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Contact-free investigation of the EL2-defect in the surface of GaAs wafers

B. Gründig-Wendrock[1], K. Dornich[1], T. Hahn[1], U. Kretzer[2], and J. R. Niklas[1]

[1] Institute of Experimental Physics, TU Bergakademie Freiberg, Silbermannstr. 1, Freiberg, 09599
[2] Freiberger Compound Materials GmbH, Am Junger Löwe Brunnen 5, Freiberg, 09599, Germany

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Abstract. The EL2 as the most important intrinsic defect in semi-insulating GaAs was already deeply studied in the past. All investigation methods applied so far to semi-insulating GaAs explore the entire depth of the sample and are therefore not suitable to analyse e.g. influences of surface treatments. In this work the detection of EL2 in the surface of samples by the application of microwave detected photo induced current transient spectroscopy will be presented. A correlation between height and sign of the signals and the concentration of acceptors, furthermore of the compensation ratio of the EL2, the position of the Fermi level as well as the specific resistivity was found. The results can be simulated by solving rate equations for the measurement process.

PACS. 71.55.Eq III-V semiconductors – 72.20.Jv Charge carriers: generation, recombination, lifetime, and trapping

1 Introduction

The EL2 is the most important intrinsic defect particularly for semi-insulating (SI)–GaAs. Because of its usual concentration of about 10^{16} cm^{-3} and its energetic position 0.75 eV below the conduction band it pins the Fermi level in the middle of the band gap. The EL2 is partially compensated by acceptors like carbon, copper or zinc. Therefore EL2^0 and EL2$^+$ coexist in thermal equilibrium. The EL2 is a double donor. The EL2$^+$/EL2^{++} - energy level was determined to lie 0.54 eV above the valence band [1]. The first transition EL2^0/EL2$^+$ causes the EL2-peak in DLTS-spectra of SC-GaAs [2]. There an activation energy of 0.82 eV was determined because of the influence of activation energies of the carrier capture cross sections.

The EL2 is one of the most deeply studied defects in semiconductor materials in the past. However, all investigation methods and tools applied so far to semi-insulating GaAs explore the entire depth of a wafer or a sample (Van der Pauw, deep level transient spectroscopy (DLTS), electron paramagnetic resonance (EPR) [3], local vibration mode spectroscopy (LVM)). Even basically spatially resolving methods (near infrared (NIR)-topography) [5] integrate over the wafer thickness. Thus all these methods are not applicable to the analysis of influences of surface treatment procedures.

Also with photo induced current transient spectroscopy (PICTS) the EL2 already was investigated. Often this method showed an abnormal negative signal as a relevant part of the spectra [4,6]. For explanation of this phenomena a lot of models and hypotheses exit, however, with no complete understanding of the experimental results so far [4,13–15].

Our aim was the detection of the EL2 in dependence of the dopent concentration contact free and therefore non-destructive using microwave detection, (MD)-PICTS [8,9]. This knowledge concerning the EL2 and the advantage of the method, that the light source can be focused, will be the precondition for future mappings of the EL2 in surface regions of wafers with fine spatial resolution.

First results on different series of semi-insulating GaAs will be presented and discussed referring to model calculations based on rate equations for the PICTS process.

2 Instrumental and experiments

Our apparatus for microwave detected photo induced current measurements was already described in [7,9]. Excess charge carriers are generated by a single mode laser of 660 nm wavelength. The light penetrates by about 0.3 μm into the sample surface. According to tests we can exclude an influence of the upper surface layer, e.g. oxidation, on the MD-PICTS-measurements. The laser spot was purposely defocused up to 1 mm diameter, thus we can neglect signal scattering caused by the structure of inhomogenities in GaAs and only compare signals of the different samples. The excess charge carriers cause a reflection of the microwave coupled to the sample and penetrating it. The

absorbed microwave proportional to the photo conductivity of the sample is measured as the final signal. Excess charge carriers also can be trapped by different levels in the bandgap and finally be reemitted by thermal excitation. Thus an exponential decay of absorbed microwave is detected, from which the PICTS-spectra is determined by a double gate technique known from DLTS. The apparatus was extended for measurements in the temperature range between 300 and 600 K.

