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Effect of epilayer's growth temperature on crystalline quality of $InAs_{0.6}P_{0.4}$/InP grown by two-step growth method

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ABSTRACT

$InAs_{0.6}P_{0.4}$ epilayers grown by low-pressure metalorganic chemical vapor deposition (LP-MOCVD) on InP (1 0 0) substrates were investigated. A two-step growth method, in which low-temperature (450 °C) $InAs_{0.6}P_{0.4}$ buffer layers were introduced into the structure, was employed to relax the mismatch between the $InAs_{0.6}P_{0.4}$ and InP substrate. The effect of epilayer's growth temperature on crystalline quality of $InAs_{0.6}P_{0.4}$ epilayer was studied by X-ray diffraction, scanning electron microscopy, Hall measurements, and photoluminescence spectrum. The characterization results showed that the growth temperature is an important factor for obtaining good quality and property of $InAs_{0.6}P_{0.4}$ epilayers and 530 °C is the optimum epilayer's growth temperature in our experimental conditions.

1. Introduction

$InAs_xP_{1-x}$ alloys show excellent promise due to the wide range of attainable band-gap energies from 0.36 eV to 1.35 eV in the application of optical devices such as the photodiodes [1], avalanche photodiodes for detection in the range 1.6–2.5 μm [2], the laser diodes used in 1.3 μm [3], the quantum dot lasers with the wavelength tuned to 1.55 μm [4], high electron drift velocity devices, and the quantum well modulators [5]. However, in $InAs_xP_{1-x}$/InP heteroepitaxy, using dissimilar materials may lead to poor structures and degrade the electrical and optical properties of the materials. The problem can be reduced by growth of buffer layers with or without graded lattice parameters. A step-graded buffer layers in composition is often used to inhibit the dislocations to propagate towards the active layer of $InAs_xP_{1-x}$ materials [6]. But a single approach can simplify the growth procedure, such as the two-step growth method. It has been adopted to grow high mismatch epilayers, in which the low-temperature growth of thin buffer layer is followed by annealing and then growth of thick epilayer at higher temperatures [7]. The low-temperature buffer layer is believed to act as a template for succeeding high-temperature grown epilayers and to accommodate lattice strain caused by both lattice mismatch and thermal one. SiGe, AlGaN, InAs and GaN with two-step growth method [8–11] have been studied. However, $InAs_{0.6}P_{0.4}$ epilayers grown on InP substrate with this growth method is rarely reported.

In this paper, we report LP-MOCVD growth of $InAs_{0.6}P_{0.4}$ epilayers on InP (1 0 0) substrates with two-step growth method and investigate the effect of epilayer's growth temperature on crystalline quality of $InAs_{0.6}P_{0.4}$ epilayers. The X-ray diffraction (XRD), scanning electron microscopy (SEM), Hall measurement and photoluminescence (PL) spectrum are used to evaluate the property of materials.

2. Experimental

Experiments were carried out in a horizontal reactor by LP-MOCVD. All the samples were grown on semi-insulating InP (1 0 0) substrates at a pressure of 70 Torr. Palladium-diffused hydrogen was used for carrier gas at a total flow of 2.0 L/min. The substrates were heated by inductively coupling RF power and temperatures were detected by a thermocouple. The growth was performed using trimethylindium (TMIn), arsine (PH_3) and arsine (AsH_3) diluted to 10% in H_2 as precursors. The two-step growth process can be described as follows. At first, an $InAs_{0.6}P_{0.4}$ buffer layer of 200 nm was grown on InP substrates at 450 °C to relax the mismatch between the $InAs_{0.6}P_{0.4}$ and InP substrate. Then, the deposition of $InAs_{0.6}P_{0.4}$ epilayer was followed after the temperature rises from 450 °C to the $InAs_{0.6}P_{0.4}$ epilayer's growth temperature. In our experiments, the epilayer's growth temperature was selected from 500 °C to 580 °C, and the thickness was fixed 1 μm. The epilayers with growth temperatures of 500 °C, 530 °C, 550 °C, and 580 °C were named as samples (A), (B), (C), and (D), respectively.

