[1]Pavlo Stakhira, [2] Roman Stakhira

[1] Lviv Polytechnic National University, Department of Electronic Devices,
[2]Institute of Applied Physics, Ivan Franko Lviv National University,
49 General Chuprynka Str. 79044, Lviv, Ukraine

DYNAMICS OF MODULATION SPECTRUMS OF PIEZOPHOTOCONDUCTIVITY OF MONOPOLAR SEMICONDUCTOR

Keywords: piezophotoconductivity, dynamics of piezophotoconductivity, phase delay

Piezophotoconductivity is being analyzed - phenomenon stimulated by common action of light from spectrum region that corresponds to interband absorption and strain. The case of interband optical absorption of the system that is under the influence of adiabatic low frequency disturbance, caused by pressure, and high frequency disturbance, caused by light action, is considered. It is shown that absorption factor of a system, which is under an action of combined disturbance, is a periodic time function with the period determined by low frequency disturbance. The equation of dynamics of nonequilibrium current carriers' concentration in the conditions of acoustic-light excitation was obtained. The peculiarities of dynamics of spectrum of interband absorption of the strained semiconductor were considered.

1. INTRODUCTION

It is known that application of combined excitation methods is the most effective way of investigation of a thin structure of semiconductors energy bands. Among the most well known method it can be called a modulation spectroscopy [1], but propagation of the modulation spectroscopy's principles on photoelectric phenomena gives additional possibilities for the investigation of semiconductors [2]. Partly, a photoconductivity piezomodulation covers all the processes of optical absorption, also causes the modulation of parameters that characterize processes of charge carriers transfer, kinetics of its concentration etc.

2. DYNAMICS OF NONEQUILIBRIUM CURRENT CARRIERS' CONCENTRATION IN THE CONDITIONS OF ACOUSTIC-LIGHT EXCITATION

Electroconductivity of semiconductor under common action of light and strain at constant temperature can be written as following sum

$$\sigma = \sigma_0 + \beta I + \pi p + \theta p I , \qquad (1)$$

where σ_0 is electroconductivity when mentioned influences are absent, βI is photoconductivity, θIp is piezophotoconductivity. Further, piezophotoconductivity, a component of electroconductivity, which is proportional to product of the pressure p and light intensity, will be considered in the paper.

Let's consider the monopolar semiconductor that is under the influence of light from spectrum region corresponding to characteristic absorption and periodic low frequency strain. Let's limit to the consideration of semiconductors with the simple structure of conduction band, where

the influence of the pressure on the charge carriers' concentration caused only by the change of the forbidden gap width [3].

The equation for concentration $n(t)$, which generated when process is steady, can be written on the basis of the equation of particles balance

$$\int_{t_0}^{t}\left[\frac{dn}{dt'} - G(t') + R(t')\right]dt' = 0, \tag{2}$$

where $G(t)$ and $R(t)$ is rate of summary generation and recombination.

As generation and recombination rates are time functions, there are no reasons to think that the function under integral always equals to zero. It is obvious that in the case of generation and recombination, which variable in time, the corresponding equation of particles balance must be written for increments of these value - $\frac{d}{dt}G(t)\delta t$ and $\frac{d}{dt}R(t)\delta t$, during time δt. Thus the equation for $n(t)$ is:

$$\frac{d^2 n(t)}{dt^2} + \Omega_0^2(n(t) - n_0) = \frac{d}{dt}G(t) - \frac{d}{dt}R(t), \tag{3}$$

where Ω_0 is frequency of alternating strain. Besides, the equation for the concentration has second order because the piezophotoconductivity is mixed derivative.

