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Optical investigation of InAs/InP(100) quantum dots grown by gas source molecular beam epitaxy

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ABSTRACT

We report on the optical characteristics of InAs quantum dots based on the InP(100) substrate grown by gas source molecular beam epitaxy without assisting any other methods. The photoluminescence was carefully investigated by adjusting the thickness of InAs layers and the growth temperature. A wide range of emitting peaks is obtained with the increase in the thickness of InAs layers. In addition, we find that the morphology and shape of quantum dots also greatly depend on InAs layers. The images of atomic force microscopy show that the quantum dots like forming into quantum dashes elongated along the [01 −1] direction when the thickness of InAs layers increased. A critical thickness of formation quantum dots or quantum dash is obtained. At the same time, we observe that the growth temperature also has a great impact on the emission wavelength peaks. High qualities of InAs/InP(100) quantum dots providing their emission wavelength in 1.55 μm are obtained, and good performances of quantum dots lasers are fabricated.

1. Introduction

There is an increasing interest in employing low dimensional quantum dots (QDs) for optoelectronic devices, since QDs exhibit unique electronic and optical properties compared with conventional quantum-well (QW) structure [1–3]. Up to now, most of studies have been carried out on the system of InAs/GaAs quantum dots due to a larger lattice mismatch between the InAs and GaAs. A high density of InAs/GaAs QDs and good performance of QDs laser have been obtained [4–7]. However, for the system of InAs/InP quantum dots, providing their wavelength in the optical communication region of 1.55 μm is still in its infancy.

For the InAs/InP system of QDs, the properties, that is, the density, size distribution, the morphology and shape of QD, greatly depend on the crystal orientation of InP substrate ((311)B InP, InP(100)). On a high-index (311)B InP substrate, it offers a high density of nucleation points for dot formation, which can strongly reduce the indium surface migration effects and leads to the formation of more symmetric QDs, and then a high gain profile and high density of $10^{11}\,cm^{-2}$ InAs QDs can be easily obtained [8,9]. Unfortunately, high-index substrates have great disadvantages in device processing, like facet cleaving and anisotropic etching. Therefore, growth on InP(100) substrates is performed to address better the manufacturability issue [10]. However, the growth process of InAs QDs on InP(100) substrate is more complex than that of InAs QDs on (311)B InP substrate, which greatly depends on the growing procedures and equipments. In particular, for high quality of InAs/InP(100) QDs, three methods have been reported to obtain the desired emission wavelength: (1) two-step growth of the InAs QDs on InP substrate [11], (2) applying ultrathin GaAs or GaP interlayer between InAs QD layer and the buffer layer [12,13] and (3) formation of QDs by (In,Ga)As layers with very low Ga composition instead of pure InAs layer [14]. Most studies were carried out on metal–organic vapor-phase (MOVPE) [14] and chemical-beam epitaxy [12,13]. Recently, Lelarge et al. [15], reported that buried ridge QDs laser was directly grown by gas source molecular beam epitaxy (GSMBE) with two steps of growing process. However, the high temperature MOVPE regrowth of p-doped InP cladding and InGaAs contact layers has a great impact on the size of QDs, which leads the emitting peaks shift to short wavelength. So far, there are a few reports about the InAs/InP(100) QD grown by GSMBE; further studies are required.

In this article, we investigate the properties of InAs QDs on the InP(100) substrate grown by gas source molecular beam epitaxy without assisting any other particular procedure mentioned above. The shape of the QDs and the emission wavelength are found to depend greatly on the thickness of InAs layers and the growth temperature. With the increase in InAs layers, the QDs on InP(100) substrate like forming into one-dimension quantum dash

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elongated along the [01 −1] direction, which decreases the size uniformity and density of quantum state. In addition, we study the growth temperature dependent emission wavelength of QDs under a fixed thickness of InAs layers. When the growth temperature increased, we observe that the emission wavelength shifts to longer wavelength. At the same time, a high density of 10^{10} cm^{-2} InAs QDs being suitable for active region of QD laser is obtained. Ridge waveguide quantum dots laser with 3.0MLs InAs layers grown at temperature of 485 °C is processed. The laser can operate up to 70 °C under continuous-wave mode.

2. Experiment

The samples of InAs QDs were grown on nominally (1 0 0) exact oriented n-type InP(1 0 0) substrates by gas source molecular beam epitaxy using gallium and indium as sources of III element. On the other hand, the V element sources are obtained by introducing AsH_3 and/or PH_3 through high temperature where the gases are thermally decomposed at 1000 °C. The InAs QDs were directly grown on a lattice matched quaternary 200 nm InGaAsP optical confinement layer (λ_g = 1.18 μm) without any capping layers. The bottom cladding layers are 600 nm n-typed InP buffer on InP(1 0 0) substrate. The QDs layer was formed with InAs growth rate of 0.1ML/s, while the AsH_3 pressure in the gas line as set at 630 Torr and the growth chamber pressure was measured as 1.5×10^{-5} Torr during the InAs QD growth. In order to investigate the size of quantum dots against emission wavelength, the thickness of InAs layer was chosen as 2.0MLs, 3.0MLs, 3.5MLs and 4.0MLs, respectively. The growth temperature is 485 °C. At the same time, another two samples with 3.0MLs InAs layers were grown at the temperature of 455 and 515 °C, respectively. The surface morphologies of InAs QDs were measured by an atomic force microscope. The photoluminescence (PL) spectra were collected by a Fourier transform infrared spectrometer. Two laser structures consisting of five-stacked InAs QD layers embedded in InGaAsP waveguide were processed with InAs layers of 3.0MLs and 3.5MLs, respectively. The growth temperature is the same as 485 °C.

