The Ionization Energy Determination of Deep Level Defects in Inhomogeneous Doped Semiconductor Barrier Structures

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***Abstract* – In this paper the high accuracy method of determination of the ionization energy of uniformly distributed defects in semiconductor barrier structures with inhomogeneous doped base is developed.**

***Keywords* – deep level transient spectroscopy, determination of ionization energy, Schottky diode.**

I. Introduction

Among the methods of investigation of defects with deep levels (DL) in semiconductors is currently the most spread DLTS method [1], having a maximum concentration sensitivity N_t and high resolution of DL ionization energy. Existing methods of determining the ionization energy and the concentration of DL are based on the following assumptions [1, 2]:

- the relaxation time of DL charge does not depend on the electric field in the space charge region (SCR) of barrier layers in the diode-like sample;
- after the end of the relaxation process of DL recharge the barrier layer will be a region with a uniform space charge density of deep centers, ionized within SCR;
- DL concentration does not exceed the concentration of the primary shallow dopant in all cases.

In DLTS method DL ionization energy is traditionally determined by the slope of the Arrhenius plot. It is necessary to study the temperature dependence of the relaxation time of the capacitance of the semiconductor barrier (diode) structure or an electrical current through it to obtain this plot. Temperature scan of the sample increases the time of measurement [1]. Moreover, the Arrhenius plot is constructed by the assuming that the DL capture cross section σ does not depend on temperature. Actually σ may depend on temperature that makes an additional error in the determination of DL ionization energy.

It is necessary task to reduce time costs for analysis and control of defects in the semiconductor industry. In some cases, modern semiconductor devices have a shallow impurity that is an integral feature of its production. In this connection the aim of the study is to develop an original method of determining the DL ionization energy in semiconductor barrier structures that will be characterized by high accuracy of analysis and less time of experiment on the one hand. On the other hand there was a problem of experimental approbation of the calculated ratios in the investigation of real semiconductor structures that satisfy to the above assumptions.

II. The Main Practical Aspects

As an example, we consider a Schottky diode with an n-type base containing one donor-like DL with uniform distribution of concentration N_t in the base and having the ionization energy ΔE_t. In addition, we assume that all small shallow impurity in the diode base are ionized, and their concentration in the base changes linearly. Suppose that in equilibrium (Fig. 1a) DL E_t is located entirely below the Fermi level E_f and is completely filled with electrons, including those on the metal – semiconductor interface. This means that we do not consider the initial depletion region of deep level, and the thickness of the SCR roughly coincides with the thickness of incomplete ionization layer λ [3]:

$$\lambda = \sqrt{\frac{2\varepsilon\varepsilon_0(E_f - E_t)}{e^2 N}}, \quad (1)$$

were ε is the relative dielectric constant of the semiconductor; ε_0 is the dielectric constant; N is the concentration of shallow donors in the area directly adjacent to the diode base; e is the elementary charge.

This assumption will make an error in the calculation of the DL concentration, that creates energy conduction bands, but this error is usually ignored [2]. In addition, the assumption that made above is quite justified for the energy levels, completely below the Fermi level, i.e. in the middle of the band gap [1].

The energy band diagram of the Schottky diode after the applying of the reverse bias voltage V is shown in Fig. 1b. After the applying of the reverse bias voltage to the diode the following processes are observed: 1) the emission of electrons from DL from the part of the base that has energy level E_t above the Fermi level (generation current appears); 2) the shift of the SCR boundary due to the current relaxation [1].

According to Fig. 1b, the region of carriers emission from DL has a thickness $\delta = d_1 - \lambda$.

