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DEFINITION OF GENERATION-RECOMBINATION CHARACTERISTICS OF THE INTERFACE OF THE SEMICONDUCTOR - GLASS ISOTHERMAL RELAXATION CAPACITY

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ABSTRACT

In this work, we propose a method for determining the rate of bulk and surface generation in the semiconductor-insulator interface.

This method allows you to determine the generation and recombination characteristics of the semiconductor-insulator interface from the measured values of the relaxation non - equilibrium capacitance in various modes (switching voltage, temperature). Using this technique, the most probable cause of the time dependence of S (t) in MIS structures was established.

KEYWORDS: *Metal-insulator-semiconductor (MDS) structures, generation-recombination characteristics, isothermal relaxation capacity, state density, surface conductivity, bulk and surface generation, n-type silicon.*

INTRODUCTION

As is known, to determine the generation-recombination characteristics of interfaces semiconductor-insulator most commonly used method of isothermal relaxation of the capacitance of metal-insulator-semiconductor (MDS) structures, based on measurement of the speed of formation of the invers layer [1]. In [2,3] this method is modified to determine the generation parameters of the interface semiconductor - insulator. In this paper, the method of determining the velocity of bulk and surface generation at the section boundaries, the semiconductor is n-type silicon with a crystallographic orientation of <100> Si and lead-Boro-glass Silikatny. Also, based on this methodology, we experimentally study the relaxation of dependence of capacity from time C(t) at different temperatures When applied to structures of metal-insulator-semiconductor voltage corresponding to the inversion of the surface conductivity, the capacity of the structure relaxes in time from its initial, non-equilibrium to the final equilibrium state. This relaxation process is due to the formation of charge of inversion-layer - charge of minority carriers, localized at the interface semiconductor-insulator. The energy diagram of the structure at some time *t* after the beginning of relaxation, the application of the pulse, shifting the structure of provision of flat zones in the inversion shown in figure -1.

MATERIALS AND METHODS

Change the width of a region of non-equilibrium depletion relaxation and capacity caused by generation of electron-hole pairs in space charge region (SCR) and at the interface (G), as well as diffusion of carriers from the bulk. Minority carriers (holes) flowing to the surface, forming the inversion layer, and screening the external field. The major carriers (electrons) flow to the edge of the SCR, neutralizing the charge depletion region $Q_{dr} = qN_dW(t)$ and reducing the width of the SCR W.

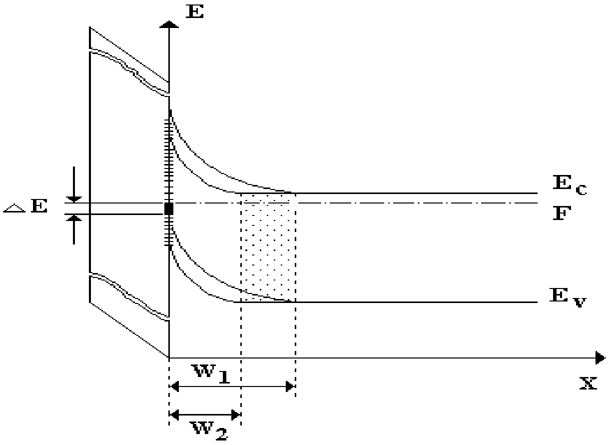

Fig .1. The model of the energy band diagrams of the structure of the MDS, indicating the energy field of rechargeable surface States when applying the pulse voltage

The overall condition of electro - neutrality is:

$$Q_g = -(Q_s + Q_{ss} + Q_f) = C_dU \qquad (1)$$

Where Q_s -is the charge of the SCR; Q_{ss} is the charge in surface States; Q_f - a fixed charge in the dielectric; C_d is the capacitance of the dielectric; and U -is the voltage applied to the MDS structure;
or according to [4]

$$-Q_g = \lfloor \Delta Q_{ss}(t) + Q_p(t) \rfloor + qN_dW(t) + [Q_f + Q_{пл}] = -C_dU \qquad (2)$$

where Q_{st} – charge in the surface traps.

