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An optical method for determining the ionization energy of the centers controlling charge transfer in GaAs-based pin-structures

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ABSTRACT. A new method is reported to determine the ionization energy of the deep centers controlling charge transfer in GaAs-based pin-structures important for applications. The idea of the method lies in measuring the dependence of kinetics of the i–layer field on temperature upon application of step voltage of inverse polarity to the structure and in subsequent processing of the experimental data on the basis of the knowledge gained during studies of dynamics of the space charge and the electric field in a pin-structure [1]. The ionization energy of a deep acceptor level has been determined, as $E_\mathrm{A} - E_\mathrm{V} = 0.38 \pm 0.05$ eV.

RESUMEN. Se describe un método nuevo para determinar la energía de ionización de los centros que controlan la transferencia de carga en estructuras *pin* a base de GaAs. La idea del método radica en la medición de la dependencia con la temperatura de la cinética del campo eléctrico en la capa i, aplicando un voltaje de escalón de polarización inversa a la estructura. Con un procesamiento subsecuente de los datos experimentales, y con base en los conocimientos obtenidos durante el estudio de la dinámica de la carga espacial y el campo eléctrico en una estructura *pin* [1], se determinó la energía de ionización de un nivel aceptor profundo; $E_\mathrm{A} - E_\mathrm{V} = 0.38 \pm 0.05$ eV.

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1. INTRODUCTION

The main feature of a pin-structure is the presence of a high-resistivity compensated i–layer where drops a considerable part of reverse bias, externally applied to the structure. This feature, along with high mobility of carriers in the i–layer, gives rise to numerous applications of the structure: photo-sensitive and fast-response pin-diodes, thyristors [2, 3] etc. A GaAs-based pin-structure has another interesting feature: under high intensity of electric field the optical properties of the i–layer change because of electro-optic effects [1, 4]. In particular, there is appreciable change in the absorption coefficient near the edge of fundamental absorption due to the Franz-Keldysh effect [5]. So the i–layer becomes less transparent in that part of it where the field intensity is higher. It is worth to mention

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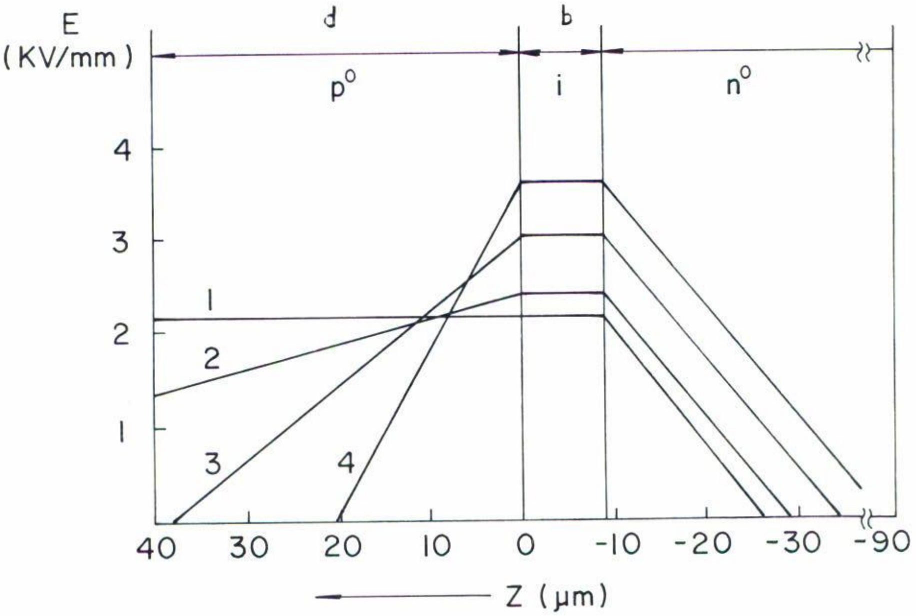

FIGURE 1. Evolution of the field in the bulk of a structure after the application of a voltage $V = 125$ V (Ref. [1]). Time t (s): 1: $t = 0$; 2: $t = 0.03$; 3: $t = 0.11$, 4: steady states.

that all these properties are required in light modulator devices with fast response in the infrared spectral region. Thus, the aim of the present work is to study fundamental optic and electric properties of a pin-structure.

