Contact free defect investigation in as grown Fe-doped SI-InP

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ABSTRACT

The methods of microwave-detected photo-induced current transient spectroscopy (MD-PICTS) and microwave-detected photoconductivity (MDP), which proved themselves as very successful for defect investigations in GaAs wafers, were applied to Fe-doped SI-InP samples. It was possible to observe characteristic defect levels. One important defect center showed a similar behavior as the well known EL2 defect in GaAs. This defect exhibits positive and negative PICTS signals depending on the Fe concentration. The associated activation energies show that these signals can be interpreted as an interaction of the $Fe^{2+/3+}$ level in InP with both, the valence and the conduction band.

Beside this major defect we discovered a wide range of shallow defects which may be important for material properties.

This result and successful microwave detected photoconductivity mappings of InP wafers show that the new non-destructive investigation methods provide valuable information on defect distribution and characteristics.

INTRODUCTION

Semi-insulating (SI) Indium Phosphide is a promising material with opto-electronic properties particularly suitable for high power and high frequency devices. Iron doping causes a deep acceptor level in the band gap. This $Fe^{2+/3+}$ level is located approximately 0.65 eV below the conduction band and is responsible for the compensation of residual donor levels [1]. In addition, it is necessary to find out, whether there are other defect levels present in as-grown SI-InP, which may affect the compensation mechanism.

In general, conventional PICTS spectra of Fe-doped InP reported in the literature show one dominant positive peak with a corresponding activation energy of 0.6 to 0.68eV. It is ascribed to the electron emission from the ionized Fe^{2+}-charge state into the conduction band [2-7]. Positive PICTS signals with an activation energy of 0.68 to 0.78eV are also assigned to the iron defect level. They are said to correspond to the transition of a hole from the iron level into the valence band [2,4,8].

Kaminski et al. [5,6] reported the occurrence of negative current transients during PICTS measurements of SI-InP samples and epitaxial layers. This means, the detected photo current falls below the equilibrium value after the photo excitation is turned off. These transients were assigned to the thermal emission of electrons from the iron acceptor level to the conduction band. Negative PICTS signals, which consequently result from such transients and are not yet published, are addressed in this paper. It is shown, that the occurrence of positive or negative

PICTS signals for the iron defect level depends on the iron concentration and can be interpreted as an interaction of this level with both the conduction and the valence band. At our best knowledge this is the first straight forward proof of the $Fe^{2+/3+}$ level acting as a recombination centre in InP. There are already several results from conventional PICTS measurements of SI-InP samples presented in the literature which point to this behavior [2]. However, we will point out, that some conclusions drawn in literature on the assignment of peaks have to be corrected.

Beside of the iron level many other defect levels are known from electrical measurements on InP in the literature. Levels with activation energies above 0.02 eV are mainly ascribed to native defects or compound defects of intrinsic defects and impurities [7,9].

An additional interest for the characterization of InP samples arises from the distribution of electrically active defects, which influence the properties of devices.

To clarify these questions, the methods of MD-PICTS and MDP, which proved themselves as very successful for defect investigations of GaAs wafers [10-13], were applied to Fe-doped InP samples for the first time. The advantage of using MD-PICTS and MDP compared to conventional methods is the possibility to investigate defect characteristics and their distribution in a contact-free, non-destructive way and with high spatial resolution. MD-PICTS provides also defect-specific topograms, e.g. the Fe-distribution in a Fe-doped SI-InP wafer.

EXPERIMENTAL DETAILS

The experimental setup for the microwave detected photocurrent measurements MDP and MD-PICTS was already described elsewhere [10-13]. Through band-to-band excitation ($h\nu \geq 1.3$eV) excess carriers are generated, which are detected via high sensitivity microwave absorption. Generated excess carriers can be trapped in different defect levels in the band gap and can subsequently be thermally re-emitted from these levels. This results in a characteristic decay of the photocurrent, when the excitation light is turned off. The MD-PICTS spectrum is derived from these photocurrent transients by analyzing them at different temperatures e.g. with the double gate technique, which is well known from DLTS measurements. Lateral inhomogeneities of the electrical properties of a wafer are obtained by scanning the wafer relative to the exciting laser spot.

The samples for the MD-PICTS and MDP investigations were taken from different parts of two VGF-grown Fe-doped crystals. The growth of the iron doped 2” InP crystals by the Vertical Gradient Freeze (VGF) technique was performed in a high pressure furnace with nine independent heating zones. In both experiments a flat bottom crucible and a seed crystal with full diameter were used. The initial Fe-concentration in the melt was $5{\cdot}10^{18}\,cm^{-3}$ (InPFe2) and $9{\cdot}10^{18}\,cm^{-3}$ (InPFe10), respectively. Therefore the observed samples also differ in their iron concentration. Taking a segregation coefficient of $k=1{\cdot}10^{-3}$ [1,14], the iron concentration varies between 0.5 and $2.1{\cdot}10^{16}/\,cm^{3}$. The resistivity of the samples is between 0.07 and $1.8{\cdot}10^{7}\,\Omega$cm. The MD-PICTS measurements were carried out from 100 to 500 K. MDP measurements were performed at room temperature to obtain the distribution of electrical active defects.

