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Influence of Fe Doping Concentration on Some Properties of Semi-Insulating InP

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Abstract: Properties of Fe-doped semi-insulating (SI) InP with different iron concentrations are studied by using Hall effect, current-voltage (*I-V*), photoluminescence spectroscopy (PL) and photocurrent spectroscopy (PC) measurements. *I-V* characteristics of SI InP strongly depend on Fe doping concentration. Fe doping concentration also influences optical properties and defective formation in as-grown SI InP. Band-gap narrowing phenomenon and defects in Fe doped SI InP are studied using PL and PC.

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1 Introduction

InP is an important semiconductor material that has been used for the fabrication and development of opto-electronic and microwave devices[1,2]. Recent advances in InP-based microwave devices and integrated circuits have spured the development of high quality semi-insulating (SI) InP materials. Fe-doped SI InP is the commercial substrate for epitaxial growth of microwave device. In most cases, a concentration above $10^{16}cm^{-3}$ of Fe doping is necessary for the manufacture of SI InP substrate by the liquid encapsulated Czochralski (LEC) growth technique. The concentration of Fe increases significantly along the growth direction due to its small effective segregation coefficient[2~4]. Thus large uneven concentration of Fe exists between SI InP wafers sliced from LEC InP single crystal ingot. It is necessary to study the electrical properties, such as current transport, breakdown voltage, etc, which may influence the properties and reliability of InP devices of SI InP wafers with such uneven Fe concentrations. In this paper we investigate the electrical and optical properties of SI InP with different Fe doping concentration. The influence of Fe doping on some material properties has been presented.

2 Experimental procedure

Fe-doped SI InP wafers are sliced from a single crystal ingot grown by liquid encapsulated Czochralski (LEC) method in our laboratory. The solidified fraction of each sample on the ingot has been identified before slicing. In this way, Fe doping concentration of the sample can be estimated by the well-known impurity segregation relation: $C = C_0 k_{eff}(1-g)^{k_{eff}-1}$, where g is the solidified fraction, $k_{eff} = 1.6\times10^{-3}$ is the effective segregation coefficient of

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Fe in InP[2,4], C_0 is the initial doping concentration of Fe in the melt. Typical size of sample for the measurements of Hall effect, current-voltage (I-V), photoluminescence spectroscopy (PL) and optical current spectroscopy is around 6mm ×6mm ×0.6mm.

Before making ohmic contacts for electrical measurements, the samples are first lapped then etched and cleaned by the standard process for InP. Ohmic contacts for Hall measurement in Van der Pauw configuration are made using soldered indium dots. Gold spots of 1mm in diameter are deposited on one side and of 6mm in diameter on the other side of the sample to make electrical contacts for I-V measurement.

The I-V measurement system consisted of a HP 3245A programmable voltage generator which drove a programmable EG&G ORTEC 556H high voltage power supply, a Keithley 485 digital programmable electrometer and an IBM XT computer.

An original setup of PL system is used for the measurement of photoluminescence property. Optical current spectrum at room temperature of Fe doped SI-InP is measured by a homemade system. The light source is a tungsten-halogen lamp passed through a chopper and is dispersed by a monochrometor before being illuminated on the sample. The PC signal is picked up with a lock-in amplifier and then recorded by a X-Y recorder. Wafers polished on one side are used for these measurements.

3 Results and discussion

3.1 Hall and I-V measurements

Resistivity determined by Hall effect of the wafers increases from $10^7\Omega\cdot$cm at the ingot top to $10^8\Omega\cdot$cm at the ingot tail, which is a common phenomenon caused by Fe concentration increasing along the growth direction in LEC InP. It is certainly that compensation defined as $N_{Fe}/(N_D - N_A)$ increases rapidly since residual donor concentration $N_D - N_A$ only has small change while Fe concentration N_{Fe} increases quickly due to its segregation effect in the growth process[5].