2. ELECTRO-OPTIC EFFECT DESCRIPTON AND DISCUSSION

The screening of the field in the GaAs-based pin-structures upon application of external voltage of a reverse bias was investigated [1,4] with the help of a technique making use of the transversal electro-optic effect. In particular in Ref. [1], the distribution in space and time of the electric field intensity $E(z,t)$ was measured in p^+-, p^0-, i- and n^0-regions. It was found that in each of these regions, the electric field $E(z)$ differs from one region to another (see Fig. 1). It has to be mentioned that the field time dependence $E(z,t)$ also varies in a different way in these regions. In three of these depleted regions, a typical distribution of the electric field $E(z)$ was observed. In regions p^+ and n^0 the field distribution was linear with a penetration depth determined by the Schottky length. It must be pointed out that the field distribution $E(z)$ in region p^+ is not shown in the figure due to the small value of the voltage drop in it. In region i the field distribution is homogeneous.

On the other hand, in region p^0 the behavior of $E(z,t)$ is more complicated. At the very begining when the bias is applied, $E(z)$ is constant (line 1 in Fig. 1). For a long enough time interval (> 1 ms) as compared with the characteristic time of the space charge formation in region n^0 (< 1 μs), the field becomes nonuniform showing a linear distribution (see lines 2, 3, and 4 in Fig. 1) but the slope of these straight lines increases with time; in contrast with the case of region n^0 where the slopes of the field distribution do not vary. This means that in p^0 appears an homogeneous negative space charge with an increasing density with time.

The sign of this charge indicates that holes are the majority carriers in p^0. The homogenity of this charge distribution in this region does not vary in time. This is due to the fact that the holes drift length L is much greater than the thickness of the p^0 region d $(L \gg d)$.

In this way because of the charge transfer processes in the p^0–region running much slower, this region determines, in the long time, the dynamics of the field changes all over the structure. So the area under the curve of $E(z,t)$ in the i– and n^0–regions increases as the field is being expelled from the p^0–region. In the steady-state, the region of the voltage drop accross the p^0–layer is determined by its acceptor concentration N_{A}, they having been completely ionized at the Schottky depth (curve 4 in Fig. 1).

The field evolution description is given [1] as result of solving a set of differential equations for the p^0–region. The only cause of the field dynamics for the region is believed to be the thermic ionization of the deep-level holes and their subsequent drift by the electric field. The initial condition is a uniform field distribution in the p^0–region: the absence of the space charge there (curve 1 in Fig. 1). The boundary condition is keeping the potential difference V at the structure boundaries constant:

$$\int_0^d E(z,t)\,dz + E(0,t)b + 0.5\,[E(0,t)]^2\,\epsilon\epsilon_0/eN_{\mathrm{D}} = V \tag{1}$$

The first term here is the voltage drop in the p^0–region of width d, the second one in the i–layer of width b, and the third one in the n^0–region with the donors concentration N_{D} (the p^+–region is considered to be heavily doped. The acceptor concentration here is much greater than N_{D} so that it acts only as a negative electrode and there is practically no voltage drop across it).

Within the problem under an assumption of the length of the holes drift being great as compared to d, the solution for the space charge density ρ in the p^0–region at as short times that the field differs a few from the uniform one, and has the form

$$\rho = -eN_{\mathrm{A}}\left[1 - \exp\left(-\frac{t}{\tau_i}\right)\right]. \tag{2}$$

This means that in the p^0–region the thermal ionization of the holes from deep acceptor levels and their subsequent complete drift from the region account for accumulation in a rising exponential way of a uniform negative space charge with the time constant τ_i equal to the time of the holes thermal ionization. The field in the p^0–region is a straight line (see Fig. 1) with a slope determined in accordance with the Poisson equation by Eq. (2):

$$E(z,t) = -\frac{eN_A}{\epsilon\epsilon_0}\left[1 - \exp\left(-\frac{t}{\tau_i}\right)\right] z + E(0,t), \tag{3}$$

where

$$E(0,t) = \frac{eN_{\mathrm{D}}}{\epsilon\epsilon_0}\left[\sqrt{(b+d)^2 + \left(\frac{N_{\mathrm{A}}}{N_{\mathrm{D}}}\right)\left[1 - \exp\left(-\frac{t}{\tau_i}\right)\right] d^2 + \frac{2\epsilon\epsilon_0 V}{eN_{\mathrm{D}}}} - (b+d)\right]. \tag{4}$$