RESULTS

Resulting PICTS spectra are shown in Fig. 1 and Fig. 2. In the temperature range below 300 K several different characteristic defect levels can be observed, which differ from sample to sample (see Fig. 1), whereas systematic results were obtained for temperatures above 300 K.

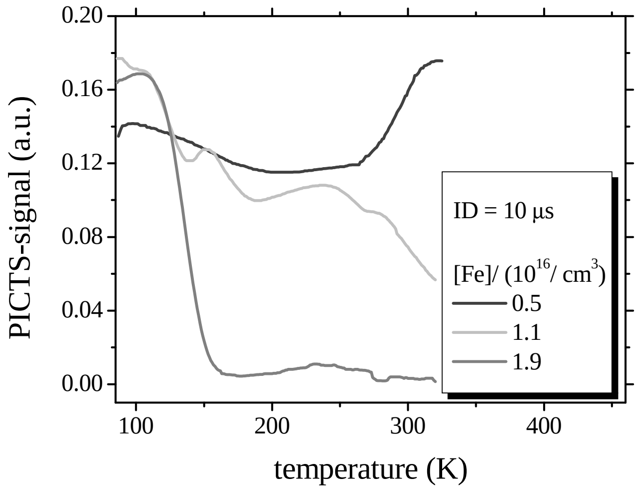

Figure 1: Comparison of MD-PICTS spectra of Fe-doped SI-InP samples with different iron content in the temperature range below 300 K (excitation energy: 1.45 eV). The samples differ in their characteristic defect levels.

For samples with comparatively low iron content, a positive PICTS peak at approximately 400 K can be observed with an activation energy of (0.6 ± 0.1) eV. The intensity of this positive peak decreases for samples with higher iron content, until the positive peak vanishes in the spectrum. Samples with an even higher iron concentration show a negative PICTS peak in the same temperature region as the former positive peak (see Fig. 2). The activation energy of the negative peak was determined as (0.7 ± 0.1) eV. PICTS peaks are denoted as negative, if the detected photoconductivity falls below the thermal equilibrium value, when the photo excitation is turned off (see Fig. 3).

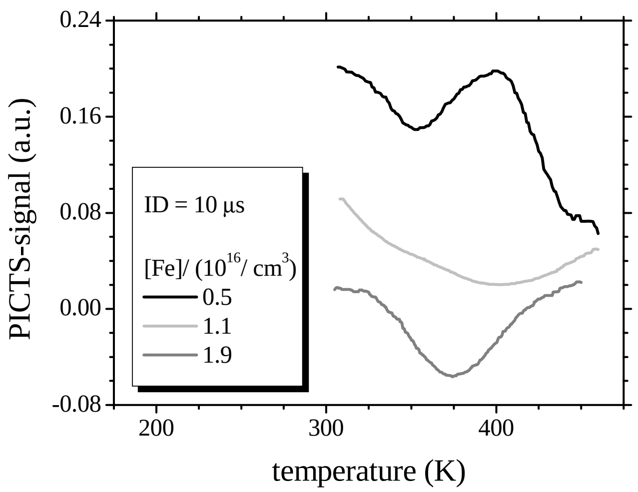

Figure 2: Comparison of MD-PICTS spectra of Fe-doped SI-InP samples with different iron content for temperatures above 300 K (excitation energy: 1.3 eV). The sign of the occurring peaks depends on the iron concentration of the samples.

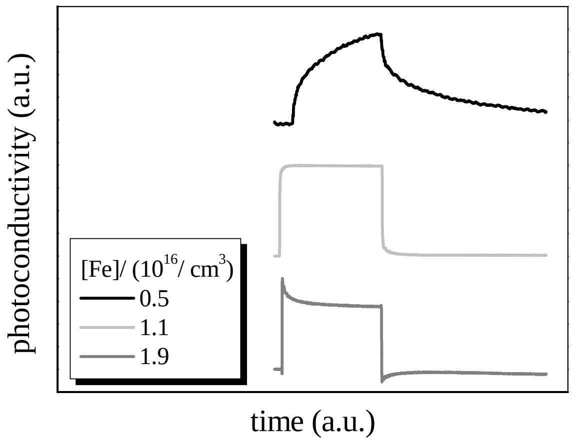

Figure 3: Measured light pulse response and transients (representative) of Fe-doped SI-InP samples with different iron contents in the temperature range with the occurrence of positive and negative MD-PICTS peaks (excitation energy: 1.3 eV).

Increasing the temperature to above 500 K during a MD-PICTS measurement leads to the observation of an additional positive peak with a maximum located at approximately 500 K. The corresponding activation energy is (1.1 ± 0.15) eV.

