MBE Growth of High Electron Mobility InP Epilayers *

Shu Yongchun[1], Yao Jianghong[1], Lin Yaowang[1,2], Xing Xiaodong[1], Pi Biao[1], Xu Bo[2], Wang Zhanguo[1,2], and Xu Jingjun[1]

(1 *Key Laboratory of Advanced Technique and Fabrication for Weak-Light Nonlinear Photonics Materials, Ministry of Education, Nankai University, Tianjin* 300457, *China*)

(2 *Key Laboratory for Semiconductor Materials Science, Chinese Academy of Sciences, Beijing* 100083, *China*)

Abstract: The molecular beam epitaxial growth of high quality epilayers on (100) InP substrate using a valve phosphorous cracker cell over a wide range of P/In BEP ratio (2.0～7.0) and growth rate (0.437 and 0.791μm/h). Experimental results show that electrical properties exhibit a pronounced dependence on growth parameters, which are growth rate, P/In BEP ratio, cracker zone temperature, and growth temperature. The parameters have been optimized carefully via the results of Hall measurements. For a typical sample, 77K electron mobility of $4.57\times10^4 cm^2/(V\cdot s)$ and electron concentration of $1.55\times10^{15} cm^{-3}$ have been achieved with an epilayer thickness of 2.35μm at a growth temperature of 370℃ by using a cracking zone temperature of 850℃.

Key words: SSMBE; high electron mobility; InP epilayers

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1 Introduction

Using a solid-state phosphorus source in molecular beam epitaxy (SSMBE) for the growth of phosphorus-containing materials is a good choice not only for environmental considerations but also for device application. Reproducible growth of quantum well lasers with excellent performance[1,2] and GaInP/GaAs heterostructure bipolar transistors (HBT) with a high yield[3] have been demonstrated by SSMBE.

Growth and electrical properties of InP epitaxial layers by SSMBE with a valve phosphorus cracker cell were first reported by Tsang *et al.*[4] in 1982. They found the growth temperature had a very significant effect on the quality of the InP layers. In 1985, Martin *et al.*[5] identified sulphur as the dominant impurity in unintentionally doped InP grown by MBE from solid sources, and obtained an electron mobility of $1.33\times10^4 cm^2/(V\cdot s)$ at 77K. In 1994, Postigo *et al.*[6] reported that a lower P/In BEP ratio had a lower carrier concentration and obtained an electron mobility of $1.48\times10^4 cm^2/(V\cdot s)$ at 65K with an epilayer thickness of 2.0μm by an atomic layer SSMBE. In 1997, Yoon *et al.*[7] reported that a high cracking zone temperature caused high acceptors, and demonstrated their electron mobility of $2.55\times10^4 cm^2/(V\cdot s)$ and carrier concentration of $5.65\times10^{15} cm^{-3}$ at 77K with a layer thickness of 2.5μm. In 1998, Yoon *et al.*[8,9] demonstrated the highest electron mobility of $4.09\times10^4 cm^2/(V\cdot s)$ and carrier concentration of $1.74\times10^{15} cm^{-3}$ at 77K by using a cracking zone temperature of 850℃.

In this paper, we report a comprehensive study of InP epilayers which have been grown on InP (100) substrates by an SSMBE system using a valve phosphorus cracker cell. The effects of (growth parameters: growth rate of epilayers, P/In

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BEP ratio, and growth temperature) on electrical properties of the epilayers have been studied. Under the optimum growth conditions, the InP/InP epilayer with a thickness of 2.35μm shows an electron mobility of $4.57\times10^4 cm^2/(V\cdot s)$ and an electron concentration of $1.55\times10^{15} cm^{-3}$ at 77K.