In this case, the total current through the semiconductor barrier structure, equal to the sum of generation and bias

currents can be calculated from the relation:

$$i(t)=\frac{eN_t\delta S\theta}{\tau}\cdot\exp\left(-\frac{t}{\tau}\right) \quad (2)$$

$$\theta=\frac{1}{2}\left[1+\left(\frac{E_{F_n}-E_t}{V-V_K}\right)^{1/2}\right]$$

is the factor that consider the effect of SCR boundary shift in the process of current relaxation [4]; S is the square of barrier Shottky contact; t is the time of transient process; δ is the thickness of the DL layer of ionization ; V_K is the contact potential difference; τ is the relaxation time [4]:

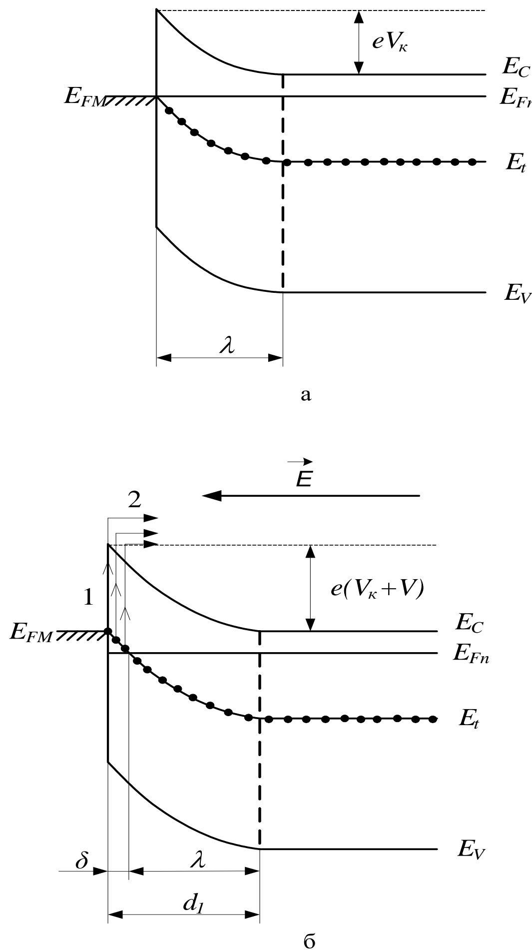

Fig. 1. Energy band diagram of the Schottky diode with the n-type base.

$$\tau=\tau_0\exp\left(\frac{E_C-E_t}{kT}\right), \quad (3)$$

$\tau_0 = 2\tau_M = \varepsilon\varepsilon_0\rho$ according to the activation-drift model of DL recharge [4] or $\tau_0 = (\sigma_n < \upsilon_T > N_C)^{-1}$ according to the model of Shockley-Read-Hall [1], τ_M is the Maxwell relaxation time in the electrically neutral part of the diode base, ρ is the resistivity of the base of the diode, k is the Boltzmann constant, T is the absolute temperature, σ_n is the DL electron capture cross section, $<\upsilon_T>$ is the electron's average thermal velocity, N_C is the effective density of states in the conduction band.

If the noticed relaxation process periodically repeats with period T_0, the output voltage ΔU of the current version of DLTS (I-DLTS) spectrometer is

$$\Delta U=\frac{meN_t\delta S\theta}{\tau}\int_0^{T_0}F(t)\exp\left(-\frac{t}{\tau}\right)dt, \quad (4)$$

where m is the transfer coefficient of the DLTS spectrometer; $F(t)$ is the weighting function of the spectrometer (for example "lock-in" or "double boxcar").

As a result of temperature scanning of the semiconductor barrier structure that has one DL, there is a characteristic maximum (peak) of the output voltage of DLTS spectrometer (Fig. 2).

The amplitude of DLTS peak depends on the amplitude of the reverse bias voltage pulse. Obviously that with the increase of the amplitude of the reverse bias voltage pulse, the thickness of the SCR increases and as a result the thickness of the ionization layer of DL δ increases also. As follows from the formula (4), the amplitude of the peak in DLTS spectrum increases.

