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A MICROELECTRONIC SENSOR WITH FREQUENCY OUTPUT FOR DETERMINING LIFETIME OF THE CHARGE CARRIERS BY THE METHOD OF CONDUCTIVITY MODULATION IN A POINT CONTACT

The technologies of manufacturing semiconductor devices use different methods for studying their parameters, which are evaluated according to the changes of their structure-sensitive electrical parameters – diffusion path length L_D of the unbalanced charge carriers and their lifetime τ [4]. The known procedures [1] for determining these parameters make it possible to estimate L_D and τ for the volume of semiconductors. Therefore, it was an important task of this research to study the possibilities to determine τ by means of voltage-to-frequency conversion as well as further analysis and processing of the frequency signal, which allows to improve accuracy of τ estimation. The procedure for measuring lifetime of charge carriers by the method of conductivity modulation in the point contact was considered.

Keywords: *lifetime, diffusion length, unbalanced charge carriers, modulation, point contact.*

Introduction

Measuring lifetime of charge carriers by the method of conductivity modulation in a point contact means that through the point contact on the surface of a sample, which serves as an emitter, current pulse of a rectangular form is passed so that charge carriers are injected into the sample volume. After the end of current pulse, excessive concentration of the charge carriers is reduced due to recombination [2].

In a certain time (delay time) after the end of injecting pulse the next current pulse passes through the point contact, by means of which measurements are performed. Voltage across the sample at the moment when the measuring pulse passes depends on the concentration of the charge carriers which have not recombined yet. Changing delay time in the range of $0 – 3\ \tau$, lifetime of the charge carriers could be determined on the dependence of voltage across the sample on the delay time [4].

Analysis of the latest research and publications

Scientific and technological progress cannot be imagined without electronics and, especially, without microelectronics. In modern microelectronics semiconductor materials and multilayer structures, serving as a basis for manufacturing various semiconductor devices and microcircuits, are widely used. Further development of the technology for manufacturing semiconductor materials involves increasing the efficiency of laboratory and industrial quality control, which determines both the amount of technological losses at different stages of production and material expenses for the industrial control of their quality. Equipping the industry with high-precision productive means of measurements, development of non-destructive control methods are directly connected with the problem of improving the quality of production of semiconductor materials and structures.

Operation of the majority of semiconductor devices is based on non-equilibrium conductivity, i.e. on injection, diffusion, drift and recombination of non-equilibrium current carriers. The value and character of non-equilibrium charge carriers and, therefore, their lifetime vary in wide ranges depending on the condition of their generation, the type of impurity centers and their concentration in the volume and on the surface of the wafer. Investigation of these irregularities is highly important for studying various physical processes as well as for increasing the output of usable non-defective semiconductor devices and reducing the spread of their parameters.

Lifetime of charge carriers is an important parameter influencing the parameters of material, which, in turn, affect the characteristics of semiconductor devices that use the properties of minority carriers [3].

The most efficient methods for measuring lifetime of the minority charge carriers are as follows:

1. Stationary methods: the methods for measuring diffusion length based on the application of movable light probe as well as the method of measuring photomagnetoelectric effect and stationary conductivity.

2. Non-stationary methods: photoconductivity decay pulse method that is used for measurements on wafers and ingots as well as the methods with the application of wafers and p - n junctions.

If the required lifetime is known, manufacturing technology for a certain product could be chosen, e.g. doping silicon with gold leads to a reduced lifetime of the minority carriers while application of hetero increases the lifetime. It should be noted that it is often important to measure lifetime in the finished device and not in the material.

Fig. 1 presents a block-diagram of classification of the methods for determining the lifetime of charge carriers in semiconductors [7].

