Structure design of InGaAs quantum well laser with mode expansion layer

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Abstract. InGaAs quantum well (QW) is grown on GaAs substrates by metal-organic chemical vapor deposition (MOCVD). The effects of growth temperature and V/III ratio on the optical properties are discussed by analyzing the photoluminescence(PL) measurement at room temperature. It is found that the PL intensity of the QWs grown at low temperature is stronger, and the luminescence intensity of the samples can be increased by increasing the V/III ratio of the QW. Crosslight software is used to simulate the laser structure with mode expansion layers. Compared with conventional lasers, it’s demonstrated that inducing the mode expansion layer would expand the near-field, reduce the confinement factor, improve the catastrophic optical damage (COD) threshold of the laser, and reduce the vertical divergence angle of the far-field.

1. Introduction

Strained QWs semiconductor lasers are widely used in civil and military fields. High strain QW lasers require high In content in the active layer, which results in a large mismatch. When the thickness of QWs is less than the critical thickness, the compressive stress caused by mismatch makes the energy band of quantum wells change greatly, which affects the performance of lasers. Due to the accumulation of strain, it is difficult to obtain high quality epitaxial materials. For example, when the wavelength of InGaAs/GaAs QW materials is 980 nm, the content of In is generally more than 20%, and the lattice mismatch is more than 1.4%. When the wavelength exceeds 1064 nm, the content of In is generally more than 30%, and the lattice mismatch is more than 2.1%. In the process of epitaxy growth, the stress caused by lattice mismatch leads to lattice relaxation, which changes from two-dimensional growth to three-dimensional growth. Three-dimensional growth causes many defects, which affects the luminescence efficiency of QW materials. In order to obtain high quality InGaAs materials, it is necessary to restrain three-dimensional growth mode as far as possible. The growth mode of QWs will change with the change of growth conditions. Gao et al. [1] obtained high quality QWs by lowering temperature and increasing V/III ratio. The PL spectra are measured at room
temperature. The wavelength is 1040 nm and the full width half maximum (FWHM) is 26 nm. Jia et al. [2] studied the influence of growth temperature on the wavelength of InGaAs strained QWs, and also analyzed the influence of growth temperature on In segregation, resolution and In-Ga intermixing. Elliott et al. [3] designed a laser structure with mode expansion layers. The lasers with mode expansion layers exhibit lower threshold current and higher characteristic temperature, compared with lasers with asymmetric waveguide structure. In this paper, we use MOCVD to study growth temperature, V/III ratio and mode expansion layer to improve the PL properties.

2. InGaAs quantum well material growth

2.1 Growth temperature

The migration length of atoms is exponentially related to temperature [4]. With the decrease of temperature, the diffusion distance of adsorbed atoms decreases rapidly [5]. Therefore, the transition from 2D growth to 3D growth can be delayed by lowering the growth temperature, thus the critical thickness of quantum well layer can be increased and PL characteristics improved. Samples S1, S2 and S3 are designed for comparison. The QW layer growth temperatures of the three groups are 650 °C, 600 °C and 550 °C, respectively, and the barrier layer growth temperatures are 650 °C. The wavelength, FWHM of PL spectrum and intensity are analyzed.

![Figure 1. PL spectra of InGaAs QWs at different growth temperatures](image)

As shown in figure 1, with the decrease of growth temperature, the wavelengths of the three samples are 1060.4 nm, 1079.7 nm and 1102.1 nm, respectively. The wavelengths of the three samples show obvious red shift, which is related to the segregation and desorption equivalence of In. The expression of segregation coefficient and temperature is as follows [6]:

\[
R = \frac{1}{\exp \left( \frac{E_s}{kT} \right)}
\]

\[
E_s \text{ is segregation energy}
\]

and the atomic desorption rate can be expressed as

\[
M \propto N \exp \left( \frac{-E_{des}}{kT} \right)
\]

Among them, \( N \) is the surface concentration of atoms, \( E_{des} \) the desorption energy, \( T \) is the growth temperature of InGaAs QWs and \( k \) is the Boltzmann constant. It can be seen from formula (1) and formula (2) that with the increase of growth temperature, the segregation coefficient R increases, which leads to the increase of the concentration of In on the surface of QWs and increases the possibility of In desorption [7]. As a result, the composition of In in sample S2 is lower than that in
sample S3. Components of In in InGaAs affects the energy band of the material\(^8\), furthermore affects wavelength. As the temperature decreases, the composition of In increases, so the wavelength appears obvious red-shift.

