Growth Modes of InP Epilayers Grown by Solid Source Molecular Beam Epitaxy*

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Abstract: The surface morphologies of InP epilayers grown by solid source molecular beam epitaxy at different growth temperatures and P/In flux ratios have been systematically studied by atomic force microscopy (AFM). The results show that the remarkable variety of surface morphologies of samples is related to the transition of growth mode. Under a critical growth condition, a transition of growth mode is induced between a two-dimensional (2D) growth mode and a three-dimensional (3D) growth mode. On the basis of these results, a summary phase diagram is proposed for the growth mode of InP epilayers. Under the 2D growth region, high quality InP epilayers are obtained.

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1 Introduction

Semiconductor thin film structures fabricated on InP substrates are crucial for a wide range of electric and optoelectronic devices[1,2]. High-quality undoped InP grown by SSMBE with a valve phosphorus cracker cell is the base for growing P-containing epilayer materials. A prerequisite to obtaining high-quality InP layers is to have a deep understanding of the growth mechanisms. The transition from the low-temperature growth mode of island nucleation to step-flow growth at higher temperature has been studied by RHEED[3] and STM[4], and a great deal of attention has been focused on unstable growth caused by the Ehrlich-Schwoebel (ES) effect[5,6], i.e., by additional barriers to adatom hopping at step edges, since these barriers hinder interlayer transport, three-dimensional (3D) features (pyramids or mounds) appear during grown on a high-symmetry (singular) surface, forming a pattern with a characteristic lateral dimension[7]. For good quality layers this must be avoided, because the appearance of 3D features is a clear sign of nonoptimum growth conditions. However, there have been few studies concerned with optimizing the growth of InP films, with examining their detailed morphology. In this paper, we investigate the effects of the growth conditions on the surface morphology of InP films grown by SSMBE. Our aim is to better understand the origin of the growth modes and analysis of the mechanisms and optimization regime of the growth condition.

2 Experiment

The unintentionally doped InP epilayers were grown on InP (100) substrates by a Riber Compact 21 MBE system equipped with a Riber KPC250 valve phosphorus cracker cell.

The cracker zone temperature was fixed at 850℃, and the bulk evaporator temperature was fixed at 250℃. The beam equivalent pressure of

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phosphorus (P_2) (BEP_{ph} = 0.266~0.665mPa) was precisely adjusted by controlling the valve opening of the phosphorus cracker cell using an automatic position controller. The beam equivalent pressures of indium (BEP_{In}) were 0.093 ~ 0.173mPa for growth rates of 0.4~0.8μm/h, respectively.

3 Results and discussion

The surface morphology and the root-mean-square (RMS) roughness exhibit a pronounced dependence on the growth temperature, as shown in Fig. 1 and Fig. 2. The results indicate that at the lowest growth temperature of 360℃, there is clear evidence of 3D pyramidal mounds[8,9] on the surface with heights of up to 17.17nm and lateral dimensions of up to 2.32μm and RMS roughness of up to 5.04nm. As shown in A1 of Fig. 1 and Fig. 2, the formation of mounds is attributed to the presence of an enhanced SE-type barrier, which increases the incorporation probability in the sites close to step edges, preventing atoms from diffusion downwards, and it is more likely for the nucleus to form on top of existing islands before the layer underneath is completed. On the other hand, at lower growth temperatures, the lager 3D growth may be associated with the adatoms' having a more limited mobility at lower growth temperature, so that clusters form by random collision on terraces and grow by accretion. When the growth temperature was increased to 365℃ (A2 in Fig. 1 and Fig. 2), the RMS surface roughness of the samples abruptly decreased to 0.30nm. There are no large islands on the surface, the height of the biggest islands is 0.72nm (<3ML), and the biggest step height is about 0.59nm (<2ML), which is typical for a 2D step flow growth mode[10]. In that case, the growth mode changes from a 3D island growth mode to a 2D step flow growth mode. When the growth temperature increases from 365℃ (A2) to 410℃ (A4), the RMS surface roughness of the samples slightly decreased to 0.2~0.3nm. The cross-section scan profile shows that there are many islands on the terraces. The biggest height of these islands is less than 0.76nm (<3ML), and the biggest step height is about 0.52nm (<2ML), which is typical for a 2D step flow growth mode. When the substrate temperature increases from 410℃ (A4) to 441℃ (A5), the RMS surface roughness rapidly increases to 1.27nm, the lateral dimension increased to 2.86μm, and there appear rough pyramidal mounds on the surface with heights of up to 3.38nm. In this interval, increasing the growth temperature leads to the growth transition from 2D growth to 3D growth[11]. This is because the