3. Results and discussions

In InAs/InP(1 0 0) quantum dots, the emission wavelength is greatly dependent on the thickness and growth procedures of InAs layer. In addition, the growth equipment also plays an important role in the formation of QDs. For example, when the InAs QDs are deposited on metal–organic vapor-phase and chemical-beam epitaxy, a short time growth interruption is needed under As flux. To find available growth conditions for InAs/InP QDs by GSMBE, we deposit the samples without assisting any other methods but adjusting the thickness of InAs layers and growth temperature.

The room temperature PL spectra of QDs with different thickness of InAs layers are shown in Fig. 1. With the increase in InAs layers, the PL peaks continuously shift to longer wavelength and reach to 1648 nm when the thickness of InAs layer rises up to 4.0MLs. However, for InAs QD layers of 2.0MLs, four peaks are observed in the PL spectrum, as shown in the inset of Fig. 1. The central wavelength peaks are around at the 1180 nm, 1422 nm, 1783 nm and 1970 nm, which are marked by peak 1, peak 2, peak 3 and peak 4, respectively. Peak 1 is from the optical confinement's layer of InGaAsP, and peak 2 comes from the wetting layer, while the longer wavelength of peak 4 and peak 3 originates from the ground-state (GS) and excited-state (ES) of larger quantum islands. The energy separation between the GS and ES is only 65 meV, which is close to the value of 55 meV reported on InP(3 1 1)B substrate [16]. In contrast, the InAs/GaAs QDs have GS–ES splitting

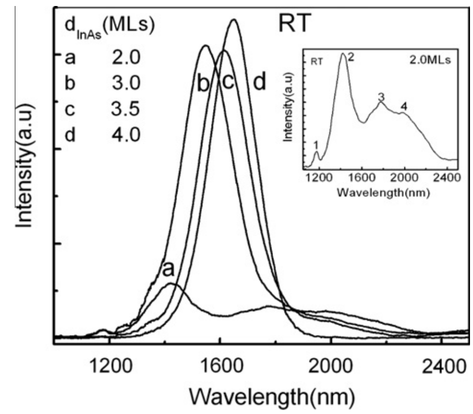

Fig. 1. PL spectra at room temperature of InAs QDs on the lattice matched InGaAsP with the thickness of InAs layers of 2.0MLs, 3.0MLs, 3.5MLs and 4.0MLs. The inset is magnifying the PL spectra of 2.0MLs InAs layers.

more than 90 meV [17]. At the same time, the intensity of PL is the lowest, indicating that the density of nonradiative center is smaller than that of the other three samples. For InAs QDs on InP(1 0 0), the thickness of wetting layer is little larger than that of InAs/GaAs quantum dots because of a small lattice mismatch between the InAs and InP (3%). On the other hand, thickness of InAs layers would be formed on the surface due to As/P exchanges. Typically, the critical thickness of InAs layer is 1–2MLs on the InP substrate [18]. So, the thickness of 2.0MLs is little above the critical thickness of InAs QDs on InP(1 0 0), only a few larger islands are formed, which lead to the longer wavelength, while for InAs thickness of 3.0MLs, the emission wavelength just happens to be the interesting optical communication window of 1.55 μm. When the thickness of InAs layers is above 3.0MLs, the emission wavelength shifts to longer wavelength and reaches to 1648 nm as InAs layers rise up to 4.0MLs. Moreover, we find that the PL linewidth is related to the thickness of InAs layers. The PL linewidth reduces from 108 meV to 92 meV when the thickness of InAs layers increases from 3.0MLs to 3.5MLs.

Compared with a high-index (3 1 1)B InP substrate, the InP(1 0 0) substrate shows a relative lower density of nucleation points for island formation, which largely increases surface migration effects. The morphology and shape of QDs largely depend on the thickness of InAs layers. The morphology of the InAs surface QDs grown on the InGaAsP barrier at the temperature of 485 °C is measured by atomic force microscope (AFM), as shown in Fig. 2. The InAs layers with thickness of 3.0MLs, 3.5MLs and 4.0MLs were measured. For InAs QDs of 3.0MLs, the QDs show a uniform size distribution with a mean dot height and mean base diameter of 2.9 nm and 76 nm, respectively, as shown in Fig. 2(a). A high density of QDs in the 10^{10} cm^{-2} range is obtained. The typical dimensions of the QDs for thicknesses of 3.5MLs and 4.0MLs are the mean dot height of 3.1 nm, 2.8 nm and base diameter of 100 nm and 160 nm, respectively. With the increase in thickness of InAs layers, the QDs like forming into quantum dash elongated along the [01 −1] direction due to the cation of indium migration in the surface of InGaAsP along [1 0 0] direction. The elongated quantum dash performs like the one-dimension quantum wire, which reduces the quantum confinement for carriers in this direction and then decreases the density of quantum state and quantum efficiency. As can be seen from Fig. 2(b), with the thickness of InAs layer rising up to 3.5MLs, only the larger size of QDs is elongated along (1 0 0) direction and forms into quantum dash. However, when the thickness of InAs rises up to 4.0MLs, one-dimension quantum dash/or wire is formed. By further increasing the thickness of InAs layers, all the QDs are formed into quantum dash, which have been reported by other groups [19]. In the GSMBE growth system, the thickness