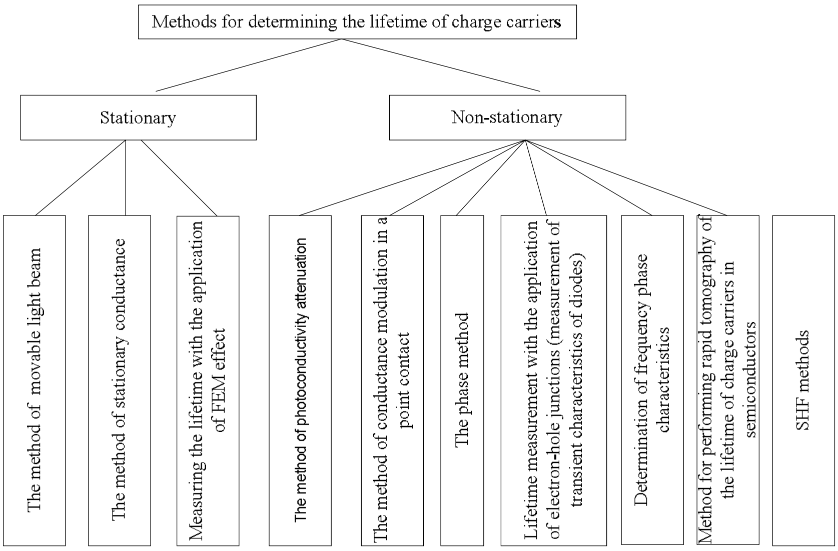

Fig. 1. Block-diagram for determining the lifetime of charge carriers in semiconductors

Mathematical model

Let $U(\infty)$ be the maximal voltage across the sample and $U(t)$ - voltage at the moment of the measuring pulse supply. Difference between these voltages is a time delay function [3]:

$$\Delta U(t) = U(\infty) - U(t) = \frac{1}{2\pi\sigma_0}\int_{t_0}^{\infty}\frac{dr}{r^2} - \frac{1}{2\pi\sigma_0}\int_{t_0}^{\infty}\frac{dr}{r^2\left[1+\dfrac{\Delta\sigma(r,t)}{\sigma_0}\right]}. \qquad (1)$$

If excessive concentration of charge carriers is small as compared with that of the main charge carriers, expression (1) takes the following form:

$$\Delta U(t) = \frac{I}{2\pi\sigma_0^2}\left[\int_{r_0}^{\infty} e\mu_p(b+1)\Delta p(r,0)\frac{dr}{r^2}\right]\exp\left(-\frac{t}{\tau_0}\right). \qquad (2)$$

Voltage $\Delta U(t)$ [3] decreases in time exponentially, provided that the delay is not very small, since the integral in square brackets does not depend on t.

Changing the delay time of the current pulse, by means of which measurements are performed, and fixing the values of $U(\infty)$, lifetime of the charge carriers could be found on the inclination angle of straight line $\ln\Delta U(t)$ as a function of the delay time [3]:

$$\frac{1}{\tau_p} = -\frac{d}{dt}\ln U(t).$$

Taking into account the surface recombination, diffusion of the charge carriers and the influence of the point contact, we obtain [2]:

$$\mu_p \xi \rangle\rangle s \text{ або } \frac{I}{2\pi r^2} \rangle\rangle s . \tag{3}$$

For samples with low surface recombination speed of the charge carriers inequality (3) is satisfied in the contact region, i.e. surface recombination may be ignored. Voltage at the contact region is rather high and, therefore, diffusion of the charge carriers could be also ignored. Thus, distribution of the charge carriers in the sample by the end of the injecting current pulse can be determined from the following expression [3]:

$$\frac{\partial \Delta p}{\partial t} = -\frac{\mu_p I}{2\pi\sigma_0 r^2}\frac{\partial \Delta p}{\partial r} - \frac{\Delta p}{\tau_p} . \tag{4}$$

Solving equation (4), we obtain the value of concentration of the excessive charge carriers by the end of the injecting current pulse t_n [3,4]:

$$\Delta p(r_1) = \Delta p(r_0)\exp\left[-\frac{2\pi\sigma_0}{3\mu_p I}(r_1^3 - r_0^3)\right] . \tag{5}$$

Relationship between the penetration depth of the injected charge carriers and pulse duration can be found from the differential equation [3]:

$$\frac{dr}{dt} = \mu_p \xi = \frac{\mu_p I}{2\pi\sigma_0 r^2} .$$

After performing integration we obtain [3]:

$$t_n = \frac{2\pi\sigma_0}{3\mu_p I}\left(r_1^3 - r_0^3\right) .$$

Function (5) describes distribution of the charge carriers in the sample in the range of r values r [3]:

$$r_0 \le r \le \left[\frac{3\mu_p I}{2\pi\sigma_0} t_n + r_0^3\right]^{\frac{1}{3}} .$$

Distribution of the charge carriers in time t after the end of the injecting pulse could be found by solving equation (6) taking into account recombinations in the sample volume.