For the recombination rate is used the main equation of Shockly-Reed theory [4] for the stationary case with one kind of a trap:

$$R(t) = \frac{n(t) - n_0}{\tau_0}\left[\frac{1 + b(n(t) - n_0)}{1 + a(n(t) - n_0)}\right], \tag{4}$$

where τ_0 is relaxation time at low excitation levels and

$$b = \frac{\tau_{p_0} + \tau_{n_0}}{\tau_{p_0}(n_0 + N_{cm}) + \tau_{n_0}(p_0 + P_{vm})},\ a = \frac{1}{n_0 + p_0}, \tag{5}$$

p_0, n_0 are equilibrium concentration of holes and electrons; τ_{p0} and τ_{n0} is holes' lifetime according to the capture by centers, which fully filled with electrons and electrons' lifetime according to the capture by the same centers but without electrons; N_{cm} and P_{vm} is effective density of states of conduction band and valence band.

The rate of optic generation for the stationary case is defined as product of light intensity and absorption coefficient α with considering the multiplication constant γ, $G=\alpha\gamma I$. Among these values only the absorption coefficient can essentially depends on pressure. However it is incorrect to use this method for the quasistationary absorption mode even as linear approximation by pressure because stationary states are absent at alternating deformation of a crystal. Transition probability between such states can be a function of time and essentially differ from transition probability into stationary states [5]. Therefore the rate of optical generation can be chosen as following:

$$G(t) = G_0 + G_1\cos(\Omega_0 t) + G_2\sin(\Omega_0 t), \tag{6}$$

where G_0, G_1, and G_2 are functions of light frequency. It is necessary note the presence of the shift of the optical generation phase relative to the strain phase caused by sensibility of energy states to deformation and by optical radiation spectral distribution.

3. EQUATION OF DYNAMICS OF FREE CURRENT CARRIERS' CONCENTRATION IN THE CONDITIONS OF ACOUSTIC-LIGHT EXCITATION

If to use the equation (6) for the optical generation rate it is possible to write the equation for dependence of nonequilibrium current carriers' concentration from time in the conditions of common influence of light and alternating strain.

$$\frac{d^2\Delta n}{dt^2}+\Omega_0^2\Delta n=\frac{d}{dt}\left\{G_0+G_1\cos(\Omega_0 t)+G_2\sin(\Omega_0 t)-\frac{\Delta n(1+b\Delta n)}{\tau_0(1+a\Delta n)}\right\}, \quad (7)$$

where $\Delta n= n(t)- n_0$. Non-linearity of the equation (7) caused by non-linearity of the recombination rate. Despite using the equation of Shockly-Reed in the case of recombination, non-linearity of recombination rate is rather rule then exclusion. The character of this non-linearity usually depends on the properties of the semiconductor. The equation (7), in view of dynamics of nonequilibrium charge carriers' concentration, describes influence generation-recombination processes on inextinguishable oscillations of this concentration. In consequence of non-linearity of these processes frequency of concentration oscillation Ω can differ from frequency Ω_0 of an impulsive member (generation rate). In view of practice, it is important to have the expression for harmonics with frequency that equal to frequency of modulation factor, because experimental measurements are usually carried out at this frequency. Taking into account these requirements, let's find the solution of equation (7), which corresponds to periodical dependence of nonequilibrium concentration with frequency Ω, that equal to Ω_0. Presence of recombination member in right part of the equation (7) causes its non-linearity. Non-linearity amount depends from the light excitation intensity and can be insignificant when intensities are not high. It is possible to use reciprocal value of frequency [6] for writing the equation (7) in standard form after following changes

$$\begin{gathered}a(n-n_0)\tau_0=f,\Omega t=\tau,\frac{\Omega_0^2}{\Omega^2}=1-\frac{\delta}{\Omega},\\ \tau'=\tau\sqrt{1-\delta/\Omega},x=b/a,g1=aG_1\tau_0,g2=aG_2\tau_0\end{gathered} \quad (8)$$

After some insignificant transformation it can be obtained

$$\frac{d^2f}{d\tau^2}+f=\frac{1}{\Omega}\left\{g_0-g_1\sin(\tau')+g_2\cos(\tau')-\frac{1}{\tau_0}\left[1+\frac{1-x}{1+f^2}\right]\frac{df}{d\tau}\right\}. \quad (9)$$

The value $1/\Omega$ is here as small parameter. Time dependence of equilibrium concentration n_0 in expression for recombination member is neglected in the equation (9). As can be seen from the equation (7) this can lead to change of amplitude G_1, but does not influence on time dependence of concentration *n(t).*