Four distinct series of samples were examined by MD-PICTS. All crystals used for preparation of the samples were grown by LEC and annealed in a special way after growth. The samples only differ from each other by the concentration of the acceptors carbon and zinc (Table 1). All samples of one series originate from one crystal with a gradient in the distribution of acceptors. Samples of series D, which is undoped, are from several different crystals.

Measurements enclose the temperature range 295–500 K. The exciting laser pulse and the recorded transient after switching off the laser had a length of 1 ms. The transients were analysed by the double gate technique in analogy to DLTS.

3 Results

The resulting PICTS spectra are summarized in Figure 1. Series A, B and C present a clear positive peak whose

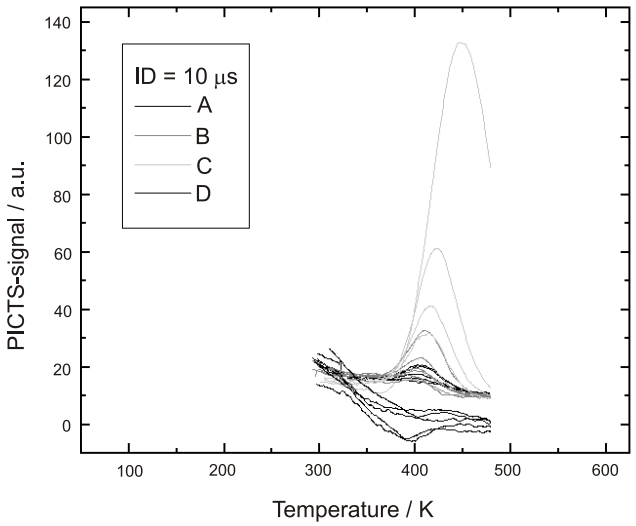

Fig. 1. Detection of the EL2 defect in SI GaAs samples with different acceptor concentrations by HT-MD-PICTS. Peak height and sign correlate to the acceptor concentration.

height increases with the concentration of acceptors. Within series A this peak is very small, partly not yet formed. In series C a shift of the peak maximum to higher temperatures with increasing acceptor concentrations can be observed. The activation energy of this positive peak varies between 0.55 and 0.73 eV. The value increases with the peak height, but cannot be determined accurately because of the too short transients.

In series D the formation of a negative peak approximately at the position of the former positive one was found in all samples. This negative peak increases with decreasing acceptor concentration. The activation energy could not be determined because the transients were again to short (Figure 2).

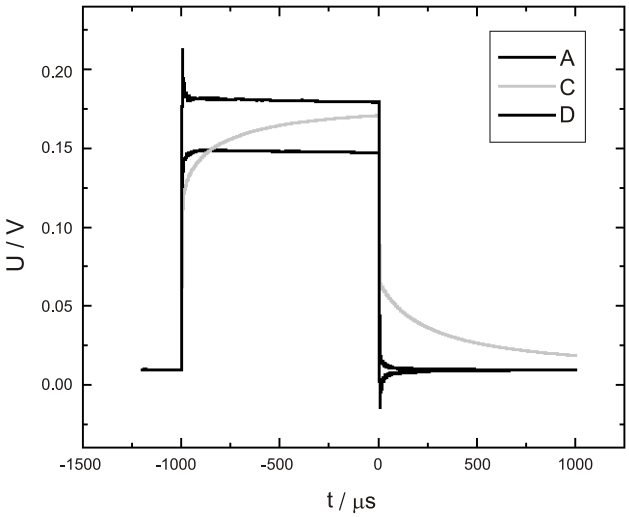

Fig. 2. Light pulse response and transients of three samples from series A, C and D, respectively.