$$\frac{\partial \Delta p}{\partial t} = -\frac{\Delta p}{\tau_p} + D_p \frac{\partial^2 \Delta p}{\partial r^2} . \tag{6}$$

Taking into account the boundary case with infinitely high speed of recombination of the charge carriers, we obtain the boundary condition [3]:

$$\Delta p(r,t)\big|_{r-r_0} = 0 . \tag{7}$$

By substitution of $\Delta p(r,t) = \Delta p_0(r,t)\exp\left(-\frac{t}{\tau_p}\right)$ equation (6) is reduced to a diffusion equation [3]:

$$\frac{\partial \Delta p_0(r,t)}{\partial t} = D_p \frac{\partial^2 \Delta p_0(r,t)}{\partial r^2}. \tag{8}$$

The following function [2] serves as a solution of expression (8):

$$\Delta p_0(r,t) = \frac{1}{2r\sqrt{\pi D_p t}} \int_0^\infty (\xi + r_0)\Delta p(\xi + r_0) \times \left\{ \exp\left[-\left[\frac{(r-\xi)^2}{4D_p t} \right] \exp\left[-\frac{(r+\xi)^2}{4D_p t} \right] \right] \right\} d\xi .$$

Thus,

$$\Delta p(r,t) = \frac{\exp\left(-\frac{1}{\tau_p} \right)}{2r\sqrt{\pi D_p t}} \int_0^\infty (\xi + r_0)\Delta p_0(\xi + r_0) \times \left\{ \exp\left[-\left[\frac{(r-\xi)^2}{4D_p t} \right] \exp\left[-\frac{(r+\xi)^2}{4D_p t} \right] \right] \right\} d\xi . \tag{9}$$

In order to calculate the voltage $\Delta U(t)$, it is necessary to substitute (9) into (6). As a result, we obtain [3]:

$$\begin{aligned} \Delta U(t) = U(\infty) - U(t) = const \frac{\exp\left(-\frac{t}{\tau_p} \right)}{\sqrt{D_p t}} \int_0^\infty \frac{1}{r^3} \exp\left[-\frac{(r-r_0)^2}{4D_p t} \right] \times \\ \times \int_0^\infty (r' - r_0) \exp\left(-\frac{r^{\frac{1}{2}}}{4D_p t} \right) sh\left(\frac{r - r_0}{2D_p t} r' \right) \Delta p_0(r' + r_0) dr' dr \end{aligned} \tag{10}$$

The analysis of expression (10) shows that the expression is considerably reduced if condition $r_0 \langle\langle \sqrt{D_p t}$ [2] is satisfied as well as in the case of a small penetration depth of the injected charge carriers.

$$\left(\frac{3\mu_p I}{2\pi\sigma_0} t_n + r_0^3 \right)^{\frac{1}{3}} \langle\langle 2\sqrt{D_p t}, \tag{11}$$

$$\Delta U(t) = const \exp\left(-\frac{t}{\tau_p} \right). \tag{12}$$

For a big penetration depth of the charge carriers the voltage will be given by [3]:

$$\Delta U(t) = const \exp\left(-\frac{t}{\tau_p} \right). \tag{13}$$

The law of $\Delta U(t)$ change corresponds to expression (13) if the following condition is satisfied [3]:

$$\frac{2\pi\sigma_0}{3\mu_p \tau_p I} (4D_p t)^{\frac{3}{2}} \langle\langle \frac{\sqrt{\pi}}{2}. \tag{14}$$

If the current is sufficiently high (in the range from τ_p to $3\tau_p$), this condition is not hard to be realized.

In Fig. 2 the generator based on a transistor structure with AC negative resistance is presented in a general form. In the circuit total inductance $L = L_0 + L_1$ and resistance $R = r_0 + R_1$, where L_0, r_0 – inductance and resistance of the outer loop, L_1, R_1 – inductance and resistance of the transistor structure terminals. Development of the processes in this circuit is connected with variations of current i_T and voltage U [6]:

$$\frac{di_T}{dt} = \frac{U_s - i_T R - U}{L}, \tag{15}$$

$$\frac{dU}{dt} = \frac{i_T - I(U)}{C(U)}. \tag{16}$$

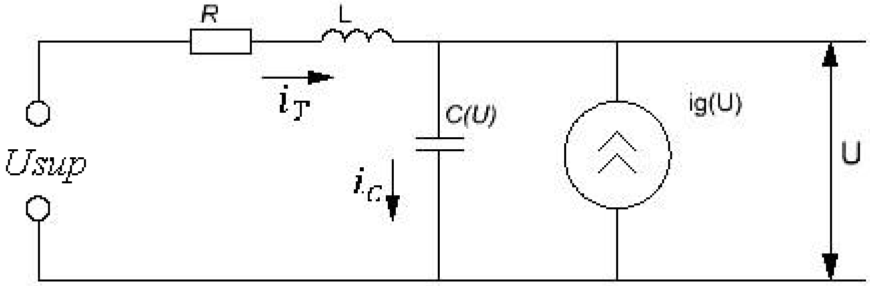

Fig. 2. AC generator circuit

Equations (15) and (16) can be combined dividing the first equation by the second one, i.e. [6]:

$$\frac{di_T}{dt} = \frac{U_s - i_T R - U}{i_T - I(U)} \cdot \frac{C(U)}{L}. \tag{17}$$

In the state of equilibrium (U_0, i_{T0}) currents and voltages of the circuit are not changed and, therefore, [6]:

$$\frac{di_T}{dt} = \Big|_{i_T = i_{T0}} = 0, \quad \frac{dU}{dt}\Big|_{U_T = U_0} = 0. \tag{18}$$

Using condition (18), from equations (15) and (16) we find [6]:

$$U_s - i_{T0} - U_0 = 0, \tag{19}$$

$$i_{T0} - I(U_0) = 0. \tag{20}$$

Differential equation of the oscillatory circuit will take the following form [6]:

$$\frac{d^2u}{dt^2} + \frac{du}{dt}\left(\frac{R}{L} + \frac{1}{R_g C}\right) + \frac{u}{LC}\left(\frac{R}{R_g} + 1\right) = 0. \tag{21}$$

Then characteristic equation could be written as [6]:

$$x^2 + x\left(\frac{R}{L} + \frac{1}{R_g C}\right) + \frac{u}{LC}\left(\frac{R}{R_g} + 1\right) = 0. \tag{22}$$

Roots of the characteristic equation are determined from (22) [6]:

$$x_{1,2} = \frac{-\left(\frac{R}{L} + \frac{1}{R_g C}\right) \pm \sqrt{\left(\frac{R}{L} + \frac{1}{R_g C}\right)^2 - 4\frac{1}{LC}\left(\frac{R}{R_g} + 1\right)}}{2}. \tag{23}$$

Solution of equation (21) may be written as [6]:

$$u(t) = A\exp\left[-\frac{1}{2}\left(\frac{R}{L}+\frac{1}{R_g C}\right)+\sqrt{\frac{1}{4}\left(\frac{1}{R_g C}+\frac{R}{L}\right)^2-\frac{1}{LC}\left(1+\frac{R}{R_g}\right)}\right]t+ \\ +B\exp\left[-\frac{1}{2}\left(\frac{R}{L}+\frac{1}{R_g C}\right)+\sqrt{\frac{1}{4}\left(\frac{1}{R_g C}+\frac{R}{L}\right)^2-\frac{1}{LC}\left(1+\frac{R}{R_g}\right)}\right]t+\frac{U_{\mathrm{s}}}{\left(1+\frac{\mathrm{R}}{\mathrm{R_g}}\right)}. \tag{24}$$

On the basis of the total resistance the generator frequency is found [6]:

$$Z = R+\frac{R_g}{(\omega C R_g)^2+1}+j\left(\omega L-\frac{\omega C R_g^2}{1+(\omega C R_g)^2}\right). \tag{25}$$

If the following condition is satisfied [6]:

$$\omega L-\frac{\omega C R_g^2}{1+(\omega C R_g)^2}=0, \tag{26}$$

resonance occurs in the circuit. From equation (21) we determine the frequency [6]:

$$F=\frac{1}{2\pi\left|R_g(\tau)\right|C_{\mathrm{eq}}(\tau)}\sqrt{\frac{R_g^2(\tau)C_{\mathrm{eq}}(\tau)}{L}-L}. \tag{27}$$

Relative sensitivity could be found using the following equation [6]:

$$S_F^{\tau}=\frac{\tau}{F}\cdot\frac{dF}{d\tau}. \tag{28}$$

Modeling results

Microelectronic sensor with a frequency output for determining the lifetime of charge carriers includes a device for finding the lifetime of charge carriers by the method of conductivity modulation in a point contact and a microelectronic frequency converter (fig.1).