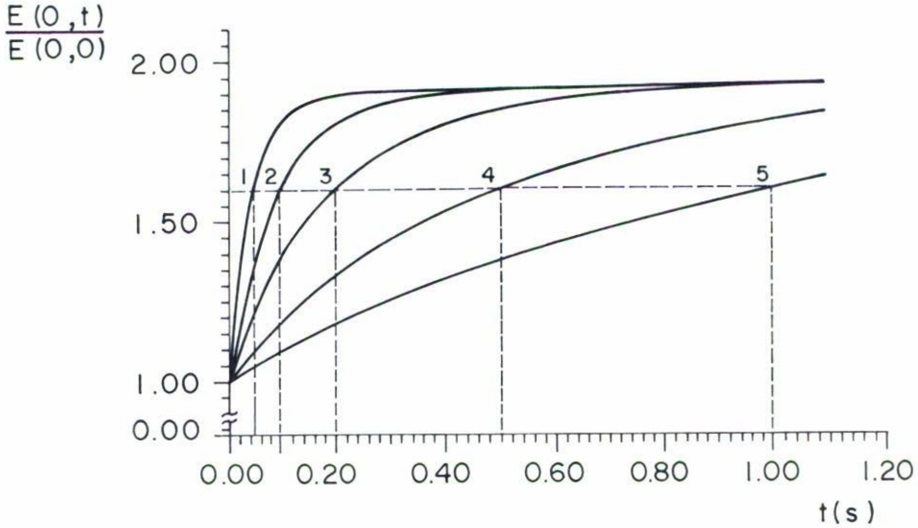

FIGURE 2. Electric field relaxation patterns in a i–layer: $E(0,t)/E(0,0)$ plotted by Eq. (4) at various values of parameter τ_i (s); 1: 0.05, 2: 0.1, 3: 0.2, 4: 0.5, 5: 1.0 ($N_{\mathrm{D}} = 0.9 \times 10^{14}$ cm^{-3}, $N_{\mathrm{A}} = 1.3 \times 10^{14}$ cm^{-3}, $\epsilon = 13.2$, $b = 9.5$ μm, $d = 40$ μm).

Figure 2 shows the normalized curves of the field relaxation $E(0,t)/E(0,0)$ plotted by Eq. (4) at various values of parameter τ_i. Two different stages in the field kinetics can be seen. The first one, practically instantaneous (< 1 ms) setting of a certain field value, is due to fast processes of charge transfer in p^+– and n^0–regions which result in practically all the voltage being applied to the high-resistivity p^0– and i–regions connected in series. The second stage of the field kinetics is due to the relatively slow thermic ionization of holes from deep acceptor levels in the p^0–region and their subsequent drift to the negative electrode, the field being expelled from the p^0–region into the i–layer and n^0–region. The analysis of the second stage of the field kinetics is our task in this case.

As follows from Eq. (4) and Fig. 2, the intensity of the uniform electric field in the i–layer $E(0,t)/E(0,0)$ increases along the curve with characteristic time τ_i. For each τ_i, all of these curves have a common starting point $E(0,t)/E(0,0) = 1$. When $t = \tau_i$ (see Fig. 2) in each curve $E(0,\tau_i)/E(0,0) = 1.6$ and for large times $E(0,t)/E(0,0)$ goes to 1.9. Processing the experimental curves of the field relaxation one should find the time τ_i as such moment t of time that $E(0,\tau_i)/E(0,0) = 1.6$, *i.e.*, the quantity $1.9 - [E(0,\tau_i)/E(0,0)]$ varying from 0.9 to 0, becomes 3 times less than the total variation 0.9.