Let's input new unknown *N* and *M* and turn to the equations set that is equivalent to the equation (9):

$$f=N\cos(\tau)+M\sin(\tau),\frac{df}{d\tau}=-N\sin(\tau)+M\cos(\tau). \quad (10)$$

Values *N* and *M* are time functions and their equation are following:

$$\frac{dN}{d\tau} = \frac{1}{\Omega} F\left(N, M, \frac{dN}{d\tau}, \frac{dM}{d0}, \tau\right)\sin(\tau),$$
$$\frac{dM}{d\tau} = \frac{1}{\Omega} F\left(N, M, \frac{dN}{d\tau}, \frac{dM}{d0}, \tau\right)\cos(\tau). \qquad (11)$$

where $F\left(N, M, \frac{dN}{d\tau}, \frac{dM}{d0}, \tau\right)$ - the right part of the equation (9), where replacement of f and $df/d\tau$ is made according to the equation (10).

Further the nonequilibrium carriers' concentration is considered in steady mode. It gives possibility to use known method [7] of averaging the non-linear equations for approximate solution of the equation set (11). After averaging the right part of the equation within infinite time interval 2π, the modificated equation set is obtained:

$$\frac{dN}{d\tau} = \frac{\pi}{\Omega}(g_1 - \delta M - NQ),$$
$$\frac{dM}{d\tau} = \frac{\pi}{\Omega}(g_2 + \delta N - MQ). \qquad (12)$$

When averaging it was accepted that $\tau' \approx \tau$; and value of Q depends on expression $N^2+M^2=A^2$ to $(1+f_0)^2$, where $f_0=an_0$.

The case of high generation levels correspond to inequation $A^2>(1+f_0)^2$, for Q

$$Q = \frac{1}{\tau_0}\left[x - \frac{2(1-x)}{A^2}\right], \qquad (13)$$

Contrary case

$$Q = \frac{1}{\tau_0}\left[x - \frac{2(1-x)}{A^2}\left\{1 - \frac{1}{\sqrt{(1+f^2) - A^2}}\right\}\right]. \qquad (14)$$

For the values N and M at quasisteady regime the equation set is obtained

$$N = \frac{g_1 Q - g_2 \delta}{Q^2 + \delta^2}, M = \frac{g_2 Q + g_1 \delta}{Q^2 + \delta^2}, \qquad (15)$$

where sum $N^2 + M^2 = A^2$ meets the equation (because Q depends on only from sum $N^2 + M^2 = A^2$), which gives possibility to find N and M.

$$N = \frac{(xg_1 + g_2\delta)\left\{g^2 + 4x(1-x) \pm \left[g^4 + 8g^2x(1-x) - 16\delta^2(1-x)\right]^{1/2}\right\} - 4gg_1(1-x)(\delta^2 + x^2)}{2g^2(\delta^2 + x^2)},$$
$$M = \frac{(xg_2 - g_1\delta)\left\{g^2 + 4x(1-x) \pm \left[g^4 + 8g^2x(1-x) - 16\delta^2(1-x)\right]^{1/2}\right\} - 4gg_2(1-x)(\delta^2 + x^2)}{2g^2(\delta^2 + x^2)}. \qquad (16)$$

It can be seen that components N and M essentially depend on expression $b/a = x$ (8), and especially at its small values. Decrease of x leads to decrease of role of dissipative member in the

equation (7), and leads the system described by this equation to non-linear resonance mode. It can be seen from dependencies of components *N* and *M* on *x*, shown in Fig.1. It must be noted that decrease of recombination with increase of the nonequilibrium carriers' concentration, which corresponds to small values of *x*, is not uncommon phenomenon [8] and usually is realized within narrow temperature interval of semiconductor.

Taking to consideration the equation (16), it is easy to obtain the value of phase shift between oscillation of concentration and strain.