Room temperature I-V curves of SI InP samples with different solidified fraction g on the ingot are shown in Fig. 1. It is apparent that the larger the g value, the stronger nonlinear I-V characteristic. Samples at the ingot top (small g value) exhibit linear I-V relationship (the slope of the curve is around unity by fitting), implying the compensation in these wafers is not so strong as those

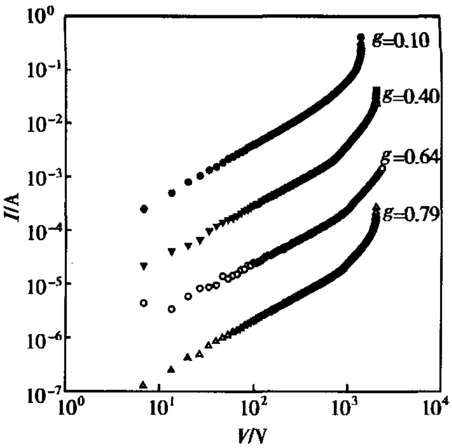

Fig. 1 Current-voltage relations of LEC Fe-doped SI InP sliced from an ingot at different solidified fractions and Fe concentrations: $g = 0.10, 3.55 \times 10^{16} cm^{-3}$; $g = 0.40, 5.33 \times 10^{16} cm^{-3}$; $g = 0.64, 8.87 \times 10^{16} cm^{-3}$; $g = 0.79, 1.52 \times 10^{17} cm^{-3}$ The curves are moved vertically for clarity.

wafers from other portion of the ingot (with big g value). This result is in agreement with the results of Hall effect and the space charge limited current theory for SI material of Lampert and Mark[6]. The voltage at which the quadratic I-V initiates is called trap filling limited voltage V_{TFL}. It is evident that V_{TFL} decreases with increasing of compensation in SI InP, corresponding to large solidified fraction. This suggests a gradual increasing concentration of uncompensated Fe impurity, i.e. Fe^{3+} concentration along the growth direction, consistent with the normal freezing relation result.

I-V curves from 295K to 400K of three samples at the ingot top, middle and tail have been measured. Resistance (R) obtained from the linear region of each curve is basically consistent to the results of Hall effect. Plots of R against $1/kT$ are straight lines with slopes of 0.60, 0.62 and 0.64 for the three samples, as shown in Fig. 2. This result can be explained with the following relation regarding electron concentration and resistivity of semiconductor in mind: $n = N_C \exp\left[-\frac{E_C - E_F}{kT}\right]$, $\rho = (\mu_n nq)^{-1}$, $R \propto \rho$. All symbols have normal meaning. At high temperature, $N_c \propto T^{3/2}$, $\mu_n \propto T^{-3/2}$, thus $R \propto \exp[(E_C - E_F)/kT]$. Therefore, the slopes of plots in Fig. 2 indicate Fermi level positions pinned by Fe deep acceptor in the three SI InP samples, suggesting a strong compensation in InP wafers from ingot tail. This result agrees well with the mentioned Hall effect and I-V results.

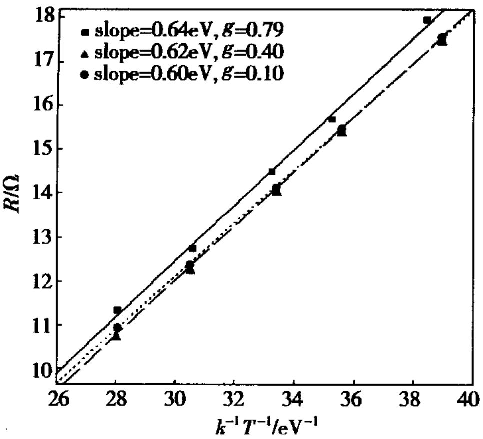

Fig. 2 Plots of resistance R vs $1/kT$ of three Fe-doped SI InP samples sliced at different solidified fractions of an ingot

3.2 PL and PC measurements

PL result of one SI InP sample with Fe concentration of about $6 \times 10^{16} cm^{-3}$ is shown in Fig. 3. A PL spectrum of a high temperature annealed undoped SI InP with very low residual Fe concentration (about $(2 \sim 4) \times 10^{15} cm^{-3}$)[7] is also shown in the figure. The PL feathers of the two samples are similar, except that the band edge luminescence intensity of the Fe-doped SI InP is very low. This is caused by the well-known fact that Fe is a deep nonradiative recombination center in InP. A small difference between the PL band-edge emission energy of annealed and Fe-doped as-grown SI InP can be seen. The band-edge energy of Fe-doped SI InP is smaller than that of annealed undoped SI InP with low Fe concentration. We attribute this phenomenon to the band-narrowing effect caused by high concentration Fe doping. It has been found that band-gap becomes narrow by a few tens meV for SI semiconductor doped with high concentration of deep level impurity[8,9]. The concentration of Fe in as-grown SI InP is higher than that in annealed undoped SI InP at least one order of magnitude, making the band gap narrowing effect be observed. The strong peak at 1.38eV and its phonon replica at 1.34eV are related with electron transition from conduction band to shallow acceptor impurity in InP[10~12].