On the other hand, τ_i depends on the sample temperature according to the following law [6]:

$$\tau_i = (\alpha T^2)^{-1} \exp\left[\frac{(E_{\mathrm{A}} - E_{\mathrm{V}})}{kT}\right], \tag{5}$$

where α is a coefficient proportional to the cross-section of the free holes trapping at an acceptor level, k is the Boltzman constant. The experimentally measured temperature dependency $\tau_i(T)$ allows one, with the help of Eq. (5), to find the ionization energy of an acceptor level, $E_{\mathrm{A}} - E_{\mathrm{V}}$.

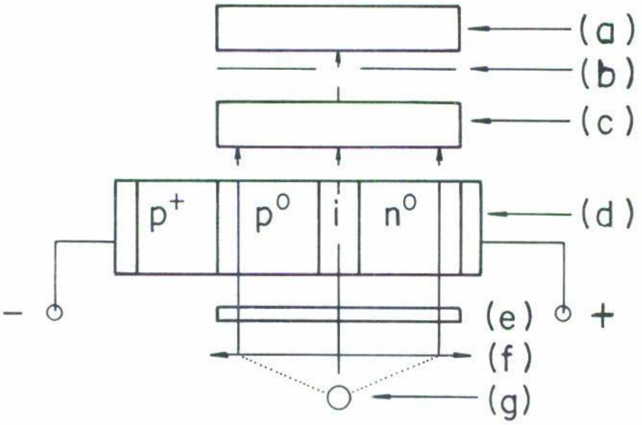

FIGURE 3. Experimental layout. (a) photomultiplier, (b) optical slit, (c) electro-optical converter, (d) GaAs-pin structure, (e) filter with $\lambda > 860$ nm, (f) collimator, and (g) filament lamp.

Thus, the idea of determination of the energy $E_A - E_V$ lies in using Eq. (5) and the "1/3" criterium following from Eq. (4) in processing the experimental data on measurements of the temperature dependence of the field kinetics in the i–layer of a pin-structure upon application of a step voltage of blocking polarity to the latter.

3. EXPERIMENTAL PROCEDURE

The measurement technique consisted of the following (Fig. 3). The pin-structure was exposed to a parallel beam of IR light with $\lambda > 0.86$ μm in the direction parallel to the structure layers. Magnified with the help of a microscope (not shown in Fig. 3), the image of the structure face was projected onto the photocathode of an electro-optic converter of IR light. One could see on the photocatode screen of the converter that the p^+–substrate was opaque to the probing IR light while the other epitaxial layers grown on it, transmitted the probing light well.

Upon application of external voltage to the structure one observed on the screen a complex image of setting of the intensity distribution of the structure-probing light. In steady-state conditions with small magnitudes ($V = 50$ V) of applied voltage, however, the i–layer is easily discerned as a narrow region (of 9.5 μm width in our case) between two very thin dark stripes. The matter is that under small voltage of a reverse bias the stationary field distribution exhibits a complex structure: the field distribution has two maxima at boundaries of the i–layer.

The i–layer in the image of the structure face was separated with the help of an optical slit and then a photomultiplier was used to measure the intensity of the i–layer-probing light against the time elapsed since the moment of application of step voltage 125 V of a reverse bias to the structure. In processing the curve one took into account the initial value of the light intensity (immediately after switching-on the voltage, $t \approx 1$ ms), the steady-state value and the moment of time t when the light intensity decreased three times