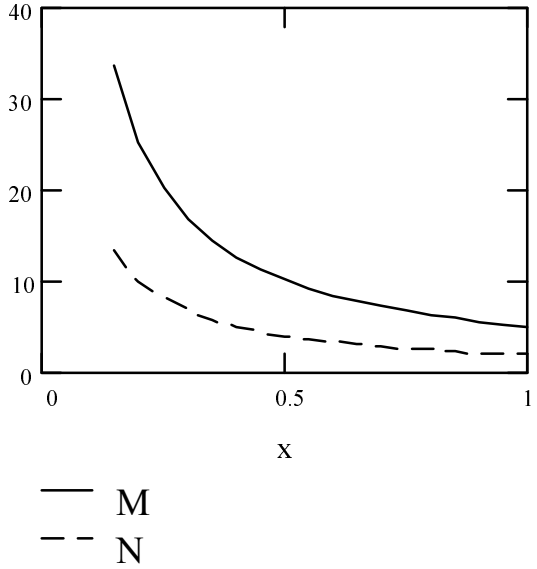

Fig. 1. Dependency of inphase M and phase shifted N components from recombination rate x for $g_1=2$, $g_2=5$, $\delta=10^{-4}$

$$\varphi = \operatorname{arctg}\frac{(xg_2 - g_1\delta)\left\{g^2 + 4x(1-x) \pm \left[g^4 + 8g^2x(1-x) - 16\delta^2(1-x)\right]^{1/2}\right\} - 4gg_2(1-x)(\delta^2 + x^2)}{(xg_1 + g_2\delta)\left\{g^2 + 4x(1-x) \pm \left[g^4 + 8g^2x(1-x) - 16\delta^2(1-x)\right]^{1/2}\right\} - 4gg_1(1-x)(\delta^2 + x^2)}. \quad (17)$$

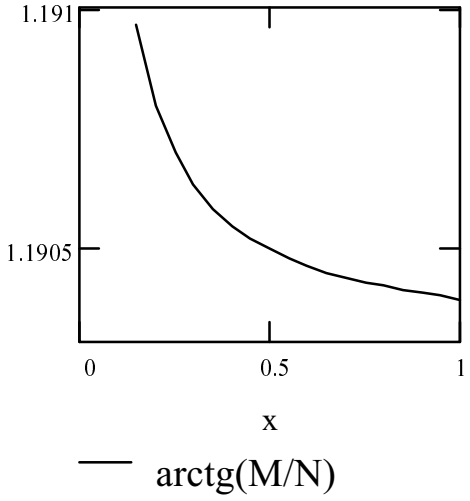

Fig. 2. Phase shift from recombination rate x for $g_1=2$, $g_2=5$, $\delta=10^{-4}$