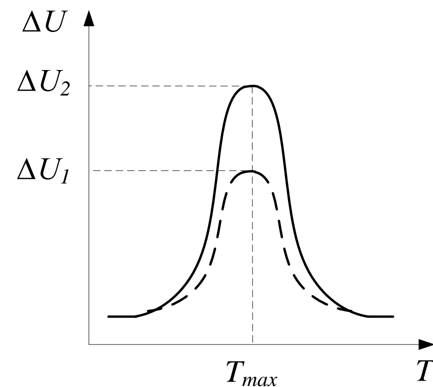

Fig. 2. Temperature dependence of output voltage of the DLTS spectrometer.

Determination of the DL concentration in the I- DLTS method is performed by amplitude of the DLTS peak ΔU from the relation [4]:

$$N_t=\frac{\Delta U}{meS\delta\theta}. \quad (5)$$

Write the formula (5) for two cases of amplitude of the reverse bias voltage V_1 and V_2 when $b = 1$ and $\theta = 1$ [4] under condition of presence of the concentration profile of shallow doping impurity in the base of diode:

$$N_t(V_1)=\frac{\Delta U_2}{m\cdot e\cdot S(d_1(V_1)-\lambda_1)};$$

$$N_t(V_2)=\frac{\Delta U_2}{m\cdot e\cdot S(d_2(V_2)-\lambda_2)}; \quad (6)$$

$$\lambda_1=\sqrt{\frac{2\varepsilon\varepsilon_0(E_{f1}-E_t)}{e^2N_1}}\quad \lambda_2=\sqrt{\frac{2\varepsilon\varepsilon_0(E_{f2}-E_t)}{e^2N_2}}$$

Under the condition of uniform distribution of the space charge of DL in the SCR and $V>>V_к$:

$$\frac{\Delta U_2}{m\cdot e\cdot S(d_1(V_1)-\lambda_1)}=\frac{\Delta U_2}{m\cdot e\cdot S(d_2(V_2)-\lambda_2)} \quad (7.1)$$

$$d_1(V_1) = \sqrt{\frac{2\varepsilon\varepsilon_0 V_1}{eN_1}} \quad (7.2)$$

We use well-known relation from the literature to calculate the Fermi level [3]:

$$E_C - E_f = kT \ln \frac{N_C}{N} \quad (8)$$

From Fig. 1 could be found:

$$E_f - E_t = (E_c - E_t) - (E_C - E_f) = \Delta E_t - (E_C - E_f) \quad (9)$$

From equations (6), (7), (8), (9) consider that $E_{f1} \approx E_{f2} = E_f$, could be obtained:

$$\Delta E_t = e\left(\frac{\Delta U_2 \sqrt{\frac{V_1}{N_1}} - \Delta U_1 \sqrt{\frac{V_2}{N_2}}}{\frac{\Delta U_2}{\sqrt{N_1}} - \frac{\Delta U_1}{\sqrt{N_2}}}\right)^2 + kT_{\max} \ln \frac{N_C}{N_{cp}} \quad (10)$$

$N_{cp} = \frac{N_1 + N_2}{2}$ is the average concentration of shallow donors in the case of its linear distribution.

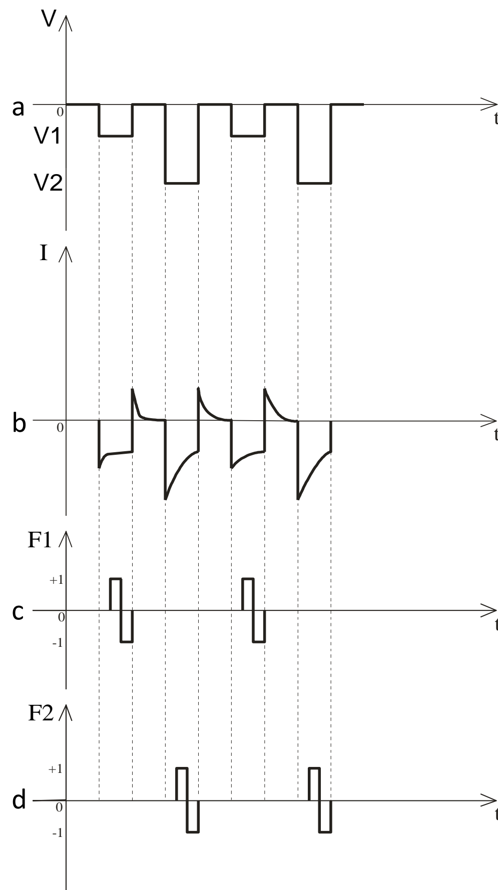

Fig. 3. Timing diagrams of the modified Lang's method [5].

