of PL spectra versus TBA/III ratio for 1215 nm QWs.

Fig. 2. RT PL intensity and FWHM of PL spectra as function of TMGa flow rate for 1215 nm QWs.

Fig. 3. Plot of PL spectra of InGaAs/GaAs double QWs with well widths of 75 Å and indium mole fractions of 39, 41, and 42%.
Fig. 4. Simulated reflectance spectrum with Febry-Perot dip and position of gain peak.

Fig. 5. Light output power and voltage drop against drive current for 15 μm oxide-confined VCSEL emitting at around 1.28 μm.
Inset: Lasing spectrum at bias current of just above threshold.