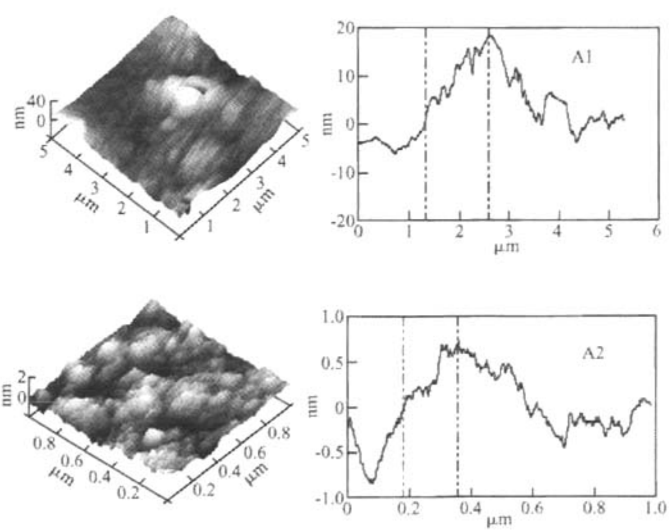

Fig. 1 3D surface plots and cross-section scan of InP epilayers grown on InP(100) at different substrate temperatures

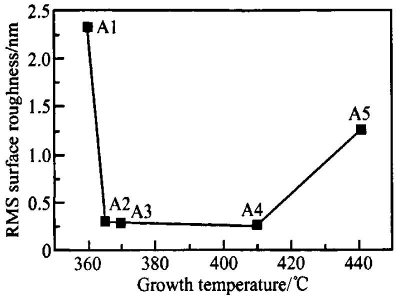

Fig. 2 Plot of RMS roughness as a function of substrate temperature

use of high substrate temperature increases the rate of phosphorus adsorption, decreases the incorporation coefficient[12], and leads to a deficiency of phosphorus at the growth front. The group V deficient growth condition probably leads to a build-up of excess In on the surface, resulting in the surplus indium accumulating on the surface to form large-scale 3D pyramidal mounds.

Figures 3 and 4 show the dependence of the morphology and the RMS roughness upon the V/III ratio for the samples grown at different P/In BEP ratios. The results indicate that at a lower V/III ratio of 2.2(B1), there are pyramidal mounds on the surface with heights of up to 5.89nm and lateral dimensions of up to 1.37μm. The RMS roughness of sample B1 is 2.11nm, as shown in B1 of Fig. 3 and Fig. 4. The formation of large-scale mounds has been attributed to a deficiency of phosphorus, which results in the surplus indium accumulating on the surface to form large-scale 3D pyramidal mounds. When the V/III ratio increased to 2.4 (B2 in Fig. 3), the RMS surface roughness abruptly decreased to 0.30nm; the cross-section scan profile shows that there are no large islands on the surface, the height of the bunched and faceted step structure reaches up to 0.72nm (<3ML), and the lateral dimension is about 0.39μm. The steps height is about 0.52nm (<2ML), which is typical for a 2D step flow growth mode. In this case, the growth mode changes from a 3D island growth mode to a 2D step flow growth mode. When the V/III ratio increases to 3.6 (B3 in Fig. 3), the RMS surface roughness slightly decreases to 0.28nm, and the growth mode, as with sample B2, is a pure 2D step flow growth mode. The RMS surface roughness from B4 to B5 is almost in the same level and below 0.24nm, indicating that there are many 2D islands on the terraces. The height of the biggest island is less than 0.58nm (<2ML), and the biggest step height is about 0.52nm (<2ML), revealing that the growth mode has changed from pure step flow to step flow accompanied by nucleation of islands on the terraces[13]. See B4 in Fig. 3 and B5 in Fig. 3 and Fig. 4. The results show that the surface morphology of layers grown at higher V/III ratios have smoother surface morphologies than layers grown at lower V/III ratios.