2 Experiment

The unintentionally doped InP epitaxial layers were carried out in a Riber Compact 21 MBE system equipped with a Riber KPC250 valve phosphorus cracker cell. The purities of phosphorus and indium charge used were 7-nine, respectively supplied by Rasa Industries of Japan. In order to reduce the background impurities, before and after loading source materials, the baking of the MBE system, and degassing of the P and In cell are very important. The cracker zone temperature has a very significant effect on electron mobility and carrier concentration; lower electron concentration and higher electron mobility were obtained at a lower cracker zone temperature[2,6,10]. If the cracker zone temperature was lower than 800 ℃, then the cracking efficiency of P_4 to P_2 was generally poor[9]. If the cracker zone temperature was lower than 850 ℃, it caused excessive white phosphorous accumulation in the growth chamber. We fixed the cracker zone temperature at 850 ℃ and the bulk evaporator temperature at 250 ℃. The beam equivalent pressure of phosphorus (P_2) (BEP_{ph}) was precisely adjusted by controlling the valve opening of the phosphorus cracker cell using an automatic position controller. The growth chamber cooled by liquid nitrogen reached a pressure less than 2.0×10^{-8} Pa before the growth run. The beam equivalent pressure of indium (BEP_{In}) was 7.0×10^{-5} and 1.29×10^{-4} Pa for growth rate 0.437 and 0.791μm/h, respectively.

Averbeck *et al*.[11] reported lowering the temperature of deoxidation could lead to higher oxygen on the InP surface and could be oxygen-free at 490 ℃. But, Barnes *et al*.[12] indicated that the incorporated coefficient of P_2 decreased from 0.94 at 360 ℃ to 0.54 at 470 ℃. This behavior is attributed to the increasing fraction of the incident P_2 flux that desorbs from the substrate at a higher temperature and does not contribute to the layer growth. The temperature-dependent incorporation coefficient implies the need for high P/In flux ratios and low substrate temperature for preparation of smooth InP epilayers. In our growth experiments, the deoxidation temperatures of 390～410 ℃ were chosen for considering the surface morphology of epilayers and impurity incorporation. Considering the effect of growth temperature on the incorporation coefficient[12], the growth temperatures were chosen from 360 to 390 ℃. The thickness of the InP epilayers was 2.0～2.50μm.

3 Results

The effect of growth rate on the electrical properties of the InP at the same P/In BEP ratio of 3.5 are shown in Table 1. It shows that the higher electron mobility ($2.85\times10^3 cm^2/(V\cdot s)$ at 300K and $3.50\times10^4 cm^2/(V\cdot s)$ at 77K) and the lower electron concentration ($9.82\times10^{15} cm^{-3}$ at 300K and $3.16\times10^{15} cm^{-3}$ at 77K) have been obtained with a higher growth rate (0.791μm/h). This can be attributed to the lower probability of impurities incorporating into the epitaxial layer at the higher growth rate. However, too high a growth rate is not beneficial for stoichiometric growth since a higher growth rate needs a higher phosphorus BEP. The results of Ref. [6] showed that the higher quality InP epilayers were grown at a lower BEP of phosphorous.

Table 1 Effect of growth rate on electrical properties of InP epilayers

Sample	L016	L018
Growth rate/($\mu m\cdot h^{-1}$)	0.437	0.791
Electron mobility at 77K/($cm^2\cdot V^{-1}\cdot s^{-1}$)	2.70×10^4	3.50×10^4
Electron mobility at 300K/($cm^2\cdot V^{-1}\cdot s^{-1}$)	1.97×10^3	2.85×10^3
Electron concentration at 77K/cm^{-3}	4.67×10^{15}	3.16×10^{15}
Electron concentration at 300K/cm^{-3}	2.43×10^{16}	9.82×10^{15}

The experiment results show that the optimum growth temperatures are in the range from 365 to 385 ℃, with the highest mobility being obtained at 370 ℃. The highest mobility was respectively reported by Yoon *et al*. [7] and Postigo *et al*. [6]; the growth temperatures used by them were 480 ℃ and 340 ℃, respectively. Our experimental results show that electron mobility at 77 K dropped remarkably at a growth temperature less than 480 ℃ or higher than 350 ℃. Each run of the growth experiment was determined from surface reconstruction transformation by the reflection high-energy electron diffraction (RHEED) [13].

Figure 1 shows the plot of electron mobility and concentration of the InP as a functions of the P/In BEP ratio at 77 K. The results clearly show a significant increase in electron mobility from 1.59 $\times 10^4$ to 4.57 $\times 10^4 cm^2/(V \cdot s)$, when the P/In BEP ratio is reduced from 7.0 to 2.5. The electron concentration exhibites a corresponding decrease from 1.06 $\times 10^{16}$ to 1.55 $\times 10^{15} cm^{-3}$ following the variation of the mobility. Further reduction in the P/In BEP ratio from 2.5 to 2.0 caused the mobility to reduce dramatically, but the electron concentrations remained at the same level.

