

## Heavily Doping of GaAs with Be for Application to $p^+$ -type AlGaAs/GaAs Heterojunction Infrared Detector

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### Abstract

The structural, electrical, and optical properties of Be-doped GaAs for various doping concentrations were studied using double crystal X-ray analysis, van der Pauw measurements, photoluminescence and infrared absorption measurement. It is found that there exists an average critical doping concentration, i.e.,  $2 \times 10^{19}/\text{cm}^3$ , beyond which the lattice mismatch between the epilayer and GaAs substrate occurs and the Be outdiffusion is significantly enhanced. The absorption coefficient of Be-doped GaAs in the 8-10  $\mu\text{m}$  region with carrier concentration of  $5 \times 10^{19}/\text{cm}^3$  are found to be about  $10^4 \text{ cm}^{-1}$  which is high enough to be applied to AlGaAs/GaAs heterojunction infrared detector.

## 1 Introduction

Be is one of the most commonly used p-type dopant for III-V compound semiconductor in molecular beam epitaxy (MBE). Among all the uses of Be-doped GaAs, heavily doped p-type GaAs ( $> 10^{19}/\text{cm}^3$ ) has been frequently used in device application such as heterojunction bipolar transistors [1], [2]. However, the heavy doping of GaAs with Be encounters a serious problem, Be outdiffuses very fast into the substrate under high doping condition [3]-[6] which degrades the device properties catastrophically. Recently, a new type of infrared detector based on ( $p^+$ ) SiGe/Si heterojunction which can detect infrared in the 8-12  $\mu\text{m}$  region [7]. The idea is to heavily dope the SiGe layer with p-type dopant, then the infrared can be detected using heavy to splitting off hole band transition and free carrier absorption. This suggests that the same idea can be applied to (p)AlGaAs/( $p^+$ )GaAs heterojunction in which the infrared can be absorbed by heavy to light hole band transition and free holes absorption in ( $p^+$ ) GaAs.

However, the Be outdiffusion problem in heavily doped ( $p^+$ ) GaAs must be first understood and solved, then its application to infrared detector becomes feasible. There have been many reports on the Be outdiffusion problem in GaAs [4]-[6]. In this paper, we present a more detail and systematic studies on the structural, electrical, and optical properties of Be-doped GaAs with various doping

concentrations. As a result, a stress-induced diffusion model is proposed to explain the fast outdiffusion of Be in GaAs.

## 2 Experiments

The films reported here were grown in VG MKII MBE system and deposited on the GaAs (100) semi-insulating substrates. The preparation of GaAs substrates involved ultrasonic degrease in  $6\text{H}_2\text{SO}_4 : 1\text{H}_2\text{O}_2 : 1\text{H}_2\text{O}$  solution for 2-minute, indium bonded on molybdenum block, followed by outgassing at  $300^\circ\text{C}$ . The growth temperature was  $600^\circ\text{C}$  and the growth rate used was  $1 \mu\text{m}/\text{hr}$  under  $\text{As}_4$ -rich conditions. The various doping level could be achieved by changing the temperature of Be effusion cell. All of the epilayer thicknesses were about  $1 \mu\text{m}$  unless otherwise noted.

## 3 Results

Material characterizations included Hall measurements, double crystal X-ray analysis, photoluminescence (PL) and infrared absorption.

The Hall measurements were made by using van der Pauw method. However, because of the fast Be diffusion into the GaAs substrate, the actual p type layer thickness might be wider than the epilayer thickness. The Be-distributed depths were determined as follows: the sample was etched step by step and its resistance is measured at each step.

Because the substrates were semi-insulating and the Be-distributed region had lower resistance, once this layer was totally etched off, the layer resistance would rise up dramatically. At this time, the sample was rinsed in deionized water, so the Be-distributed depth could be measured using the surface profiler. Once the thickness of the p-type layer is determined, the average hole concentration could be calculated. Fig.1 shows average hole concentration thus measured as a function of the reciprocal Be cell temperature. The highest hole concentration achieved is  $6.3 \times 10^{19}/\text{cm}^3$  under a Be cell temperature of  $1150^\circ\text{C}$ . Fig.2 shows the relation between the Be outdiffusion length into the GaAs substrate and the average hole concentration. The Be outdiffusion length is defined to be the Be-distributed depth subtracting the epilayer thickness. From Fig.2 we can find when the hole concentration exceeds  $2 \times 10^{19}/\text{cm}^3$ , somehow, Be outdiffusion seems to be enhanced. Due to the outdiffusion process, it is found in Fig.1 that the doping concentration gradually saturates with increasing Be cell temperature. Hence, the maximum doping concentration seems to be limited to below  $10^{20}/\text{cm}^3$ .

