Contact free defect investigation of wafer annealed Fe-doped SI-InP

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Abstract

The new developed methods of microwave detected photoconductivity (MDP) and microwave detected photo-induced current transient spectroscopy (MD-PICTS) were applied to characterize defects in as-grown and wafer annealed Fe-doped SI-InP. It is shown that as-grown samples differ in their defect content in dependence on the crystal position they originate from. In wafer annealed samples an equivalent set of defect levels is prominent, which is independent of the crystal position of the samples. Some of the levels, which occur in wafer annealed samples, seem to be due to the annealing process; however, their origins are still under investigation. From the experimental results it must be furthermore concluded, that the occurrence of different defect levels before and after the annealing process may have some impact on the spatial distribution of the electrical properties of the samples.

Keywords

MD-PICTS, MDP, InP, defects

Introduction

SI-InP is a promising material with opto-electronic properties suitable for high-power and high-frequency devices. It is produced by doping with iron, which incorporates a deep level lying approximately 0.63 eV below the conduction band [1]. Iron therefore compensates residual shallow defect levels under equilibrium conditions. Under non-equilibrium conditions these levels gain major importance, because the electrical behaviour of the material may be strongly influenced by present defect levels. With regard to the proper function and the quality of devices it is of big interest, to learn more about defect levels and their spatial distribution in the material, which may affect the electronic properties. Furthermore it is important to investigate, whether annealing processes (e.g. during device fabrication) influence the defect content and the distribution.

The methods of MDP and MD-PICTS, which already proved themselves as successful for the defect investigation of GaAs [2-4] were applied to as-grown and wafer annealed Fe-doped SI-InP. Comprehensibility between the results is guaranteed by taking the as-grown and wafer annealed samples from the same original wafers. The advantage of using MDP and MD-PICTS in contrast to conventional methods is the possibility to investigate defect characteristics and spatial distribution in a contact-free, non-destructive way and with high spatial resolution. Combining both methods includes the potential to get mappings, which visualize the distribution of special defects.

Experimental details

The experimental setup which was used for the microwave detected photoconductivity measurements was already described elsewhere [2-4]. Through intrinsic excitation (excitation energy = 1.3 eV) excess carriers are generated, which interact with the microwave penetrating the sample. The excess carriers therefore can be detected by measuring microwave absorption by the use of a very high sensitive microwave detection system. That means the quantity to be measured is the photoconductivity of the sample. Once generated, excess carriers can either recombine or can be trapped in defect levels in the band gap and subsequently reemitted from these levels by thermal excitation. Due to the very high sensitivity of the detection system, it was possible to also observe the resulting slow exponential decay of the photoconductivity signal after the free carrier lifetime transient after the exciting light is turned off. This exponential decay is due to the thermal reemission of carriers from defect levels and therefore contains information about the electronic properties of the inherent defect levels of the sample. 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. Information about lateral inhomogeneities of the electrical properties and thus of the distribution of defect levels in the wafers is achieved with high spatial resolution by scanning the sample relative to the exciting laser spot.

The examined InP samples were taken from different positions of Fe-doped crystals. The samples consequently differ in their iron content, which is due to the segregation coefficient of iron in InP. The iron content is lowest in sample A and increases towards sample C. To guarantee comprehensibility, the as-grown and wafer annealed samples originate from identical wafers. The resistivity of the samples is between 0.01 and 0.7×10^8 Ωcm before annealing and between 0.03 and 2×10^8 Ωcm for wafer annealed samples. The annealing process was done at 950°C in a phosphorous ambience of 1 bar. After annealing, a surface layer of less than 0.1 mm was removed through etching.

The MD-PICTS measurements cover a temperature range between 100 K and 500 K. MDP measurements were carried out at room temperature to visualize the distribution of electrically active defects which may influence the function of devices, which are produced on such a wafer.

Experimental results and discussion

The resulting MD-PICTS spectra are shown in figures 1 and 2. By investigating as-grown wafers from different crystal positions a wide range of shallow defect levels is discovered which differs from one sample to another (see fig. 1). Additionally, negative MD-PICTS peaks occur in the spectra of some samples for temperatures above 350 K with the amplitude of the peak increasing with increasing crystal length. An activation energy of (0.7 – 0.9) eV can be ascribed to these negative peaks. In a former work [5] we have shown, that the occurrence of peaks with different magnitude and sign in this temperature range is Fe-related. The negative peak is assigned to the transition of a hole leaving the Fe^{3+} levels towards the valence band. MD-PICTS signals of different sign were interpreted as being due to the interaction of the defect level with both bands [6]. The observation of MD-PICTS signals of both signs in Fe-doped InP provided to our knowledge the first straight forward proof of iron acting as a recombination centre in InP [5].

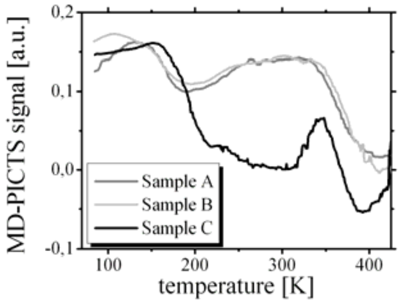

Fig. 1 Comparison of MD-PICTS spectra of as-grown Fe-doped SI-InP samples from different crystal positions (excitation energy: 1.3 eV, penetration depth of light: approx. 600 nm). The samples differ in their characteristic defect levels.