At relatively high temperature, the thickness of QW is increased due to the diffusing effect of In atoms, resulting in a red-shift wavelength.

2.2 V/III ratio
The experimental results showed that with the increase of V/III ratio, the optical properties were significantly improved. Figure 2 shows the PL spectra of samples S4, S5 and S6.

![Figure 2. PL spectra of InGaAs quantum wells with different V/III ratio](image)

As can be seen from figure 2, the wavelengths of S4, S5 and S6 are 1031.8 nm, 1028.5 nm and 1051.2 nm, respectively. The wavelength of S4 is close to that of S5, but the wavelength of S6 shows a significant red-shift. The diffusion of In atoms is inhibited because of rising V/III ratio, resulting in increasing of In content and a red-shift wavelength. The PL peaks of the three samples are 0.07 mV, 0.13 mV and 0.23 mV, respectively. The PL peak of S5 is 1.8 times of that of S4, while the PL peak of S6 is 3 times of that of S4. Increasing V/III ratio decreases the time of In atom residence on the surface, inhibits the transformation of growth mode from 2D to 3D\(^9\), and improves the intensity of PL.

2.3 Mode expansion layer
Lastip module in crosslight software is used to simulate and compare the conventional quantum well structure and lasers with mode expansion layer structure\(^{10}\). The width of the laser is 50 µm, the cavity length is 1000 µm, and the reflectivity of the front and back cavity films is 5% and 95%, respectively. Ordinary laser epitaxy structure: In\(_{0.2}\)Ga\(_{0.8}\)As/GaAs single QW in active layer, 10 nm in width. The waveguide layer is trapezoidal, which is Al\(_{0.35}\)GaAs, the thickness is 0.02 µm, and the component gradient layer is Al\(_x\)GaAs with thickness of 0.15 µm, and X is gradient from 0.35 to 0.55. The confinement layer is 1.2 µm thick Al\(_{0.55}\)GaAs.
Figure 3. Refractive index profile versus distance of the structure with mode expansion layer and the calculated electric field amplitude at facet (near-field) for device with extra mode expansion layers (solid line) and the general structure (dotted line).

Figure 4. Calculated far-field intensity profile in the vertical direction for structure with extra mode expansion layers (solid line) and for the general structure (dotted line). The peak intensities have been normalized for ease of comparison of the FWHM angles.

The doping concentration of N-type extended waveguide layer is $1 \times 10^{18}$ cm$^{-3}$ and the P-type is $7 \times 10^{17}$ cm$^{-3}$. The refractive index of the laser with the mode-extended layer structure and the near-field optical field comparison with the conventional structure laser are shown in figure 3. The left longitudinal axis is the intensity of the optical field, and the right longitudinal axis is the effective refractive index. The transverse axis is the thickness of the laser epitaxy layer. Refractive index difference effectively limits the optical field. At the same time, it can be seen from the figure that the distribution of the central optical field in the two laser structures is the same, while the structure of the mode spreading layer producing a secondary peak on both sides of the main peak$^{[11]}$. The secondary peaks locate exactly where mode expansion layers are as shown in figure 3. Inducing mode expansion layers leads to the expansion of near-field, thus the confinement factor and far-field divergence angle...
are decreased. Figure 4 shows a comparison of the vertical divergence angles of two different structures in the far-field\(^{12}\).

3. Conclusion

The effects of growth temperature and V/III ratio on the growth quality of strained InGaAs quantum wells are studied by MOCVD. Reducing the growth temperature is conducive to inhibiting the segregation and desorption of In, affecting the composition of the actual In and the width of the well layer, resulting in the red-shift of the wavelength, and improving the optical properties. Increasing the V/III ratio can improve the PL intensity. Crosslight software is used to simulate the laser epitaxy structure with mode expansion layer. Compared with conventional structure lasers, the mode expansion layer expands the near-field, reduces the optical confinement factor, improves the COD threshold of the laser, and reduces the vertical divergence angle of the far-field.

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