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Determination of Deep-Level Parameters by Isothermal Deep-Level Transient Spectroscopy with Optical Excitation

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A modified isothermal deep level transient spectroscopy method, where the electrical excitation pulse is replaced by an optical one, is introduced. Results received by three measuring methods — modifications of DLTS (MCTS, IDLTS, and IDLTS with optical excitation) of measuring two deep energy levels on identical samples (Schottky barriers on epitaxial GaAs layer grown on bulk n-GaAs by VPE) are compared. It is shown that the data extracted from all three measuring methods are practically the same for the dominant electron trap (EL2 in all cases). It is more complicated to get correct results for hole traps (minority carrier traps). The peculiarities of all the measuring methods are discussed from this aspect and the results are compared. After having applied a non-exponential mathematical analysis, our modified IDLTS with optical excitation gives the most reliable results in this case.

Es wird eine isothermische DLTS-Methode, bei welcher die elektrische Anregung durch einen optischen Impuls ersetzt wird, beschrieben. Im weiteren wird eine Schottky-Diode auf GaAs-Basis Messungen mit verschiedenen Modifikationen der DLTS-Methode unterworfen (MCTS, IDLTS und IDLTS mit optischer Anregung). Die Ergebnisse zeigen, daß für die dominante Störstelle EL2 die gleichen Parameter erhalten werden. Diese Übereinstimmung wird nicht für Löcherstellen erreicht. Die zuverlässigsten Ergebnisse werden mit der optischen DLTS-Methode unter Verwendung der mathematischen Analyse für nichtexponentielle Kurven erreicht.

1. Introduction

The presence of deep energy levels in the band gap of semiconductors has considerable influence on the electrical parameters of semiconductor materials and devices. Deep level transient spectroscopy (DLTS) [1] is a fundamental measuring method for the characterization of deep energy levels or deep traps. It gives the main parameters of deep levels: type, enthalpy of ionization, concentration, and capture cross section.

In order to enhance the capabilities of the DLTS method various modifications were introduced:

MCTS (minority carrier trap spectroscopy) [2, 3] enables to study minority carrier traps which can act as efficient recombination centers in Schottky barriers and majority carrier traps, in more detail.

Isothermal DLTS (IDLTS) [4, 5] enables to avoid ambiguous results from samples with large thermal capacity, and traps with identification parameters which are temperature dependent (bistable and metastable defects).

A modified IDLTS method, where the electrical excitation pulse was replaced by an optical one, is introduced in this paper.

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These three measuring methods (MCTS, IDLTS, and IDLTS with optical excitation) are compared by measuring the dominant electron and the deep hole energy levels on the same samples. The possibilities and disadvantages of the methods are discussed in the conclusions. In the case when the measured signal is represented by non-exponential capacitance transients, a numerical filtering method [6] is used to get more correct results.

2. Experimental

2.1 Samples

Samples with n-GaAs ($N_D - N_A = 5 \times 10^{20}\ m^{-3}$) epitaxial layers grown by vapor phase epitaxy onto n^{++}-GaAs ($N_D - N_A = 10^{24}\ m^{-3}$) substrates were used for our experiment [7]. Schottky barriers were created by Au evaporation ($\varnothing = 0.5$ mm, $h = 20$ nm) and an ohmic back contact on the n^{++}-substrate was formed by Au + Ge (88:12) evaporation and subsequent annealing at 420 °C.

2.2 Experimental equipment

We used a Polaron DLTS spectrometer with a pulsed GaAs laser source. This spectrometer uses a boxcar detection system for providing a DLTS output signal. The software for measuring and processing IDLTS signals was developed at our laboratory [8].

Fig. 1 presents a schematic picture of the experimental setup.

The laser excitation unit used for generation of charge carriers had 100 mW maximum power and typical wavelength of 850 nm at the peak intensity.