The dependence of the height of the EL2-PICTS-peak in all series on the concentration of acceptors seems to be exponential (Figure 3). The same can be observed for the

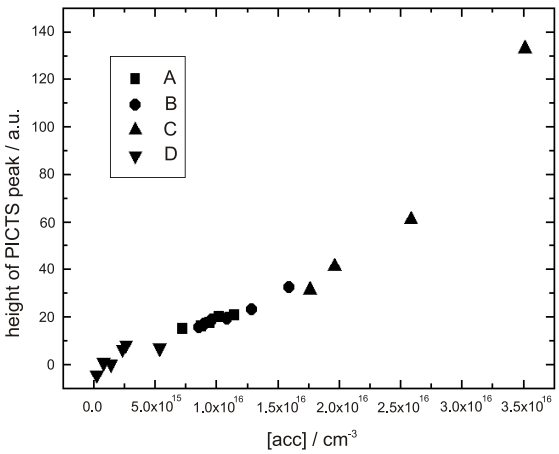

Fig. 3. The increase of the EL2 PICTS peak with increasing acceptor concentration tends to be exponential.

series (samples)	[acc] / 10^{16} cm.3	K $\left([EL2^+]/[EL2]\right)$	(E_F-E_V) / eV	$\rho/10^8 \Omega$ cm
A	0.72 – 1.14	0.36 – 0.62	0.78 – 0.76	2.7 – 6.2
B	0.86 – 1.59	0.47 – 0.73	0.77 – 0.74	4.6 – 10.1
C	1.76 – 3.51	0.50 – 0.77	0.76 – 0.64	11.3 – 0.6 (p)
D	0.02 – 0.53	0.01 – 0.28	0.89 – 0.79	0.06 – 1.2

Table 1. Concentration of acceptors, degree of compensation, Fermi level position and specific resistivity of the investigated series of samples

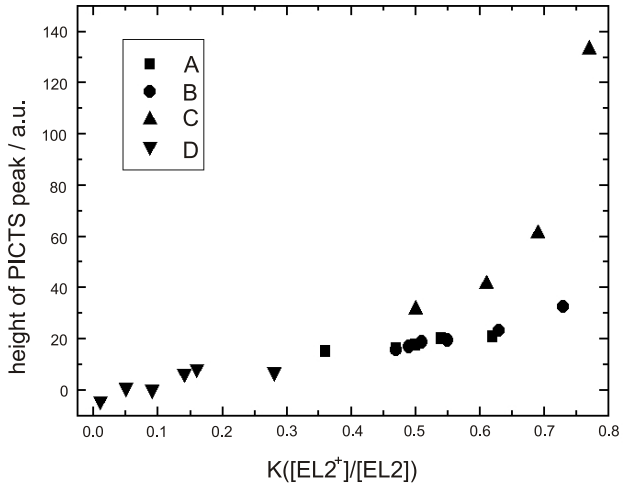

Fig. 4. There is also an exponential increase of the EL2 PICTS peak with the degree of compensation, K, of the EL2.

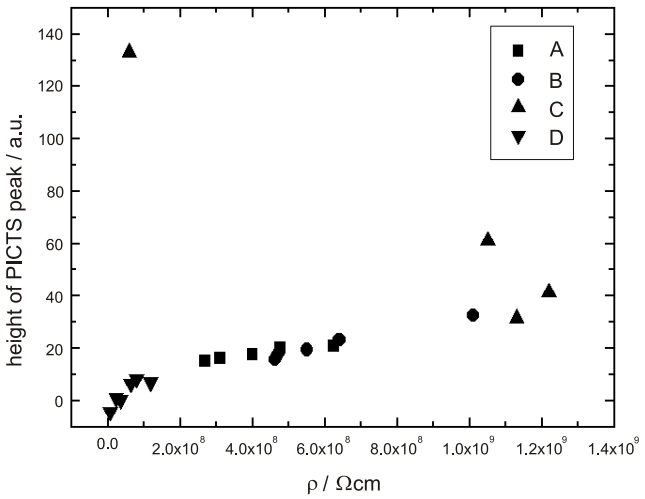

Fig. 6. The EL2 PICTS peak increases linearly with specific resistivity. When the material turns to p-type, peak heigths further increase strongly.