At the initial moment of time the rectangulr pulse does not pass through the point contact on the sample surface in straight direction. Increase of the voltage of the constant voltage source E_s to the value when at the electrodes of transistors *VT1* and *VT2* a negatve resistance appears causes electric oscillations in the circuit formed by a parallel connection of the full resistance with a capacitive component at the electrodes of transistors *VT1* and *VT2* and inductance *L*. Capacitor *C* prevents alternating current from passing through the constant voltage source E_s. A rectangular current pulse passes from generator *G1* to the sample. In a certain time, regulated by time delay line *Л3*, the next current pulse is supplied to the sample from generator *G2*. generators *G1* and *G2* with time delay line *L3* form a generator of paired pulseses (fig. 1). Through a pulse limiting device voltage at the sample is supplied to the mictoelectronic frequency converter, which leads to effective change in the oscillation frequency of the microelectronic frequency converter.

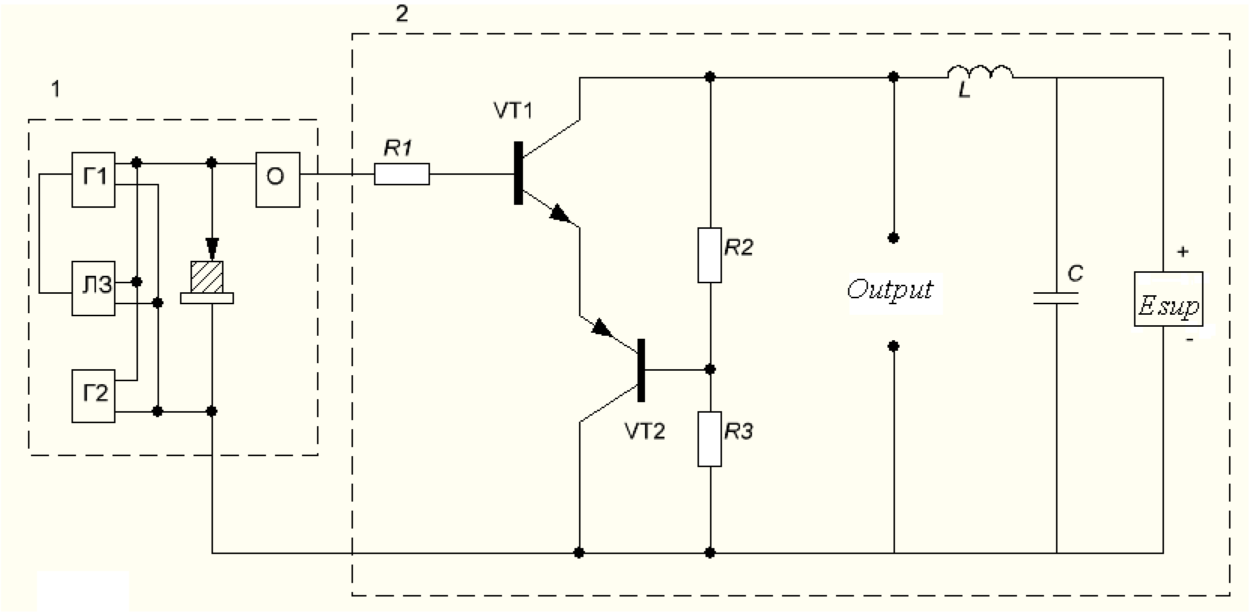

Fig. 3. Microelectronic sensor with frequency output for determining lifetime of the charge carriers my the method of conductivity modulation in a point contact

For accuracy of modeling, performed in OrCad 9.2 environment, the device for finding the lifetime of charge carriers by the method of conductivity modulation in the point contact (fig. 1) is replaced by voltage source *V2*, to which voltage found by experimental investigation is supplied [5].