2.3 Experimental procedure

A forward bias filling step is used to fill the carrier traps during the DLTS experiment. In the case of MCTS and isothermal DLTS with optical excitation, the bias filling pulse was replaced by an optical pulse focused onto the sample. The provided optical pulse is absorbed by the semiconductor [3]. If the photon energy $h\nu$ is larger than the energy gap E_g, both minority and majority carriers are generated. These charge carriers separated by

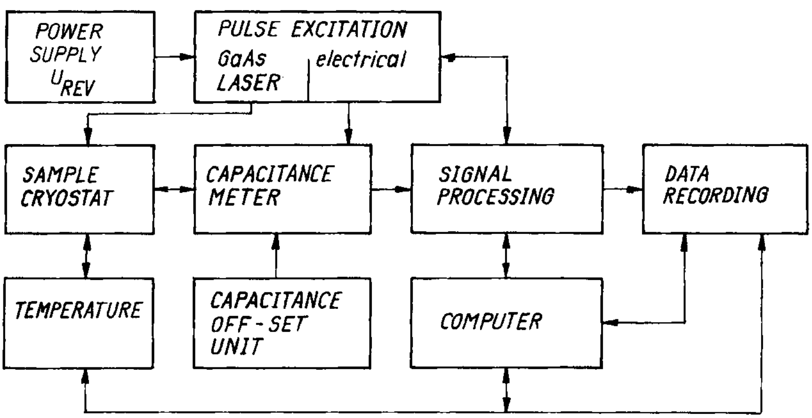

Fig. 1. Schematic picture of the experimental setup used for DLTS method and modifications of the DLTS method

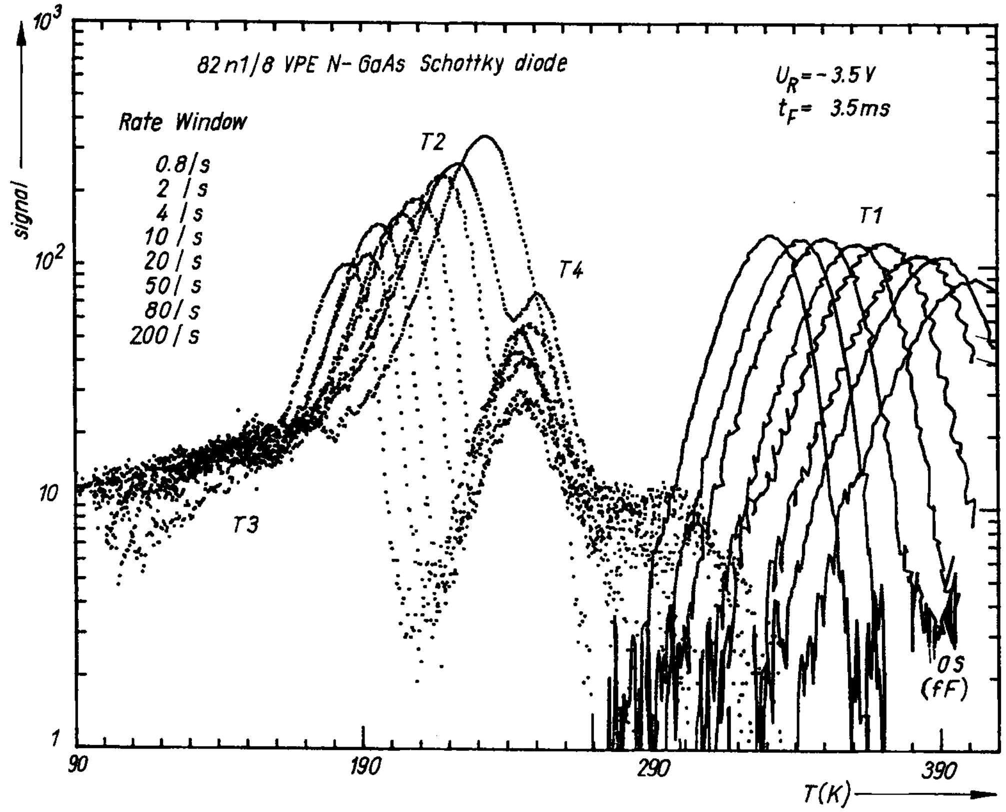

Fig. 2. The typical measured MCTS spectra of the samples. Dotted curves: signal corresponding to minority deep level, solid curves: signal corresponding to majority deep level, U_R reverse voltage, t_F duration of the optical filling pulse, T1, T2, T3, T4 traps mark, OS output signal

the barrier field, which is maintained by the constant reverse bias, are available for being captured and emitted and so are exploited by the isothermal DLTS signal processing. The basic idea of IDLTS is to measure DLTS spectra in the rate window domain, instead of the temperature domain.