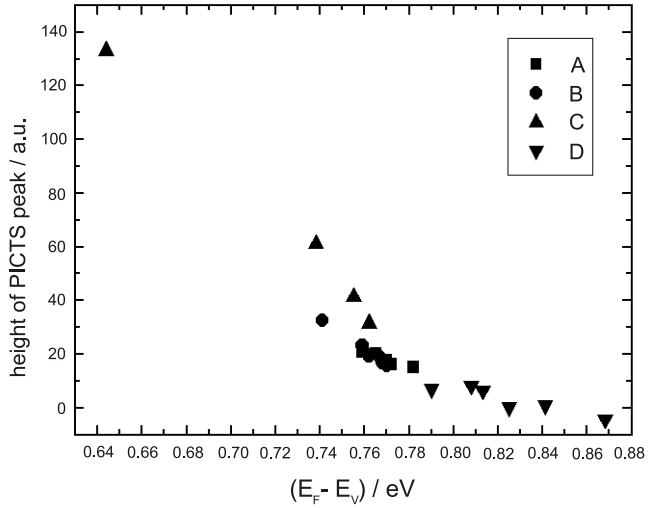

Fig. 5. The EL2 PICTS peak tends to turn to negative values by shifting the Fermi level to the conduction band.

dependence of the peak height on the degree of compensation (Figure 4). Figure 5 shows a decrease of the PICTS peak with decreasing distance of the Fermi level to the conduction band. From Figure 6 a maximum specific resistivity of about 1.2 $^*10^9 \Omega$ cm can be observed as well as a further increase of the peak when the material already tends to get p-type.

4 Discussion

An activation energy of 0.82 eV for the EL2 known from DLTS [2] or PICTS [4] was not found in our experiments. Other groups [10,11] report on EL2-families in dependence on annealing temperature or – duration. There were also lower activation energies of 0.72 eV found. Uncertainties in our work may arise from difficulties in the analysis of the transients due to their limited length. This problem will be addressed by a future improvement of the apparatus. Concerning series C, to our hypothesis the detected peak may be formed by a superposition of two single peaks, where the energetically higher one still increases with acceptor concentration whereas the other one saturates. We suppose that such a superposition may also influence the determination of the activation energy. We tentatively associate the energetically higher peak to the second level of the EL2 – the $EL2^{++}$.

If the concentration of the $EL2^+$, $[EL2^+]$, dominates over that of the $EL2^0$ a positive peak results, whereas a predominating $[EL2^0]$ causes a negative PICTS signal. Around a distinct degree of compensation of the EL2 defect by acceptors no peak will be observed. According to

our experiments this degree of compensation is around 0.35 ($[EL2^+]/[EL2^0]$).

First attempts were made to simulate these phenomena by the solution of rate equations according to Brasil [12]. Our calculations comprise interactions of the defect with both the conduction and the valence bands and both types of charge carriers as well as the degree of occupation of the defect in thermal equilibrium (prior to the light pulse) as a function of the Fermi level position. The possible influence of the second EL2 level was not yet included in these first calculations. According to our first results the occurrence of a negative peak does require interactions of the defect also with the valence band which is mostly neglected in simple models for the PICTS mechanism. This agrees with hypothesises of Hurtes at al. [13], Deveaud and Toulouse [14] and Ogawa et al. [15]. Thus the position of the Fermi level determines the sign of the peak as well as the observed peak shift.

5 Conclusion

The EL2 in SI GaAs can be detected in a thin (0.3 μm) surface region by HT-MD-PICTS. To our experience, a positive signal is caused by the single ionised state $EL2^+$, the negative one by the $EL2^0$. For a distinct ratio of these two charge states the signals can extinguish each other. The EL2 peak is obviously dependent on the concentration of acceptors. The experimental data can be simulated by extended model calculations based on rate equations for the PICTS process.

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