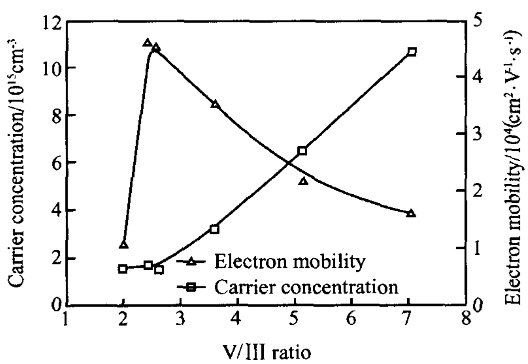

Fig. 1　Electron mobility and concentration of InP as functions of P/In BEP ratio at 77 K

Figure 2 shows the plot of electron mobility and concentration of the InP as functions of the P/In BEP ratio at 300 K. We can notice that the electron mobility and concentration varied from 3.17 $\times 10^3$ to 2.11 $\times 10^3 cm^2/(V \cdot s)$ and from 2.16 $\times 10^{16}$ to 7.70 $\times 10^{15} cm^{-3}$, respectively, as the P/In BEP ratio varied from 7.0 to 2.5. At the same time, the electron mobility decreasing with electron concentration increasing is observed as the P/In BEP ratio is lower than 2.5. A similar experiment had been observed by Postigo *et al*. [5]. The surface morphology of the sample grown at a P/In ratio of 2.0 was badly damaged, which appeared to be a serious phosphorus deficiency, and too low BEP ratio was not beneficial for stoichiometric growth. We suggest the reason is attributed to phosphorus vacancies or deep level defects, and more discussion will be reported in another paper.

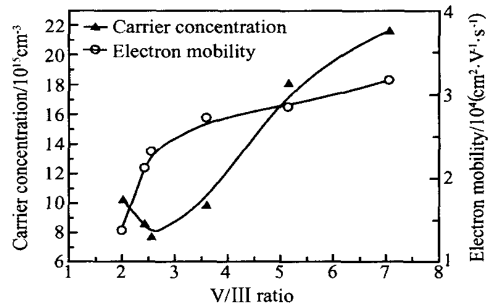

Fig. 2　Electron mobility and concentration of InP as functions of P/In BEP ratio at 300 K

4　Summary

In summary, high quality InP epitaxial layers have been grown on InP (100) substrates by SSMBE using a valve phosphorus cracker cell. The experimental results demonstrate that the electron concentration of the unintentional doped InP epilayers can be reduced from 1.06 $\times 10^{16}$ to 1.55 $\times 10^{15} cm^{-3}$ at 77 K by variation of the growth parameters which are the P/In BEP ratio, the growth rates of InP epilayers, and the growth temperatures. The 77 K electron mobility of 4.57 $\times 10^4 cm^2/(V \cdot s)$ and the concentration of 1.55 $\times 10^{15} cm^{-3}$ with epilayers thickness of 2.35 μm have been achieved via optimizing growth parameters. To the best of our knowledge, it is the highest value ever achieved in an InP epilayer grown by MBE.

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高电子迁移率 InP/InP 外延材料的 MBE 生长*

舒永春[1] 姚江宏[1] 林耀望[1,2] 邢小东[1] 皮 彪[1] 徐 波[2] 王占国[1,2] 许京军[1]

(1 南开大学弱光非线性光子学材料先进技术及制备教育部重点实验室, 天津 300457)

(2 中国科学院半导体研究所 材料科学重点实验室, 北京 100083)

摘要: 采用固态磷源分子束外延技术在 InP(100) 衬底上生长了高质量的 InP 外延材料. 实验结果表明 InP/InP 外延材料的电学性质与诸多生长参数密切相关. 根据霍耳测量结果, 对生长条件和实验参数进行了优化, 在生长温度为 370 ℃, 磷裂解温度为 850 ℃, 生长速率为 0.791μm/h 和束流比为 2.5 的条件下, 获得了厚度为 2.35μm 的 InP/InP 外延材料. 在 77K 温度下, 电子浓度为 $1.55 \times 10^{15} cm^{-3}$, 电子迁移率达到 $4.57 \times 10^4 cm^2/(V \cdot s)$.

关键词: 固态源分子束外延; 高电子迁移率; InP/InP 外延材料

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