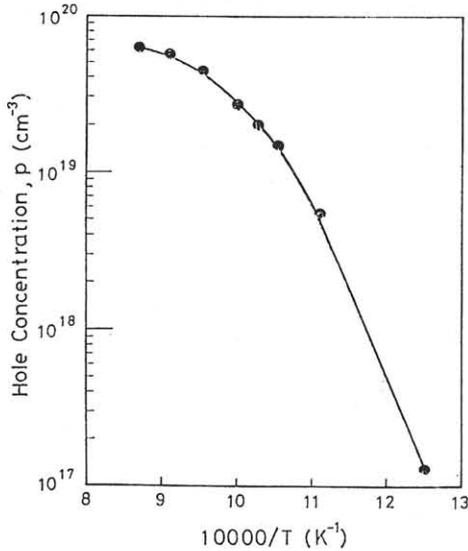


Figure 1: Hole concentration of Be-doped GaAs versus reciprocal Be cell temperature

In order to investigate what happens when the doping level exceeds the critical concentration of  $2 \times 10^{19}/\text{cm}^3$ , the double crystal X-ray spectra are taken. Fig.3 shows the double crystal X-ray spectra for various doping concentrations. For the average concentration less than the critical concentration,  $2 \times 10^{19}/\text{cm}^3$ , the spectra consist of only one diffraction peaks which is caused by (400) diffraction beam. However, when the average concentra-

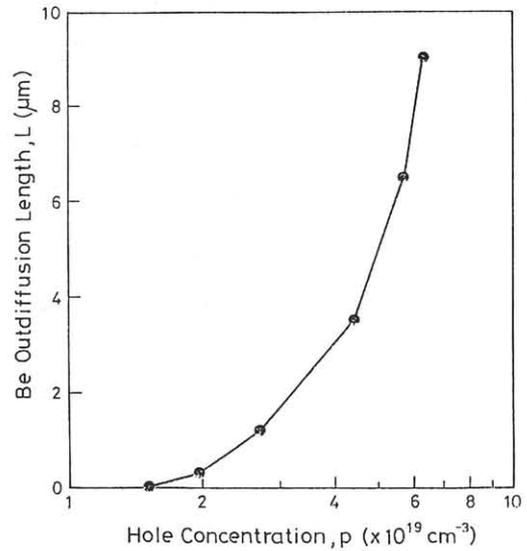


Figure 2: Be outdiffusion length versus hole concentration

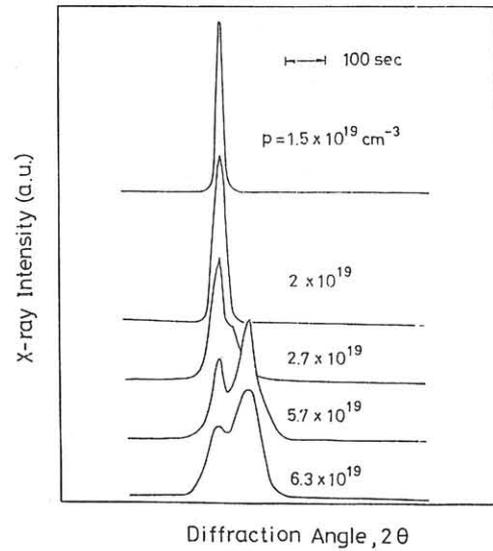


Figure 3: Double crystal X-ray diffraction curve of Be-doped GaAs with different hole concentration

tion is above the critical concentration, an additional peak emerges at the diffraction angle larger than the original (400) peaks. It means that when the doping level exceeds the critical concentration the epilayer starts to shrink. This is because the size of the Be atom is smaller than Ga. When the Be atoms enter into GaAs and occupy the Ga sites to become p-type dopant, the material becomes strained. Once the amount of dopant is too much and the stress exceeds the limit, the epilayer shrinks and the Be starts to outdiffuse quickly into the GaAs substrate. This clearly suggests that the Be outdiffusion process is related to the lattice mismatch between the epilayer and substrate, which tends to strain the GaAs substrate and enhance the

Be diffusion rate in it.

