

Microwave Absorption Transient Spectroscopy for Investigation of Deep Levels in Semiconductors

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A novel method for deep level transient spectroscopy is reported, which is called microwave absorption transient spectroscopy (MATS), where we need no electrode contacts to the samples. The present method is based on a measurement of microwave absorption transient induced by excess carriers excited by laser pulse. Measurements were made using 35GHz microwave and He-Ne laser of 15mW modulated by A0 modulator. Obtained signals are analyzed by a usual DLTS method, and give energy levels and their cross sections. Measurements and analysis were made in semi-insulating GaAs, n-GaAs and n-InP. We found $\Delta E_T = 0.33 \pm 0.01 \text{ eV}$ for In-doped semi-insulating GaAs.

§1. Introduction

Deep level transient spectroscopy (DLTS) have been widely used for the characterization of semiconductors. The basic idea of this method is to utilize the fact that the transient of the electrical properties of a semiconductor reflects the charging states of the deep level.¹⁾ In order to improve this method and achieve spectroscopic analysis, various techniques have been developed, for example, transient capacitance methods such as usual DLTS²⁾ and optical DLTS,³⁾ or transient current analysis of diode structures.⁴⁾ These methods, however, cannot be used for high-resistivity semiconductors because of the difficulty in injection of carriers in these specimens. To overcome this difficulty, photo-induced (current) transient spectroscopy (PITS) method⁵⁾ has been proposed in which excess carriers are optically injected by pulse light.

All the methods stated above require the electrode contacts to the samples, and thus the experimental results are subject to the condition of the electrical contacts. These methods are called "destructive measurements" in the sense that they require processing of semiconductors, cutting into small pieces, doping, evaporation of metal films and so on. From the view point of semiconductor characterization, non-destructive method is the best. In addition the characterization of semi-insulating materials, for example high-resistivity GaAs, is very important

because these materials are used for substrates of high speed devices.

In this paper we will report a new DLTS method which requires no electrode contacts and can be used for characterization of both conductive and high-resistive semiconductors. The present method is based on a measurement of transient microwave absorption due to excess carriers excited by pulse laser, where the sample is inserted in a waveguide and thus we need no electrode contacts. We call this "microwave absorption transient spectroscopy (MATS)". Analysis is quite similar to the PITS method. In this paper we present experimental technique of the MATS and how to analyze the data. We also report a model calculation of transient of excess carriers in semi-insulating GaAs, which supports the present analysis. Experimental results will be shown for semi-insulating GaAs, n-GaAs and n-InP.

§2. Principle of Microwave Absorption Transient Spectroscopy

When a light pulse is incident on a sample, excess carriers are excited and decay by recombination. Change in absorption coefficient of microwave $\Delta\alpha$ due to excess conductivity $\Delta\sigma$ is given by

$$\Delta\alpha = \frac{1}{cn_0\epsilon_0} \Delta\sigma \quad (1)$$

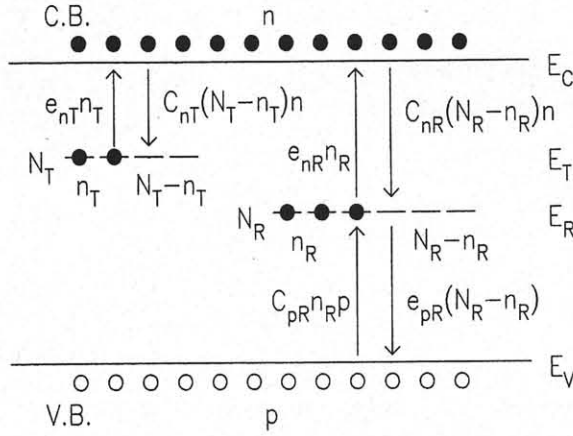


Fig.1 Schematic diagram of the energy levels of trapping and recombination centers, where the arrows indicate electron and hole transitions and e_j and C_j are emission and capture rate for the process j .

where c is the light velocity in vacuum, n_o is the refractive index of the material and ϵ_o is the dielectric constant in free space. When the excess conductivity is dominated by excess electrons, it is given by

$$\Delta\sigma = \frac{e^2}{m^*} \left\langle \frac{\tau}{1 + \omega^2 \tau^2} \right\rangle \Delta n \quad (2)$$

and it is approximated for $\omega\tau \ll 1$

$$\Delta\sigma = \frac{e^2 \tau}{m^*} \Delta n \quad (3)$$

where Δn is excess electron density, e the electronic charge, m^* the electron effective mass, τ the relaxation time of the electrons, ω the angular frequency of microwave and the brackets indicate average of the quantity using an appropriate distribution function, usually Maxwell-Boltzmann distribution is used. Electron mobility is much larger than hole mobility and thus we can neglect a contribution of holes to the absorption when the hole density is comparable or less excess electron density. In the present work we assume that excess electrons dominate the microwave absorption, which is supported by the analysis given later.