3. Results and discussions

The crystalline quality of $InAs_{0.6}P_{0.4}$ epilayers with different epilayer's growth temperatures were studied by XRD measurement. Fig. 1 shows the XRD results of the samples (A), (B), (C), and (D). The alloy composition was estimated from XRD peak position of the alloy using Vegard's law [12], which is displayed in inset of

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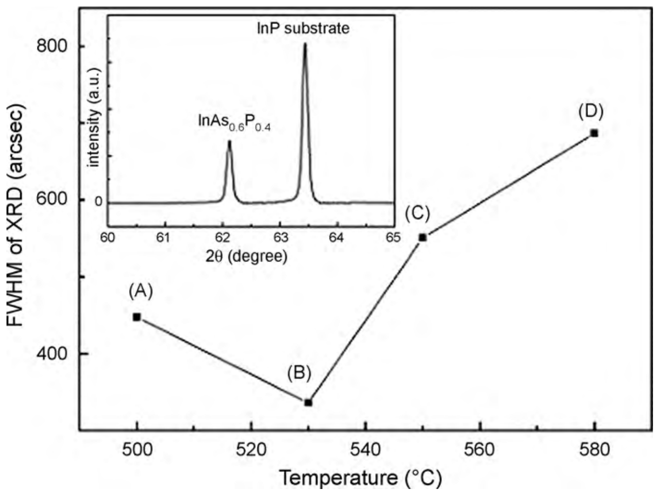

Fig. 1. Dependence of the FWHM of the X-ray diffraction of samples on epilayer's growth temperatures. The inset is the X-ray diffraction of the sample (B).

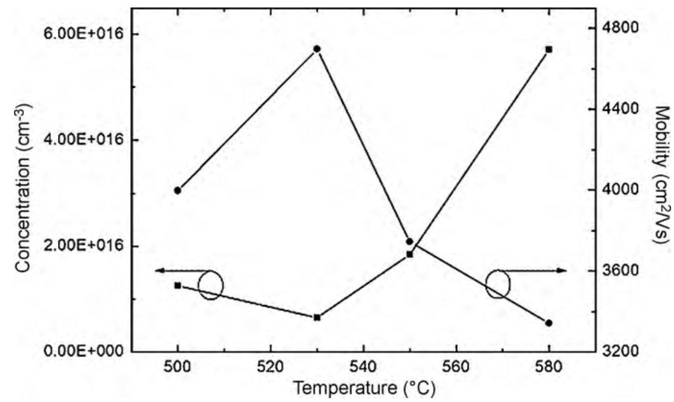

Fig. 3. Variation of carrier concentration and mobility for $InAs_{0.6}P_{0.4}$ epilayers with growth temperatures.

Fig. 1. For samples (A), (B), (C), and (D), the full width at half maximum (FWHM) of XRD is 448 s, 336 s, 550 s, and 686 s, respectively. It is clear that the FWHM of sample (B) is the smallest of the four samples and indicates the crystalline quality of the sample (B) is optimum. In our experiments, the growth parameters such as the thicknesses of buffer layer and epilayers, the As content, and the reactor pressure are identical of the four samples except for the epilayer's growth temperature. It is reasonable to speculate that the change of the FWHM of the XRD of $InAs_{0.6}P_{0.4}$ epilayer is related to the epilayer's growth temperature. It is found that the selection of growth temperature is important to improve the crystalline quality of $InAs_{0.6}P_{0.4}$ epilayers.