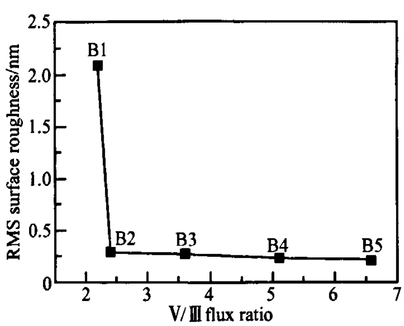

Fig. 3 Plot of RMS roughness as a function of V/III flux ratio

Analysis of these data produced the map of the growth regimes with growth conditions shown in Fig. 5. It is important to notice that the presence of a critical T_s ($[T_s]^{Min}$) between 360 and 370℃ (about 365℃), a critical T_s ($[T_s]^{Max}$) between 410 and 441℃ (about 417℃), and a critical V/III ratio ($[V/III]^{Min}$) between 2.2 and 2.6 (about 2.4) which divide the growth region into two distinct regimes. These critical parameters of $[T_s]^{Min}$, $[T_s]^{Max}$ and $[V/III]^{Min}$ mark the transition between the 2D growth mode and the 3D growth mode. We can obtain an acceptable optimization growth region according to the results of RMS roughness. Region A is a 2D smooth growth regime with RMS roughness below 0.5nm, and region B is a 3D roughened growth regime with RMS roughness above 0.5nm.

4 Conclusion

The results show that the morphology of InP epilayers are affected mainly by growth temperature and P/In flux ratio. The remarkable variety

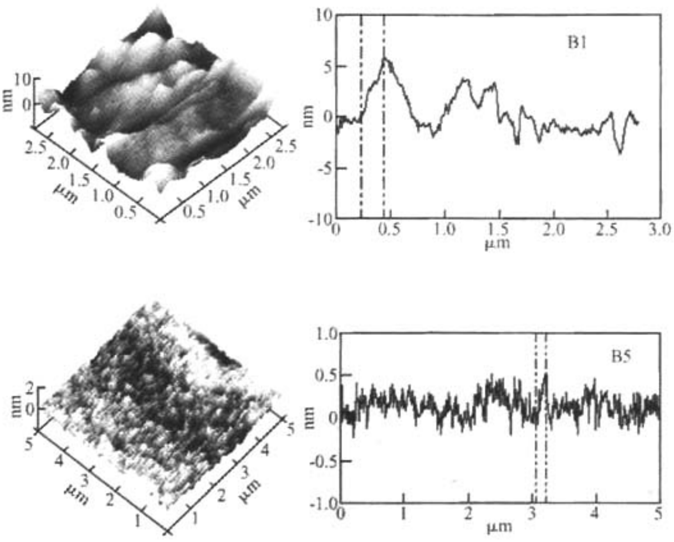

Fig. 4 3D surface plots and cross-section scan of InP epilayers grown at different P/In BEP ratios

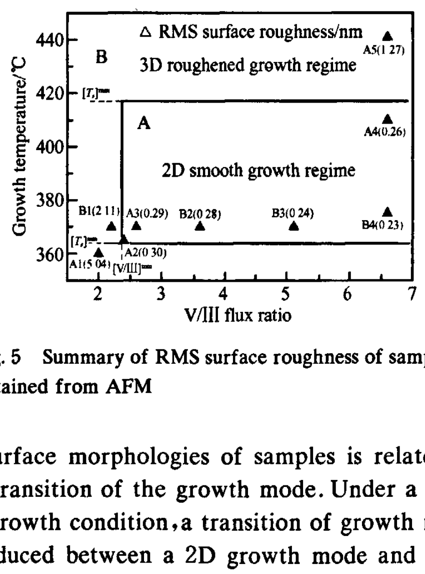

Fig. 5 Summary of RMS surface roughness of samples obtained from AFM

of surface morphologies of samples is related to the transition of the growth mode. Under a critical growth condition, a transition of growth mode is induced between a 2D growth mode and a 3D growth mode. In the optimized growth process (growth temperature 364～417℃ and P/In flux ratio bigger than 2.37), the smooth 2D growth surface morphology have been achieved.

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InP外延材料的MBE生长模式*

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摘要：采用固态磷源分子束外延技术，在不同的生长条件下生长了InP外延材料，并用原子力显微镜对样品表面形貌进行了系统研究. 实验结果表明，样品表面形貌的显著变化与生长模式发生变化有关；二维(2D)生长模式和三维(3D)生长模式之间存在转换的临界工艺条件. 通过对实验数据的分析，绘制了InP外延生长模式对应工艺条件的区域分布图；在2D生长区域获得了高质量的InP/InP外延材料.

关键词：固态源分子束外延；InP；生长模式

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