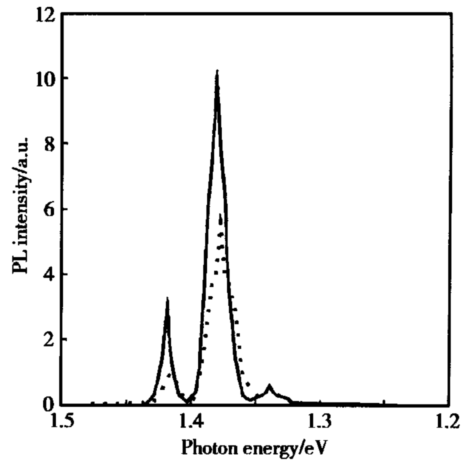

Fig. 3 PL spectra at 10K of a Fe-doped (dotted line) and an annealed undoped SI InP samples

A typical PC spectrum of two Fe-doped and one annealed undoped SI InP is shown in Fig. 4. Three peaks at 0.45, 0.66 and 1.32eV have been found in a Fe-doped InP. In other Fe-doped SI InP with relative low doping concentration, five peaks at 0.45, 0.49, 0.56, 0.66 and 1.33eV have been detected. Similar results of Fe-doped InP have been reported by photoconductivity and photo-induced transient current spectroscopy study before[13~15]. In contrast, eight peaks at 0.43, 0.45, 0.49, 0.57, 0.65, 0.77, 1.34 and 1.43eV have been de-

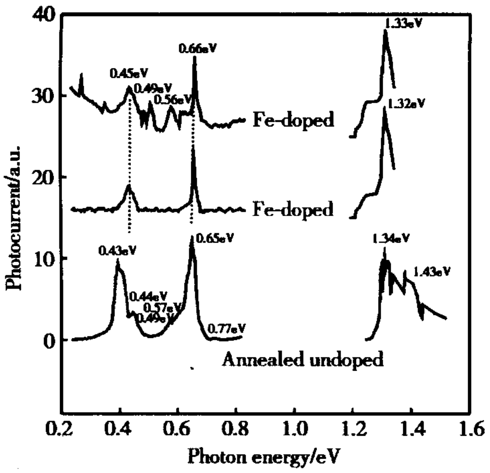

Fig. 4 Photo current spectra of Fe-doped and annealed undoped SI InP samples at room temperature

tected in annealed undoped SI InP. The two peaks at 0.45 and 0.64eV in Fe-doped SI InP are related to the electron excitation from two deep levels $^5T_2$ and ^5E of Fe in InP[13]. The peak at 1.33eV corresponds to the band edge excitation. The 1.43eV detected in annealed undoped InP is resulted from the electron excitation to the higher conduction band minimum[16]. It seems that Fe doping concentration influences the formation of defects in SI InP. The higher the Fe doping concentration, the less the number of defects in SI InP. Some defects in annealed undoped SI InP, which have been confirmed to be thermally induced[17,18], are absent in Fe-doped InP materials. Defects related with the 0.49 and 0.57eV peaks exist in both low Fe doping and annealed undoped SI InP. They are most likely native defects in the samples because such defects are absent in another SI InP with high Fe-doping concentration, excluding the possibility of impurity contamination. The result suggests that Fe doping concentration influence the formation of defects in InP. This is in agreement with the result of Zerrai *et al*[19]. It also indicates that annealed undoped SI InP sample contains residual Fe since the Fe-related 0.44 and 0.65eV are detected simultaneously.

4 Summary

Fe doping concentration has strong influence on electrical transport property of SI InP. Band-gap narrowing effect has been observed in SI InP with very high concentration of Fe. Fe doping concentration influences the formation of defects in as-grown InP.

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掺铁浓度对半绝缘磷化铟的一些性质的影响

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摘要: 利用霍尔效应、电流-电压 (*I*-*V*)、光致发光谱 (PL) 和光电流谱 (PC) 研究了不同掺铁浓度的半绝缘 InP 的性质. 半绝缘 InP 的 *I*-*V* 特性明显地依赖于掺铁的浓度. 掺铁的浓度也对半绝缘 InP 的光学性质和材料中缺陷的形成有影响. 用 PL 和 PC 分别研究了掺铁半绝缘 InP 的禁带收缩现象和材料中的缺陷.

关键词: 磷化铟; 半绝缘; 缺陷

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