SEM is used to study the surface morphology of the samples. The surface morphology of samples (A), (B), (C), and (D) is shown in Fig. 2. In Fig. 2(A), the surface corrugations that form weak cross-hatched patterns are visible. In Fig. 2(B), the cross-hatched patterns disappear and the surface becomes flat and smooth. The surface morphology is improved. The surface morphology in Fig. 2(C), is similar to that of Fig. 2(B), but some pyramid-like pits appear in the smooth surface. In Fig. 2(D), a grainy surface with some pits defects is developed. This indicates that 3-dimensional (3D) growth mode takes place. It is evident that the surface morphology of sample (B) is better than those of samples (A), (C), and (D). The improvement of surface morphology indicates that the epilayer's growth temperature is optimized. It is known that growth temperature can provide migration power for the surface atoms in the surface-diffusion process during growth and play an important role in the transition of growth mode. When the growth temperature decreases, surface atoms diffusion is restricted and the 3D growth mode is delayed. Therefore, when the epilayer was grown at 500 °C, lower than the optimum temperature, the surface atom migration and nucleation or motion of dislocations in the epilayers was restricted, the corrugations were formed and then cross-hatched patterns appeared [13,14]. However, when the growth temperature increased to 530 °C, the surface was flat and smooth. The morphology is improved greatly. When the growth temperatures were higher than 530 °C, such as 550 °C and 580 °C, the surface atom had so much energy to migrate that the 3D growth enhanced and the residual strain was relaxed by introduction of misfit dislocations as the appearance of the pyramid-like pits. The surface morphology was degraded. This indicates that the growing of $InAs_{0.6}P_{0.4}$ with two-step growth method at an appropriate growth tem-

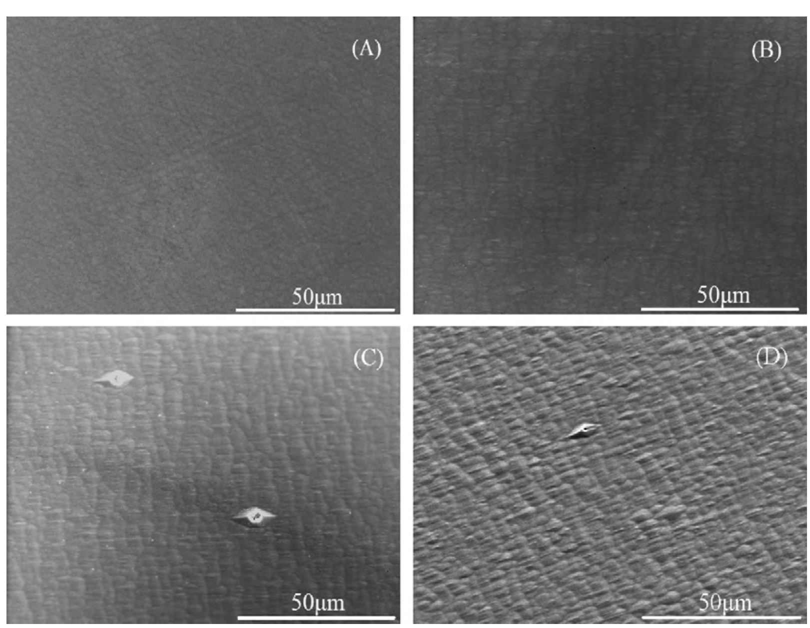

Fig. 2. Surface morphology of $InAs_{0.6}P_{0.4}$ epilayers grown on InP substrates for samples (A), (B), (C), and (D), respectively.

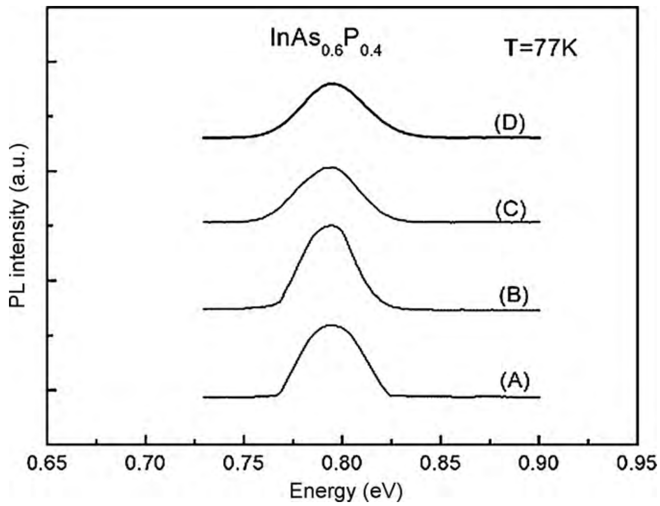

Fig. 4. PL spectra of $InAs_{0.6}P_{0.4}$ epilayers on InP grown at (A) 500 °C, (B) 530 °C, (C) 550 °C, and (D) 580 °C, respectively.