When we measure transient of the microwave absorption, we obtain time evolution of the excess electrons in the conduction band. Since the electrons are determined by recombination and trapping, detrapping is monitored by microwave

absorption measurements as a function of temperature. Therefore the usual DLTS analysis can be applied to the MATS experiments. To make it clear we consider a case shown in Fig.1, where trapping centers N_T located at E_T and recombination centers N_R located at E_R are considered. We consider the processes indicated by arrows only, where e_j and C_j are respectively emission rate and capture rate for the process j , and n_T and n_R are densities of the trapping and recombination centers occupied by electrons, respectively. Rate equations are given by

$$\frac{dn}{dt} = e_{nT}n_T - C_{nT}(N_T - n_T)n + e_{nR}n_R - C_{nR}(N_R - n_R)n + g \quad (4)$$

$$\frac{dp}{dt} = e_{pR}(N_R - n_R) - C_{pR}n_R p + g \quad (5)$$

$$\frac{dn_T}{dt} = -e_{nT}n_T + C_{nT}(N_T - n_T)n \quad (6)$$

$$\frac{dn_R}{dt} = -e_{nR}n_R + C_{nR}(N_R - n_R)n + e_{pR}(N_R - n_R) - C_{pR}n_R p \quad (7)$$

where n and p are the free electron and hole densities, and g is the generation rate of electron-hole pairs. The charge neutrality condition is

$$n + (n_T - n_{To}) + (n_R - n_{Ro}) = p \quad (8)$$

where subscript o indicates its thermal equilibrium value. First we consider the fast decay of the electrons in a very short period. In this case n_T is assumed to be constant and we obtain from eq. (4)

$$n = \bar{n} \cdot \exp(-t/\tau_n) \quad (9)$$

where $\bar{n}$ is an initial value of n and

$$\frac{1}{\tau_n} = C_{nR}(N_R - n_R). \quad (10)$$

For slow decay we can put $dn/dt = 0$ in eq. (4) and equation (6) can be approximated as

$$\frac{dn_T}{dt} = -e_{nT}n_T \quad (11)$$

and therefore we obtain

$$n = e_{nT} \tau_n \bar{n}_T \exp(-e_{nT} t) \quad (12)$$

where $\bar{n}_T$ is an initial value of n_T . Equation (12) governs the decay of excess electrons in the region of the present experiments. From eqs. (1), (3) and (12) we obtain

$$\Delta\alpha = Ae_{nT}\exp(-e_{nT}t). \tag{13}$$

By the derivation of $\Delta\alpha(t_1)-\Delta\alpha(t_2)$ (for $t_2>t_1$) with respective to temperature, we find that a maximum occurs at a temperature T_{max} , and we can obtain e_{nT} as a solution of

$$e_{nT} = \frac{\exp(-e_{nT}t_1)-\exp(-e_{nT}t_2)}{t_1\exp(-e_{nT}t_1)-t_2\exp(-e_{nT}t_2)}. \tag{14}$$

The relation between T_{max} and e_{nT} is given by

$$e_{nT} = \sigma_{nT}v_nN_c\exp(-\Delta E_T/kT_{max}) \tag{15}$$

where $C_{nT}=\sigma_{nT}v_n$, σ_{nT} the capture cross section of the trap, v_n the thermal velocity of electrons and ΔE_T the activation energy of the trap.

The energy and the cross section of the trapping center are easily found by running spectra with different sampling time window t_1, t_2 as in classical DLTS measurements. In other words, the plot of $\log(T^2/e_n)$ versus $1/T$ gives the energy and the cross section.