PL measurements were taken at 40K. Fig.4 shows the function of the full width at half maximum (FWHM) of PL peaks versus the average hole concentration. From Fig.4, it can be found that the FWHM of PL peaks increase from 6 meV to 30 meV as the average hole concentration increase from  $1.3 \times 10^{17}/\text{cm}^3$  to  $2 \times 10^{19}/\text{cm}^3$ . However, when average hole concentration reaches  $2.7 \times 10^{19}/\text{cm}^3$  the PL peak shrinks from 30 meV to 13 meV and is broadening again at higher hole concentration. Because the FWHM of PL peaks is a indication of the quality of the material, so the abrupt change of the FWHM of the PL peak seems to indicates that the epilayer quality become better when the doping level exceeds  $2 \times 10^{19}/\text{cm}^3$  and the epilayer is relaxed.

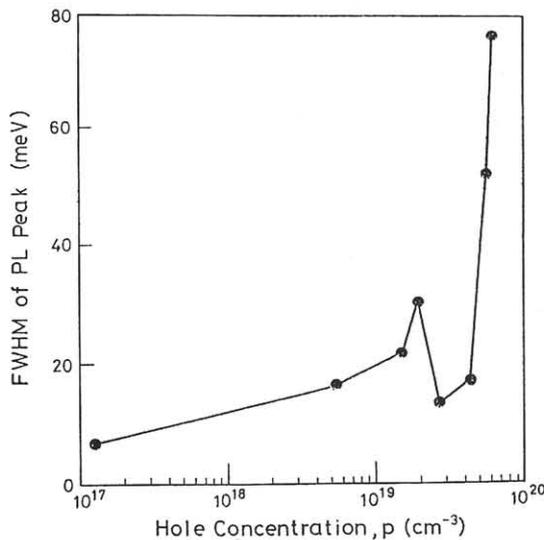


Figure 4: FWHM of PL peaks as a function of hole concentration

Another striking feature for the heavily Be-doped GaAs is its ability to absorb the infrared radiation. Because the doping level is so high, it is believed that the free carrier absorption and the heavy to light hole absorption occur. The infrared absorption measurements are taken and the absorption coefficient  $\alpha$  at  $10 \mu\text{m}$  wavelength versus the average hole concentration is shown in Fig.5. It is clear that for hole concentration changing from  $2 \times 10^{17}/\text{cm}^3$  to  $5 \times 10^{19}/\text{cm}^3$ ,  $\alpha$  increase from  $500 \text{ cm}^{-1}$  to  $10^4 \text{ cm}^{-1}$ . This suggests that the heavily Be-doped GaAs is a good candidate for infrared detectors.

## 4 Conclusion

In summary, the physical properties of the Be-doped GaAs for various doping concentrations were investigated. It is found that there exists a critical

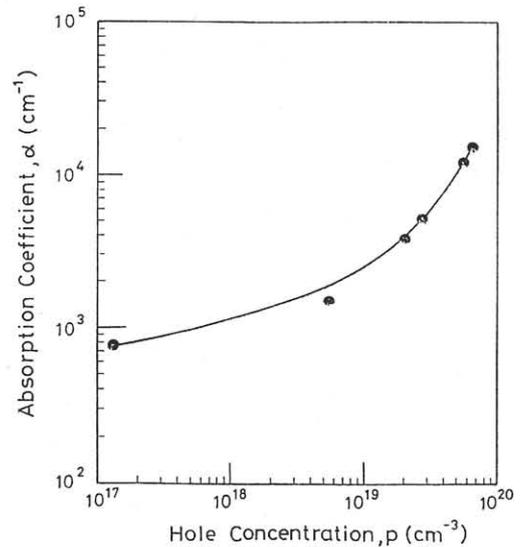


Figure 5:  $\alpha$  at  $10 \mu\text{m}$  versus hole concentration

hole concentration of  $2 \times 10^{19}/\text{cm}^3$  beyond which the lattice mismatch between epilayer and GaAs substrate will occur and the Be outdiffusion is greatly enhanced. This is attributed to the stress-enhanced diffusion in the GaAs substrate. The heavily Be-doped GaAs also show strong IR absorption in the  $8\text{-}10 \mu\text{m}$  region which can be applied to fabricate (p)AlGaAs/(p<sup>+</sup>)GaAs heterojunction infrared detector.

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