From the measured spectra we can get the rate window (RW) and temperature (T) pairs for the peak maxima as in the classical DLTS. Therefore, in the case of IDLTS and IDLTS with optical excitation the same analysis can be used to obtain the enthalpy of ionization and the capture cross section.

The values of the activation enthalpies ΔE_n, ΔE_p of electron (hole) traps and the capture cross section for electrons and holes σ_n, σ_p were determined from an Arrhenius diagram using known equations [1, 9, 10]. This was done for MCTS, isothermal DLTS, and isothermal DLTS with optical excitation spectra and the results were compared to each other.

3. Results and Discussion

Typical measured MCTS spectra of the samples are shown in Fig. 2, equivalent measured IDLTS spectra in Fig. 3, and finally measured IDLTS with optical excitation spectra in Fig. 4. As is shown in Fig. 2, four peaks labelled T1, T2, T3, T4 were detected in our

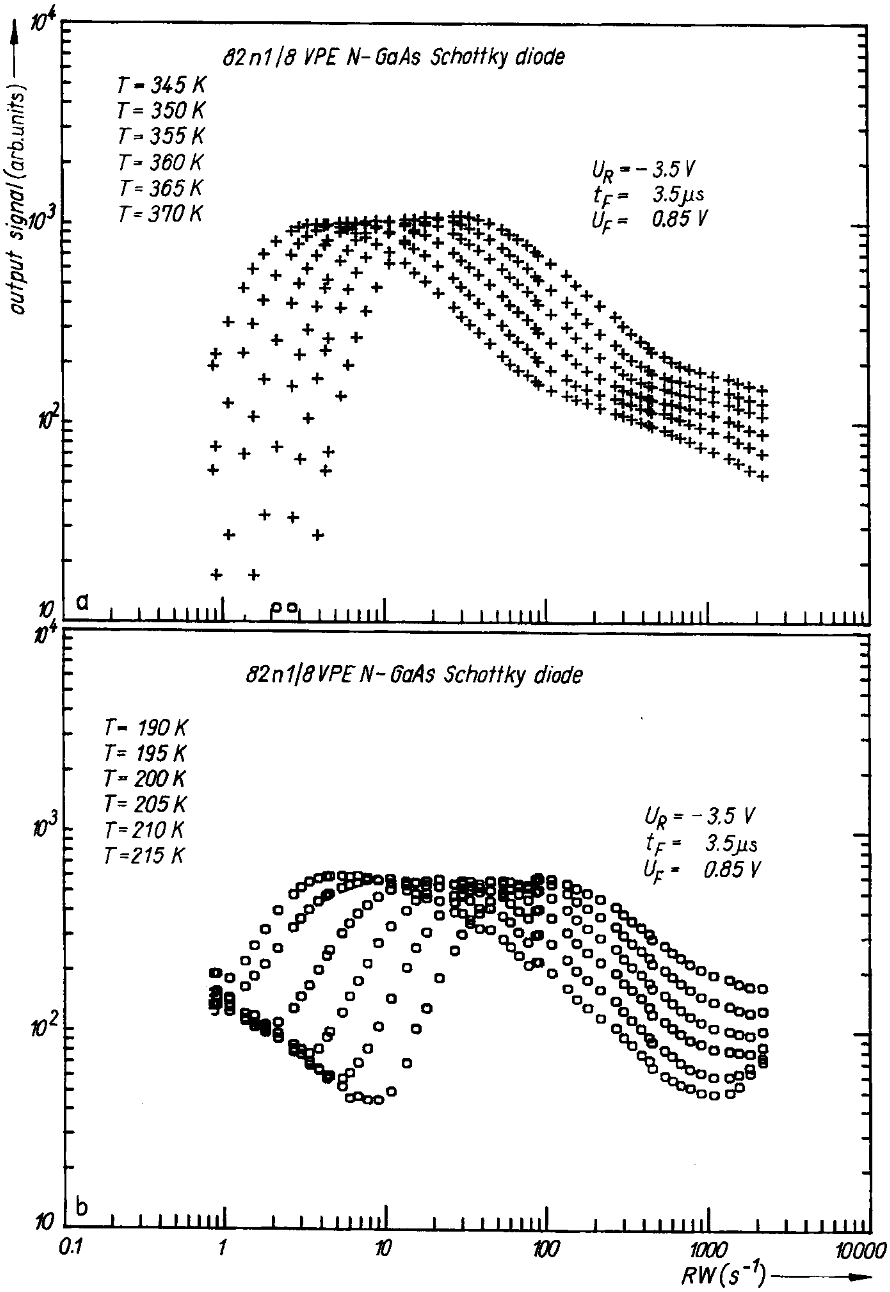

Fig. 3. The typical measured IDLTS spectra of the samples for a) trap T1 and b) trap T2. Crosses: signal corresponding to majority deep level, circles: signal corresponding to minority deep level, T temperature, U_R reverse voltage, t_F duration of the electrical filling pulse, U_F filling voltage, RW rate window