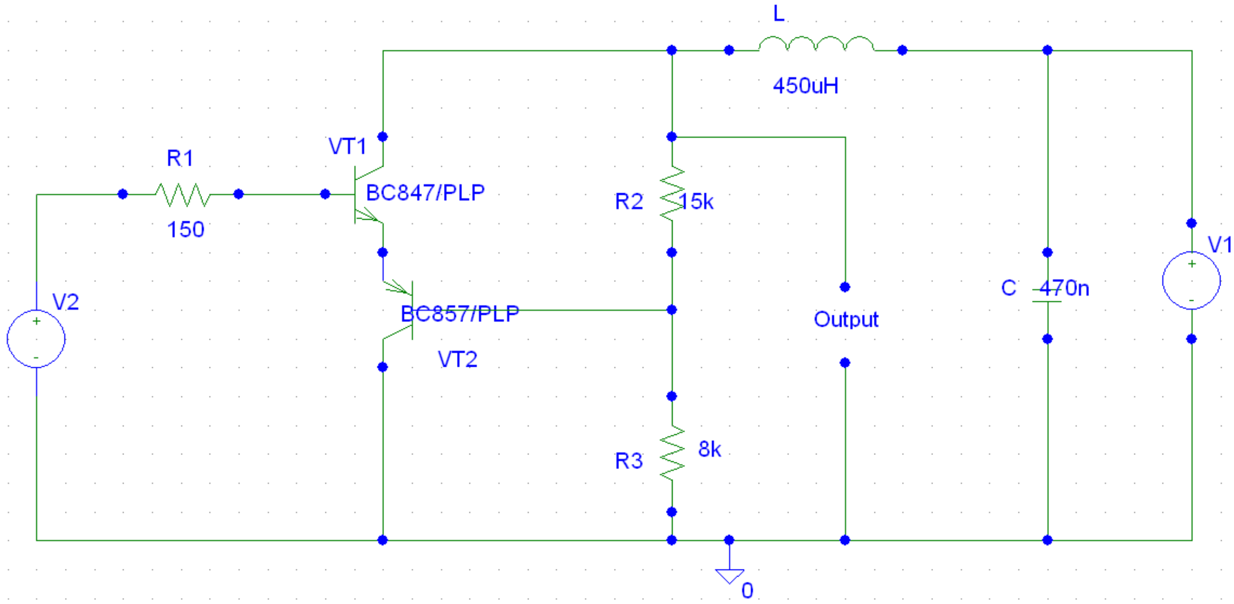

Fig. 4. Modeling circuit

By changing the voltage value at the voltage source *V2* the respective oscillation frequency values of the frequency converter were registered. On the modeling results a plot of the output signal frequency dependence on the delay time was built (fig. 3).

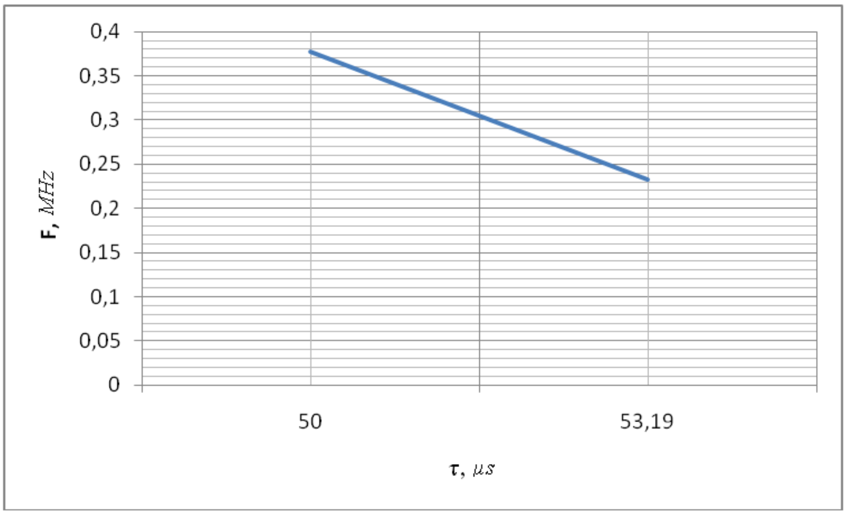

Рис. 5. Frequency dependence on the change of delay time

To calculate the relative sensitivity, a number of plots were built. Their study has shown that relative sensitivity of the proposed method is almost an order of magnitude higher as compared with theoretical studies [5].

Conclusions

On the basis of the presented mathematical model a microelectronic sensor with frequency output for finding lifetime of the charge carries by the method of conductivity modulation in the point contact has been developed and simulated. As the calculations have shown, relative sensitivity of the proposed method is almost an order of magnitude higher as compared with theoretical studies.

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