Note that the last term $[Q_f+Q_{st}]$ does not depend on time, and the first member of $[\Delta Q_{ss}(t)+Q_p(t)]$ is the total charge in surface States and inversion layer located in a very thin region at the boundary of the semiconductor-dielectric and changing the accumulation of lasing media. Taking this into account and neglecting the influence of the difference of the work output, we have the following condition for the applied voltage:

$$V_g = U + V_{об} = -\frac{1}{C_d}\left[qN_dW + \frac{qN_dW^2C_d}{2\varepsilon_0\varepsilon_S} + (\Delta Q_{ss} + Q_p)\right] \qquad (3)$$

Where $V_{об}$ the voltage drop across the depletion layer; ε_0 - permittivity of vacuum; ε_0 - dielectric constant on the surface.

Using the definition $C_d = \frac{\varepsilon_0\varepsilon_d}{d_{ox}}$ (d_{ox} - thickness) and denoting the total charge

$\Delta Q_{ss}(t) + Q_p(t)$ by $Q(t)$, from the last equality we get:

$$Q(t) = -C_dV_g - \frac{qN_d}{C_d}\left(C_dW + \frac{\varepsilon_dC_dW^2}{2\varepsilon_sd_{ox}}\right) \qquad (4)$$

Because the. with non - equilibrium depletion, the high-frequency (HF) capacitance of the MIS structure C (t) is related to the depletion width W (t) by the ratio:

$$\frac{1}{C}=\frac{1}{C_d}+\frac{1}{C_{об}}=\frac{1}{C_d}+\frac{W}{\varepsilon_0\varepsilon_s} \qquad (5)$$

where *C*-is the capacity of the structure; C_{ob} - the capacity of the depleted layer.
Then relation (4) takes the form

$$Q(t)=-C_dV_g-\frac{qN_d\varepsilon_0\varepsilon_s}{2C_d}\left[\left(\frac{C_d}{C(t)}\right)^2-1\right] \qquad 6$$

Differentiating (6) and taking into account that the rate of change of charge *(Q (t))* is the total rate of its generation G (t), we obtain:

$$G(t)=\frac{dQ(t)}{dt}=-\frac{qN_d\varepsilon_0\varepsilon_s}{2C_d}\frac{d}{dt}\left(\frac{C_d}{C(t)}\right)^2=\frac{qN_d\varepsilon_0\varepsilon_sC_d}{(C(t))^3}\frac{dC}{dt} \qquad (7)$$

Thus, the total rate of charge generation in the inversion layer of the SCR and on surface states, according to (7), can be determined experimentally in two ways. For example, to calculate *G(t)* at an arbitrary time moment, it is necessary to measure the effective RF capacitance of the structure *C(t*) corresponding to this moment and determine at this point the slope of the relaxation curve $\frac{dC}{dt}$ (by graphical differentiation). Another way is to rebuild the relaxation curve *C(t)* in the coordinates $\left(\frac{C_d}{C(t)}\right)^2=f(t)$ and graphically differentiate the resulting dependence.

The term «pace» of surface generation-recombination R_s is understood to mean the number of generation-recombination events per unit surface per unit time [4]. However, it turned out to be more convenient to characterize the processes of recombination and generation on the surface, by the value of the surface generation-recombination rate S_{gr}, which under the condition *Δn=Δp (Δn =n-n₀* and *Δp=p-p₀* is the concentration of excess charge carriers) can be introduced in stationary conditions through the rate of surface recombination R_s and the non - equilibrium concentration of charge carriers *Δn* and *Δp* on the surface (at x=0) by the following relationships:

$$R_S=S_{gr}\cdot\Delta p\big|_{x=0}=S_{gr}\cdot\Delta n\big|_{x=0} \qquad (8)$$

If the concentration of excess carriers *Δn* and *Δp* are equal to each other, *Δn=Δp,* i.e. Since there is no capture process in the volume, we can talk about a single recombination lifetime τ_r:

$$R_n=R_p=\frac{\Delta n}{\tau_r}=\frac{\Delta p}{\tau_r} \qquad (9)$$

Consider a discrete (monoenergetic) surface level with a concentration of N_{ts} and an energy position $\varepsilon_{ts.}$ According to the generally accepted theory of generation-recombination, the resulting rate of surface recombination can be written as [4]:

$$R_s=\frac{\alpha_n\alpha_pN_{ts}(n_sp_s-n_{1s}p_{1s})}{\alpha_n(n_s+n_{1s})+\alpha_p(p_s+p_{1s})} \qquad (10)$$

where $n_sp_s> n_{1s}\ \ p_{1s}=n_{i2}$, and the capture coefficients α_n and α_p are expressed by the relations

$$\alpha_n=\sigma_{ns}\upsilon_n\ ,\quad \alpha_p=\sigma_{ps}\upsilon_p \qquad (11)$$

where σ_{ns}, σ_{ps} are the capture cross sections of electrons and holes, $\upsilon_{n,}$ υ_p are the thermal velocities of electrons and holes.