Fig. 4 presents one of the first results of photoconductivity mappings of InP wafers. That means it is possible to visualize electrical inhomogeneities of InP wafers by using the method of MDP non-destructively and with a high spatial resolution. Dark areas represent low photo-conductivity signals, whereas bright areas stand for higher signals. The contrast in this mapping symbolizes differences in photoconductivity which amount up to a factor of six. The photoconductivity is proportional to the square of the diffusion length of the minority carriers.

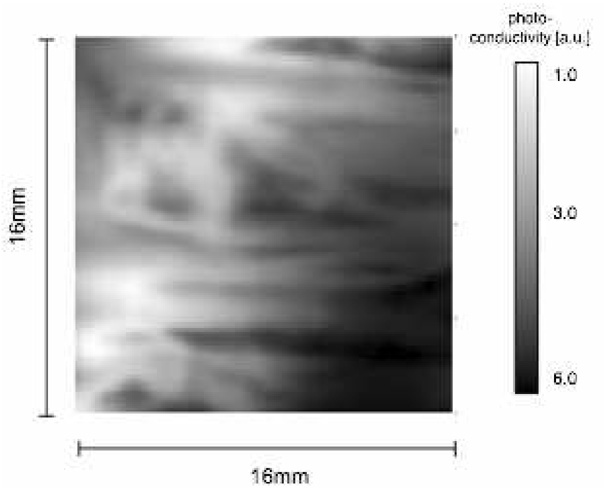

Figure 4: MDP-mapping of a Fe-doped SI-InP sample visualizing the distribution of defects with a noticeable influence on the electrical characteristics of the wafer at room temperature

DISCUSSION

A defect level with an activation energy of approximately 0.6 eV in Fe-doped InP, as can be found in the case of the positive MD-PICTS peak, was reported by several other groups from conventional PICTS and other electrical measurements. This level is ascribed to the thermal emission of electrons from the ionized Fe^{2+}-level into the conduction band [2-7]. This is why the occurrence of the positive MD-PICTS peak in our case is believed to be due to the same transition.

Positive conventional PICTS peaks with activation energies of approximately 0.7 eV, which agrees with the activation energy of our negative MD-PICTS signal, were also detected by other groups. These signals were assigned to hole emissions from the iron $Fe^{2+/3+}$ level into the valence band [2,4,8].

From a comparison of the results for InP with similar results for the EL2-defect in GaAs we can furthermore conclude, that the negative MD-PICTS peak must be assigned to the Fe-defect, too. The EL2-defect in GaAs as well as iron in InP incorporates a deep defect level in the band gap and therefore is responsible for the compensation of shallow defects. As it was proved for the EL2-defect in GaAs, the sign of the MD-PICTS peak related to this defect level depends on the occupation of the level with electrons and consequently on the transition rates between this level and both bands [15,16].

Because of this analogy it is concluded, that iron in InP (as well as the EL2-defect in GaAs) interacts with both bands. This assumption is underlined by the fact, that the sum of the activation energies of the positive and the negative MD-PICTS signals equals the band gap energy in InP. That means, iron was identified as a recombination centre in InP. The transition rates into both bands seem to depend on the iron concentration of the samples. This concentration is believed to be responsible for the occupation of the iron level and therefore determines the sign of the MD-PICTS signal.

In contrast to earlier publications [2,4] it was shown, that the interaction of the $Fe^{2+/3+}$ level with both bands cannot be assigned to two adjacent positive PICTS peaks. The corresponding PICTS signals must be of opposite sign in this case. There it makes no difference, whether conventional PICTS using contacts or MD-PICTS is employed.

A theoretical explanation of these observations on the basis of rate equations for the EL2-defect in GaAs will be published soon [16]. It is the aim to establish a compensation model for Fe-doped SI-InP, too. Whether or not such a model has to include other deep defect levels beside the iron $Fe^{2+/3+}$ level is still under discussion. The existence of a level with an activation energy of approximately 1.1 eV was shown by MD-PICTS measurements at temperatures above 500 K. So far an assignment of this level to a specific defect is not possible. In the literature such deep levels are associated with iron related defects or P-deficiency centers [9,14].

Moreover, it is shown that the method of microwave detected photoconductivity (MDP), which was successfully applied to investigate the homogeneity of GaAs wafers [10-16], works as successfully for InP wafers. The nature of the contrast causing defects is not yet known. There are hints that a relationship between contrasts in a MDP map and the inhomogeneous iron content in the wafer exists [17].

CONCLUSIONS

The experimental results presented give a first idea of the potential of MDP and MD-PICTS for a non-destructive characterization of InP. From the close analogy to the EL2 defect in GaAs it was concluded, that the iron $Fe^{2+/3+}$ defect level interacts with both bands and therefore acts as a recombination centre. Furthermore, several other characteristic defect levels were observed by MD-PICTS measurements. The spatial distribution of defects with a noticeable influence on the electrical characteristics of InP wafers was successfully examined by MDP measurements.

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