When calculating ΔE_t the value of $T_{\max}$ corresponds to the temperature of the peak maximum in DLTS spectrum (Figure 2). If a sample has several DLs all information about their ionization energies could be obtained as a result of one temperature scan with a fixed relaxation time constant of settings of the weighting function discriminator in the DLTS spectrometer. To calculate the density of states in the conduction band N_C a standard methodology is used. So, for silicon $N_C = 5{,}5 \cdot 10^{15} \cdot T^{3/2}$ [3]. The values N_1, N_2 could be easily found from the capacitance-voltage characteristics (C-V characteristics) of the diode.

Thus, the formula (10) allows to determine the DL ionization energy according to data of I-DLTS measurements without building the Arrhenius plot. The technique is as follows. In the Lang's method [1] is introduced an additional reverse bias voltage pulse with an amplitude $V_2 > V_1$, and $|V_2 - V_1| >> kT_{\max}/e$. On the investigated semiconductor structure reverse bias voltage pulses V_1 and V_2 are alternately used (Figure 4a). After each pulse a current relaxation process is obtained (Figure 4b). A signal proportional to these processes is multiplied by the reference signal the weighting function $F_1(t)$ (Figure 4c) and $F_2(t)$ (Figure 4d) and $F_1(t) = F_2(t)$, where the time t is counted from the beginning of the corresponding voltage pulse. As a result the relaxation times are selected and two values of amplitude of peaks in DLTS spectrum ΔU_1 и ΔU_2 are determined, corresponding to the same relaxation time constant and different amplitude of the reverse bias voltage pulses V_1 and V_2.

Formula (10) can also be used as an algorithm for calculating the ionization energy in automated systems DDLTS [6].

III. Conclusions

The method of determination the ionization energy of uniformly distributed defects in semiconductor barrier structures with inhomogeneous doped base is developed. The technique has high accuracy and rapid measurement at the level of the existing analogues. Application of the considered method for determining the DL ionization energy allows to reduce research time in a half or even more. Measurement error of the DL ionization energy does not exceed 0.03 eV.

Acknowledgment

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References

[1] *Lang D.V.* Space charge spectroscopy in semiconductors // Thermally Stimulated Relaxation Processes in Solids. – New York, 1979. – P. 93 – 133.

[2] *Thurzo I., Gmukova K.* On the theory of current DLTS // Acta Phys. Slov. – 1984. Vol. 4. № 1.–P. 217 – 223.

[3] *S.M. Sze*, Physics of semiconductor devices, New York: John Wiley&Sons, 1981.

[4] *Zubkov M.V.* Opredelenie koncentracii glubokix centrov s uchetom polevoy zavisimosti vremeni relaksacii toka // Electronnaya texnika. Ser.10. Mikroelektronniye ustroystva. Vyp. 6(78), 1989. – P.42-45.

[5] *Vishyakov N.V., Gudzev V.V., Zubkov M.V., Litvinov V.G.* Patent na izobretenie № 2431216 «Sposob opredeleniya energii ionizacii glubokix urovney v polyprovodnikovyx barernyx structurax i ystroystvo dlya ego osyshestvleniya» Zayavka № 2010124341. Registered in the State Register of Inventions of the Russian Federation in 10 October 2011.

[6] *Denisov A.A., Laktyushkin V.N., Sadofyev Yu.G.* Relaksacionnaya spektroskopiya glubokix urovney // Obzory po electronnoy texnike. Ser.7. Vyp. 15 (1141).-M.: CNII «Electronica», 1985. 52p.