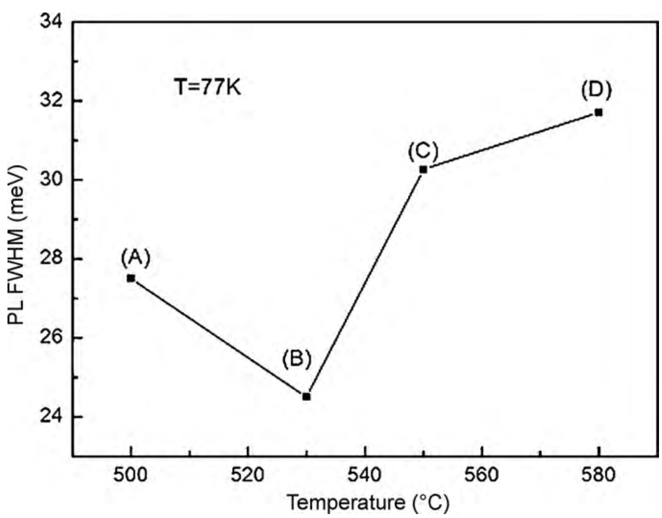

Fig. 5. The FWHM of PL for samples (A), (B), (C) and (D) with different growth temperatures of the $InAs_{0.6}P_{0.4}$ epilayer.

perature is essential in improving the surface morphology of its epilayers.

Hall measurements are used to further characterize the crystalline quality of $InAs_{0.6}P_{0.4}$ epilayers. Room temperature electron property of the $InAs_{0.6}P_{0.4}$ epilayers is measured with magnetic field of 2100 G. The results of Hall measurements are shown in Fig. 3. The carrier concentration of samples changes from 1.25×10^{16} cm^{-3} to 5.72×10^{16} cm^{-3} with the growth temperature rising from 500 °C to 580 °C, and it has lowest value at 530 °C. On the other hand, the mobility of samples increases from 3998 cm^2/Vs to 4697 cm^2/Vs with increasing the growth temperature from 500 °C to 530 °C, and it decreases from 4697 cm^2/Vs to 3342 cm^2/Vs with rising the growth temperature from 530 °C to 580 °C. It is clear that sample (B) has the lowest carrier concentration and highest electron mobility. It is obvious that the changes of carrier concentration and mobility are related to epilayer's growth temperature. In the epilayers, the residual misfit dislocations in epilayers act as scattering centers and reduce the carrier mobility [15,16]. Defects of the $InAs_{0.6}P_{0.4}$ epilayer are decreased by optimizing the epilayer's growth temperatures. Hereby, the density of misfit dislocations in the epilayer of sample (B) is the least.

PL spectrum is another useful way to characterize the crystalline quality of $InAs_{0.6}P_{0.4}$ epilayers. Fig. 4 shows the PL spectrum of the four samples measured at 77 K. The band-gap energy of the samples is about 0.7944 eV that is consistent with the value of 0.7952 eV calculated with the formula $E_g = 1.407 - 1.073x + 0.089x^2$ in [17]. The FWHM of PL is 27.5 meV, 24.5 meV, 30.2 meV, and 31.7 meV, as shown in Fig. 5, corresponding to samples (A), (B), (C), and (D), respectively. For sample (B), the FWHM of PL is the minimum. Generally, luminescent efficiency for the band edge emission increases when the purity of the crystal increases. Some defects such as misfit dislocations are known to quench luminescence due to nonradiative recombination as well as to broaden photoluminescence linewidths. So the change of the FWHM of PL is related to the growth temperatures of the epilayers. The PL results also indicate that sample (B) grown at 530 °C has better crystalline quality.

4. Conclusions

In summary, $InAs_{0.6}P_{0.4}$ epilayers with different growth temperatures were grown on InP substrate by LP-MOCVD with two-step growth method. The crystalline quality of the samples was characterized using the XRD, SEM, the room temperature Hall measurement and PL spectrum. The experimental results show that the crystalline quality could be improved by employing an appropriate epilayer's growth temperature. In particular, the epilayer's quality is optimum when the growth temperature of the epilayer is 530 °C. Our work shows a simple way on how to design for the suitable epilayer in the heteroepitaxy of $InAs_xP_{1-x}$ on InP substrate.

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