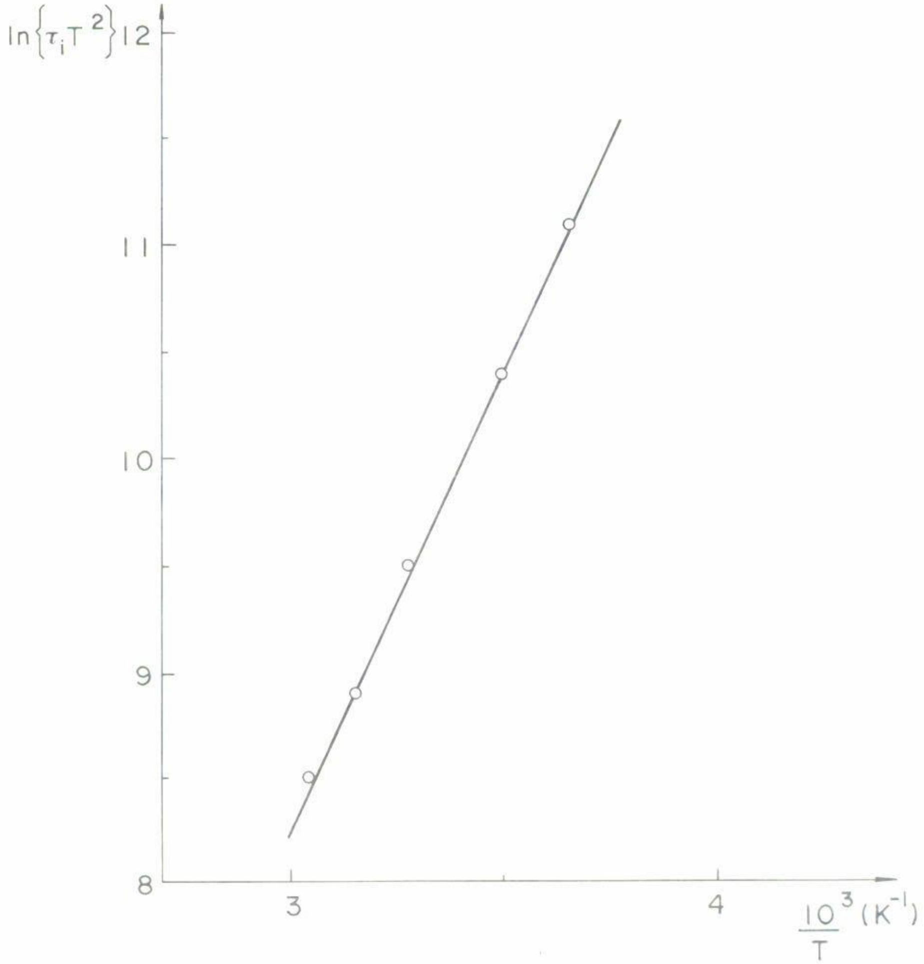

FIGURE 4. Dependence of $(\tau_i T^{-2})$ on the reciprocal temperature, plotted logarithmically.

(the level 1.6 in Fig. 2), the moment being equal to the value τ_i to be found. The curves were obtained at different temperatures.

The change of the structure temperature was achieved by cooling it with liquid nitrogen vapors or heating it with the help of an electric heater. The temperature measurements were made by means of a thermocouple. The measurements are carried out in the interval $250\ \mathrm{K} < T < 330\ \mathrm{K}$. The processing of a fixed-temperature curve gives one experimental point on Fig. 4.

This figure gives the quantity $\ln(\tau_i T^2)$ against inverse temperature. It can be seen that the time τ_i decreases with the growth of the sample temperature and the experimental points fitted to a straight line with its slope corresponding, according to Eq. (5), to the energy of acceptor level ionization $E_{\mathrm{A}} - E_{\mathrm{V}} = 0.38 \pm 0.05$ eV.

The value of $E_{\mathrm{A}} - E_{\mathrm{V}}$ found in our experiment coincides with the value 0.400 eV reported in [7], where p-GaAs grown by liquid phase epitaxy was investigated by DLTS method. This level is belived to be due to gallium atoms in arsenic sites.

4. CONCLUSIONS

It must be noted that the optical method, described here, for the determination of the center ionization energy is more sensitive in comparison with the methods based on current measurements [6, 7]. Indeed, under certain conditions, the relaxation of the field in the structure can proceed very slowly (see, *e.g.*, the point τ_i at $T = 250$ K in Fig. 4) so that the current flowing in the external circuit would be negligibly small (0.5 nA in our example) and hard to measure with good accuracy whereas the optical measurements of even very slow field relaxation would not present here much difficulty. Another important feature of this method, is the certainty that we are dealing with acceptors belonging to the p^0–regions which controlling, at long times, the processes of charge transfer and field relaxation all over the pin-structure.

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