53. Experimental Procedures and Results

Block diagram of the experimental setup is shown in Fig.2, where a Gunn oscillator of 35GHz is used for the microwave source and a sample is inserted in a waveguide. Electron-hole pairs are generated by modulated laser pulses (15mW He-Ne

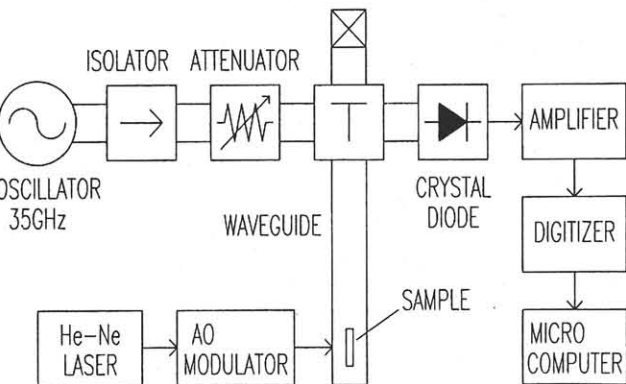


Fig.2 Block diagram of microwave absorption transient spectroscopy(MATS).

laser of 6328Å with AO modulator). These photoexcited carriers are captured by electron or hole traps. After the excitation of 0.1~50ms duration, the trapped carriers are detrapped resulting in a transient microwave absorption. The change in microwave absorption is detected by a crystal detector and digitized after amplification. Data at different temperatures are stored on a desktop computer (YHP9836A). Using this system we can set arbitrary time-window (t_1, t_2) after the measurements and a double-gate technique can be used. Temperature is controlled in the range from 77K to 350K.

We present a typical result of the MATS spectra in Fig.3 as a function of temperature for In-doped semi-insulating GaAs, where the time window is set as $t_1=0.1, 0.2, 0.3, 0.5$ and $1ms$ and $t_2=10ms$. We find in Fig.3 one peak which shifts to lower temperature with increasing t_1 . The plot of $\log(T^2/e_n)$ versus $1/T$ is shown in Fig.4, which provides $\Delta E_T=0.33\pm 0.01eV$ and $\sigma_n=2\times 10^{-12}cm^2$. This

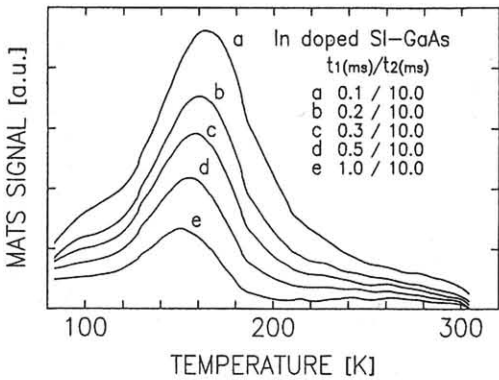


Fig.3 MATS spectra as a function of temperature for different time windows in In-doped semi-insulating GaAs.

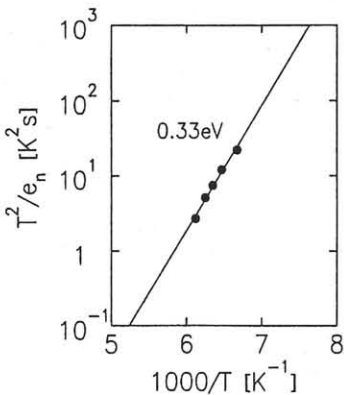


Fig.4 Plot of T^2/e_n versus $1/T$ for In-doped semi-insulating GaAs.

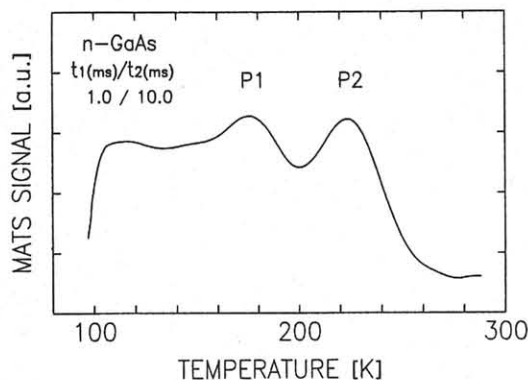


Fig.5 MATS spectrum as a function of temperature in epitaxial n-GaAs.