In contrast to the spectra of as-grown wafers, all MD-PICTS spectra of the wafer annealed samples show an equivalent set of defect levels (see fig. 2). Some of these levels are probably introduced by thermal annealing. Each wafer annealed sample exhibits a negative signal originating from the iron defect, the amplitude of which again depends on the crystal position of the sample. In this case activation energies between 0.5 eV and 0.8 eV were determined for the negative peaks. Furthermore, at least three dominant defect levels are observed below 300 K. To the first level an activation energy below 0.1 eV is ascribed. The activation energies of the levels which occur between 200 K and 300 K lie between 0.2 eV and 0.5 eV. A contribution of more than these four levels to the MD-PICTS signal of wafer annealed samples can not be completely excluded. Such a contribution may result in the uncertainty of the activation energies determined.

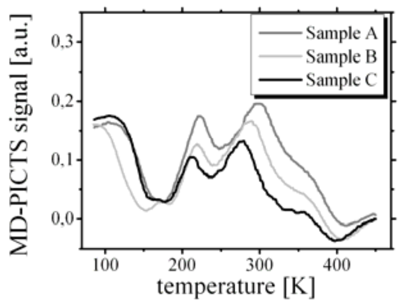

Fig. 2 Comparison of MD-PICTS spectra of wafer annealed Fe-doped SI-InP samples taken from the same wafers as the as-grown samples (excitation energy: 1.3 eV, penetration depth of light: approx. 600 nm). All spectra show an equivalent set of defect levels.

Defect levels with activation energies below 0.1 eV have been reported by other groups as being due to levels, which result from the incorporation of impurities, from native point defects or from complexes of both [7]. Concerning the two dominant defects levels between 200 K and 300 K other groups made similar investigations for annealed Fe-doped InP by using conventional PICTS. Kalboussi et al. [8] observed two peaks with activation energies of 0.41 eV and 0.53 eV. The first one is ascribed to a complex defect containing phosphorous vacancies and other defects. The second peak is ascribed to an acceptor level. Kadoun et al. [9] propose a complex consisting of iron and a phosphorous vacancy as origin of the acceptor level. Other groups claim other structural origins for defect levels in the regarded energy range (see e.g. [10, 11]). This means, the origin of the detected defect levels still needs further investigation to explain the compensation mechanism of wafer annealed InP. Based on the present experimental results we suppose donor levels to be introduced by thermal annealing, which finally results in an increasing Fe^{2+} content of wafer annealed samples in contrast to as-grown samples. This assumption is underlined by the magnitude of the Fe^{2+}-related negative PICTS signal, which is more prominent for annealed samples. The correlation between the iron concentration, the occupation of the iron level resulting from the presence of other defect levels and the resistivity of the samples still needs further investigation which is in progress.

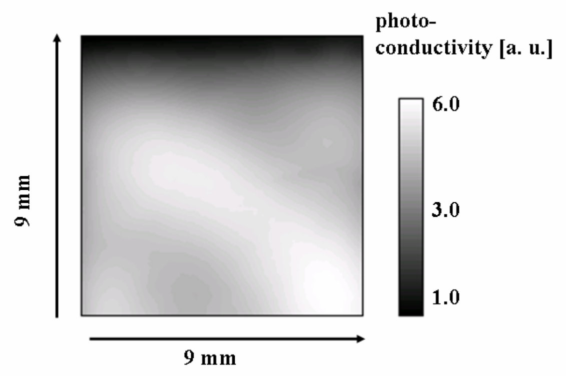

Fig. 3 MDP mapping (9 × 9 mm²) of the as-grown Fe-doped SI-InP sample B (excitation energy: 1.9 eV, penetration depth of light: approx. 200 nm). It indicates the distribution of defects with a noticeable influence on the electrical characteristics of the wafer at room temperature.

Figure 3 and 4 depict some of the first results of photoconductivity mappings of an as-grown and a wafer annealed sample (see fig. 4) originating from the same wafer. The photoconductivity map of the as-grown sample (see fig. 3) exhibits inhomogeneities of electrical properties on a relatively large area scale. This is possibly due to the fact that many different defect levels, which are distributed inhomogeneously over the sample, contribute to its electrical properties before annealing (see fig. 1). As far as electrical properties are concerned, the wafer annealed sample shows a granular structure (see fig. 4). This structure may be related to the distribution of a few defect levels, which are prominent for the electrical behaviour of the wafer annealed sample (see fig. 2). A verification of these assumptions is possible by MD-PICTS measurements with high spatial resolution which are underway.

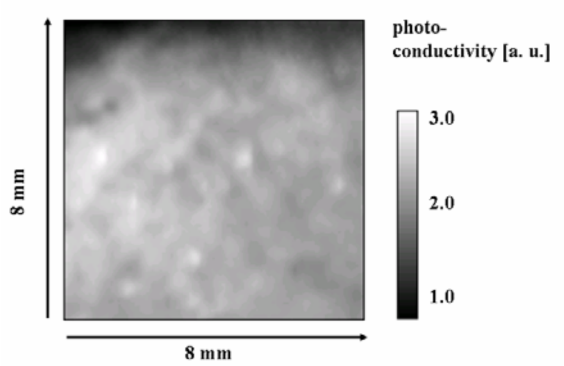

Fig. 4 MDP mapping (8 × 8 mm²) of the wafer annealed Fe-doped SI-InP sample B (excitation energy: 1.9 eV, penetration depth of light: approx. 200 nm). The granular structure of the electrical inhomogeneities is possibly due to the distribution of a few prominent defect levels.

Conclusions

The experimental results presented show that the new developed non-destructive investigation methods MDP and MD-PICTS provide valuable information about defect characteristics and spatial defect distribution. It was shown that the defect content of InP samples changes during annealing processes, which may also have impact on the distribution of electrical properties. Whereas the defect content of as-grown samples depends on their position in the crystal, an equivalent set of defect levels is prominent in wafer annealed samples. The underlying mechanisms are still under discussion. A thermal generation of donors seems to take place during the annealing process, since annealing results in an increase of the negative MD-PICTS peak related to Fe^{2+}.

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