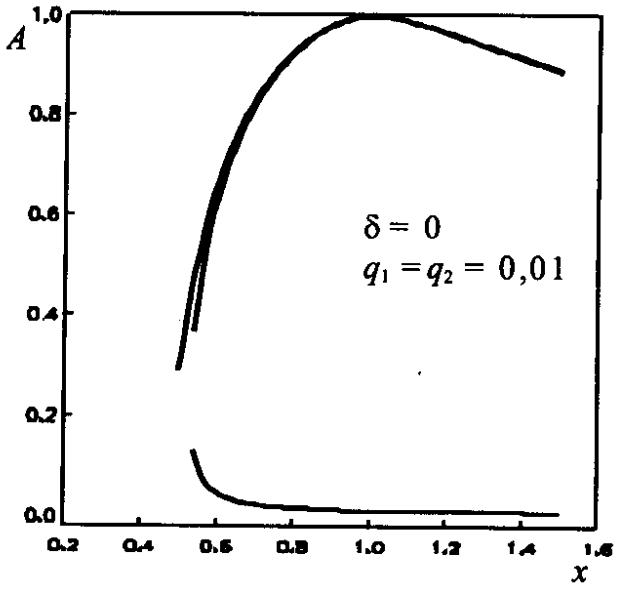

Fig. 3. Dependency of amplitude A from relation b/a at low excitation levels

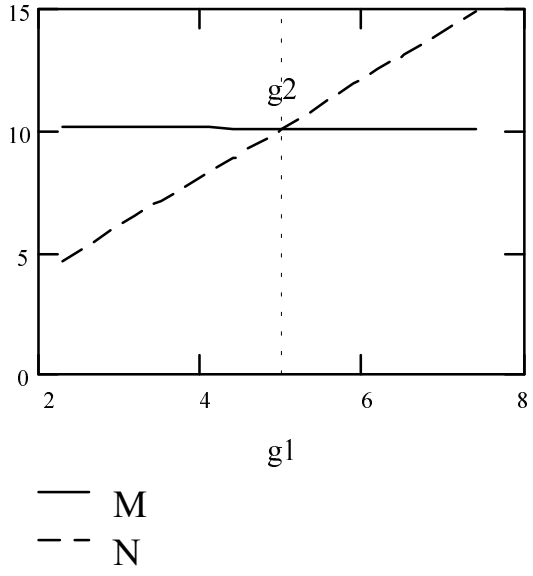

Fig. 4. Dependency of inphase and phase shifted by π/2 components of nonequilibrium charge carriers' concentration from value of inphase recombination components for $x=0.5$, $\delta=10^{-4}$

It can be seen from expression (17) that oscillation phase of nonequilibrium charge carriers and photoconductivity current at the same time is shifted relative to deformation phase (Fig.2). Generation components g1 and g2, and character of non-linearity of recombination member x determine this increase.

It is difficult to solve the algebraic system (15) at high excitation levels because of high order of the equation. Fig.3 shows results of numerical computation of dependence of the value $A^2=N^2+M^2$ from relation x. As in previous case dependence of these values from x shows tendency to their increase when x is decreasing and it has evident interpretation while roots, value of which decreases when generation is increasing, has not any physical meaning.

Spectral dependence of components N and M mainly caused by dependencies g_1 and g_2 (Fig. 4.).

REFERENCES

[1] М.Кардона, Модуляционная спектроскопия (Мир, Москва, 1977).

[2] A.Abbaet, K.J.Han, I.V.Ostrovskii, P.Das, Solid-St. Electron. 36, 697 (1993).

[3] Г.Л.Бир, Г.Е.Пикус, Симметрия и деформационные эффекты в полупроводниках (Наука, Москва, 1972).

[4] W.Shokley, W.T.Jr.Read, Phys.Rev. 87, 835 (1952).

[5] Л.С.Демків, Р.Й.Стахіра Вісник Львівського Університету: фізика і хімія матеріалів електронної техніки. 31, 38 (1998).

[6] А.М.Заездный, В.Ф.Кушнир, Б.А.Фереман, Теория нелинейных электрических цепей (Связь, Москва, 1968).

[7] Ю.А.Митропольский, Метод усреднения в нелинейной механике (Наукова думка, Київ, 1971).

[8] Полупроводники в науке и технике, 2, 12 (АН СССР, 1958).

Grzegorz Błąd [1], Zenon Hotra [1,2],
Dariusz Klepacki [1], Jerzy Potencki[1]

Rzeszów University of Technology, Dept. of Electronic and Communication Systems,
W. Pola 2, 35 959 Rzeszów, Poland
Lviv Polytechnic National University, Dep. of Electronic Devices, 12 Bandera St.,
290646 Lviv, Ukraine

TRANSIENT TEMPERATURE FIELD IN THICK-FILM MULTILAYER STRUCTURES

Keywords: temperature field, thick-film ` echnology

The paper presents two methods of temperature field simulation in thick-film multilayer structure with local pulse heating. The first method is based on the equivalent electrical model of heat transfer. Simulations have been made using PSPICE program. The basis of the second one is solving the heat equation through integral transforms. Calculations were made on example thick-film laser power detector.

1. INTRODUCTION

Due to trends towards large scale integration the problem of thermal reliability of microelectronics devices has become important during the last decade. Modern electronic devices operate at a high power level. Thus a single chip which represents a multilayer thin coating-substrate assembly dissipates a heat flux of 0,1-1MW/m^2. Since the components of this assembly