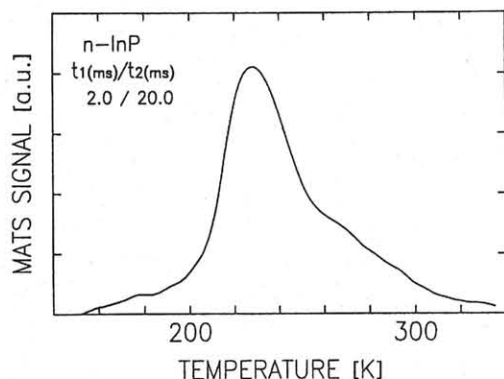


Fig.6 MATS spectrum as a function of temperature in n-InP.

level corresponds to ET5 reported by Taniguchi.⁶⁾

Similar measurements were carried out on non-doped semi-insulating GaAs and epitaxially grown n-GaAs. An example of the MATS spectrum in epitaxial n-GaAs is shown in Fig.5, where we find two peaks. The plot of $\log(T^2/e_n)$ versus $1/T$ provides $\Delta E_T = 0.28\text{eV}$ and $\sigma_n = 6 \times 10^{-16}\text{cm}^2$ for P1, and $\Delta E_T = 0.47\text{eV}$ and $\sigma_n = 2 \times 10^{-13}\text{cm}^2$ for P2. These two levels are assigned to the levels reported by Martin,⁷⁾ where the peak P1 corresponds to EL8 and P2 to EL4.

MATS measurements were also performed on n-InP and the results are shown in Fig.6, where we find only one peak. The plot of $\log(T^2/e_n)$ versus $1/T$ provides $\Delta E_T = 0.46\text{eV}$ and $\sigma_n = 4 \times 10^{-14}\text{cm}^2$ which is very close to the deep level $\Delta E_T = 0.43\text{eV}$ reported by Tapster.⁸⁾

§4. Model Calculation of Excited Carrier Transient

Transient properties of the excited carriers can be calculated using eqs. (4) to (8). In the

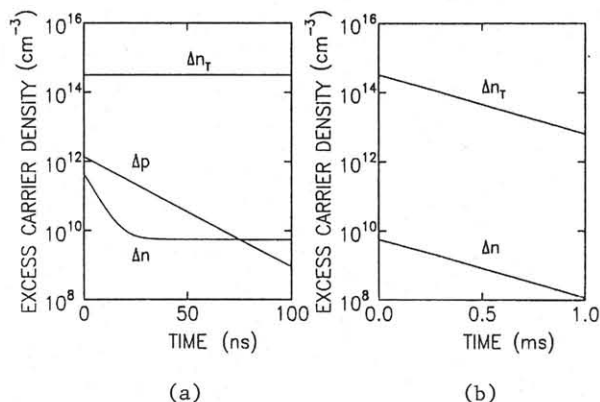


Fig.7 Calculated time dependences of Δn_T , Δn and Δp . (a) the region of fast decay ($t < 100\text{ns}$), (b) the region of slow decay. (See text in detail.)

present calculations we used Runge-Kutta method. As an example we will present here the result of semi-insulating GaAs. The following parameters are used and temperature is $T = 270\text{K}$, $\Delta E_T = 0.3\text{eV}$, $N_T = 10^{15}\text{cm}^{-3}$, $\sigma_{nT} = 10^{-16}\text{cm}^2$, $E_R = E_F$, $N_R = 10^{16}\text{cm}^{-3}$, $\sigma_{nR} = \sigma_{pR} = 10^{-15}\text{cm}^2$, $g = 10^{20}\text{cm}^{-3}\text{s}^{-1}$. The results are shown in Fig.7 (a) for early stage of the decay ($t < 100\text{ns}$) and in (b) for the slow decay ($t < 1\text{ms}$), where the excess electron and hole densities and trapped electron density are shown. We find in Fig.7 (a) that the electrons decay faster than the holes in the time range $t < 25\text{ns}$ and after that the electrons decay very slowly. At $t > 75\text{ns}$ the density of excess electrons is larger than the hole density. In Fig.7 (b) we find that the decay times of the excess electrons and trapped electrons are the same and the decay time determines the transient of the MATS signals we are interested in.

§5. Summary

A new method for DLTS, MATS, has been developed. This method requires no electrode contacts and it is very simple and powerful, applied to conductive or semi-insulating crystals.⁹⁾

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