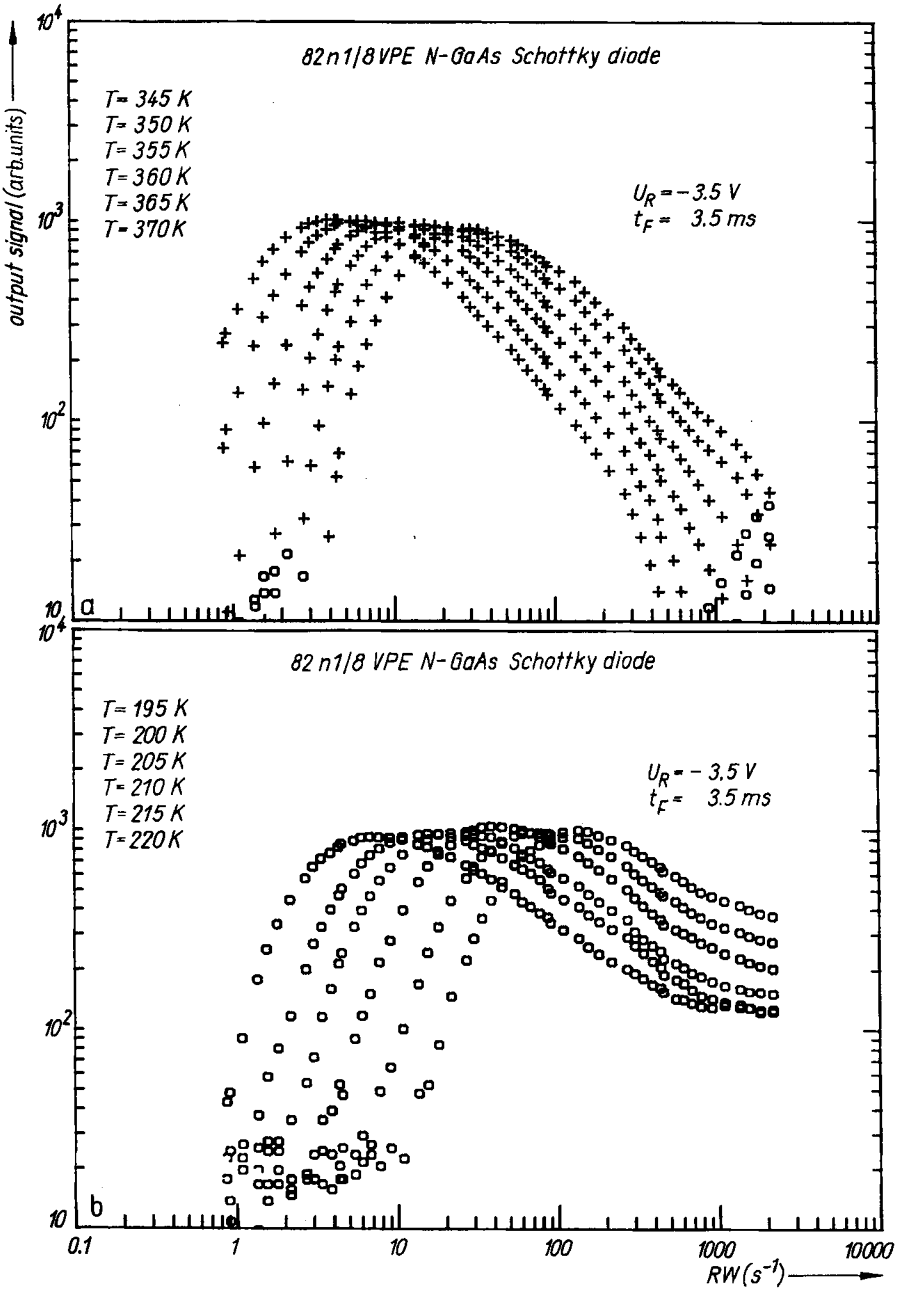

Fig. 4. The typical measured IDLTS with optical excitation spectra of the samples for a) trap T1 and b) trap T2. Crosses: signal corresponding to majority deep level, circles: signal coressponding to minority deep level, T temperature, U_R reverse voltage, t_F duration of the optical filling pulse, RW rate window

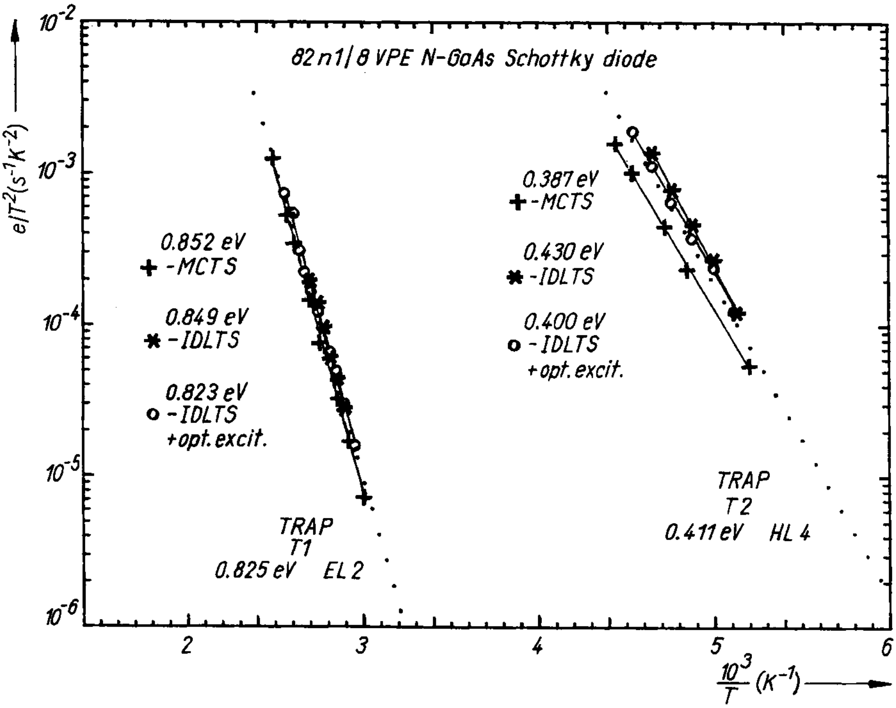

Fig. 5. The plots of eT^{-2} as a function of $1/T$ for two detected deep levels T1, T2. Solid lines: data from our measurement, dotted lines: data from literature

samples. The trap T1 is a trap of majority charge carriers (electrons) and traps T2, T3, T4 are traps of minority charge carriers (holes).

We have chosen the traps T1 and T2 for our experiment. Fig. 5 presents the plots of eT^{-2} as a function of $1/T$ for these two detected levels. Parameters of the trap T3 are very close to the detection limit, so results are ambiguous (traps T3 probably correspond to the HL6 level [11]). The trap T4 represents in reality several traps with similar parameters (Fig. 2). Absolute values of energies of these deep levels are difficult to obtain.

The characteristic parameters of traps T1 and T2 are listed in the Table 1, together with the results of different authors obtained by transient capacitance DLTS experiments.

Measurements by all the measuring methods were realized at the same reverse voltage $U_R = -3.5$ V.

MCTS and IDLTS with optical excitation were measured with filling time of the optical pulse $t_F = 3.5$ ms and IDLTS with electrical excitation used electrical filling pulses of $t_F = 3.5$ µs.

The majority carrier trap T1 dominates the spectra. Computed values of the enthalpy of ionization of the trap T1 are in good agreement with the corresponding values (0.825 eV, 2×10^{-17} m^2) reported for the EL2 defect [12].

Values ΔE_n and σ_n for the trap T1 from Table 1 exhibit slight differences. These differences are the consequence of the measuring principle.

Results of MCTS are influenced by the thermal inertia of the sample when changing the temperature. This influence can be suppressed to a minimum by lowering the current heating

Table 1
The characteristic parameters of traps T1 and T2 with the results from literature

method	T1		T2	
	ΔE_n (eV)	σ_n (10^{-17} m^2)	ΔE_p (eV)	σ_p (10^{-19} m^2)
MCTS	0.852	2.48	0.387	0.422
IDLTS	0.849	3.12	0.430	9.95
IDLTS with optical excitation	0.823	1.31	0.400	1.61
similar traps	0.825	2.00	0.411	2.51
in literature	EL2 [12]	As-antisite	HL4 [13]	Cu

(cooling) temperature rate (0.15 K/s in our case), but the measurement is then time consuming.

An isothermal DLTS method suppresses this drawback. During IDLTS we change the rate window RW electronically, which is much faster than the change of temperature with time and at the same time we avoid the temperature gradient on the sample because the IDLTS is measured at a constant temperature.

In principle, it was shown that for this dominant electron trap the results of all three measuring methods are practically the same. The best agreement with published results is achieved using IDLTS with optical excitation. This confirmed our assumption that by combining IDLTS and MCTS the advantages of both methods can be interconnected.

The trap T2 of minority carriers corresponds to the HL4 defect [13]. It is usually related to Cu impurity.

It is interesting that on our samples we achieved a measurable signal from minority carrier traps by IDLTS with electrical excitation. We can explain this fact on the basis of the height of our Schottky barrier (0.85 eV) [14] which is higher than half the energy gap E_g in GaAs, so a significant concentration of minority carriers can exist in the excited region [15].

Except for the above-mentioned temperature inertia effects and the shortening of the time of measurement the IDLTS with optical excitation enables also a measurement of minority carrier traps (trap T2) without electrical charging of the sample during the trap filling period. The evaluation of majority carrier trap parameters acquires higher precision in the latter case.

From the spectrum in Fig. 2 we can see that the influence of the trap T4 on the trap T2 increases with rising temperature. The dependence $\ln(eT^{-2})$ as a function of $1/T$ (Fig. 5) deviates from a linear one in the high temperature region. The value of activation energy is then computed by the low temperature approximation. This effect is due to the non-exponential measured response. The filtering procedure [6], which has been used for parameter determination from IDLTS and IDLTS with optical excitation, allows an extraction of the components of a multi-exponential signal. The optimum parameters of the deep trap T2 were obtained by using IDLTS with optical excitation after application of this filtering procedure.

4. Conclusions

The MCTS, IDLTS, and IDLTS with optical excitation techniques were applied to a comparable study of two deep level traps in GaAs Schottky barriers prepared on VPE layers. After having compared the achieved results we can now summarize the advantages of the IDLTS method with optical excitation, which actually combines some of the most desirable features of IDLTS and MCTS techniques:

- minority carrier traps can be investigated directly on Schottky barriers;
- the large perturbation induced by forward-to-reverse bias transition is avoided, thus allowing better conditions for the observation of fast recombination centers;
- the measurement is realized at constant temperature, therefore, the sample is not stressed by annealing during the measurement;
- the change of frequency (rate window) is realized at thermal equilibrium. It enables a more exact determination of the temperature of the sample;
- the change of frequency is controlled electronically and for this reason is quicker than the change of temperature (scanning);
- application of the numerical filtering method [6] enables to achieve more correct results in the case when the output signal is influenced by non-exponential capacitance transients.

On the other hand, exploiting the laser unit has some disadvantages compared to the classical capacitance DLTS or IDLTS with electrical excitation:

- more complex experimental equipment (+ optical excitation source);
- analysis of the dynamical process [8] is more complicated.

Emissions of both majority and minority carriers exist if photon energies are nearly equal to the energy gap and the deep levels are at the midgap.

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