Similarly expressed is the rate of surface generation

$$G_s = \frac{\alpha_n \alpha_p N_{ts}(n_i^2 - n_s p_s)}{\alpha_n (n_s + n_{1s}) + \alpha_p (p_s + p_{1s})} \qquad (12)$$

where $n_s p_s < n_i^2$. In both relations, the concentrations of n_{1s} and p_{1s} are numerically equal to the corresponding equilibrium concentrations of electrons and holes in the allowed zones, when the Fermi level coincides with the monoenergetic surface level ε_{ts}.

Relations (11) and (12) are valid under the following conditions:

- Quasi-equilibrium energy and electron distribution of holes and holes in allowed zones. With a non - equilibrium distribution, the capture coefficients α_n and α_p will no longer be determined by the thermal velocities of electrons υ_n and holes υ_p.
- Quasi-stationary state of a semiconductor, when the filling of levels is determined by the position of the quasi-Fermi levels of free charge carriers. In this case, the recharging of these levels does not affect the distribution of potentials in the MIS structure, which imposes a restriction on the concentration of these levels

$$N_{ts} << \frac{Q_{об}}{q} = (N_d - N_a) \cdot W \qquad \text{for } t \approx 0 \qquad (13)$$

$$N_{ts} << \frac{Q_p}{q} \qquad \text{for } t \to \infty \qquad (14)$$

It is obvious that the rate of surface generation up to a certain point (starting from which the SCR becomes close to completely equilibrium) can depend only on the surface concentration of minority carriers, since the main carriers near the surface under unequal conditions are practically absent.

Thus, for an n - type semiconductor at times not close to equilibrium, we have:

$$n_s << n_{1s}, \quad n_s p_s << n_i^2 \qquad (15)$$

In connection with this expression for the rate of surface generation (12) will have the form:

$$G_s = \frac{\alpha_n \Delta p N_{ts} n_i^2}{\alpha_n n_{1s} + \alpha_p (p_s + p_{1s})} = n_i S_g \qquad (16)$$

where the S_g value is introduced, which has a dimension of cm/s, it is called the surface generation rate and is defined as

$$S_g = \frac{\alpha_n \alpha_p N_{ts} n_i}{\alpha_n n_{1s} + \alpha_p (p_s + p_{1s})} \qquad (17)$$

The general expression for the rate of volume recombination in the SCR through monoenergetic levels with concentration N_t, energy position ε_r, and capture coefficients $\alpha_n = \upsilon_n \sigma_n$, $\alpha_n = \upsilon_p \sigma_p$ has the form:

$$R_{об} = \frac{\alpha_n \alpha_p N_t \left[n(x)p(x) - n_i^2\right]}{\alpha_n \left[n(x) + n_1\right] + \alpha_p \left[p(x) + p_1\right]} \qquad (18)$$

where the quantities N_t, α_n and α_p are taken independent of the x coordinate, and the product $n(x)p(x) > n_i^2$. Accordingly, the volume generation rate is equal to:

$$G_{об} = \frac{\alpha_n \alpha_p N_t \left[n_i^2 - n(x)p(x)\right]}{\alpha_n \left[n(x) + n_1\right] + \alpha_p \left[p(x) + p_1\right]} \qquad (19)$$

where $n(x)p(x) < n_i^2$, n_1 and p_1 are the equilibrium concentrations of electrons and holes in the semiconductor. In contrast to generation-recombination through surface levels, here the dimension N_n is [cm^{-3}], and in contrast to generation- recombination in volume due to bending of zones in the SCR, the concentrations $n(x)$ and $p(x)$ depend on the coordinate.

The total flux G into the surface layer of the SCR semiconductor is equal to the sum of the rates of thermal generation

$$G = G_s + G_0 + G_{sk} + I_{pd} = n_i S_g + \left(1 - \frac{np}{n_i^2}\right)\left(\frac{n_i W}{\tau_{go}} + \frac{n_i W_k}{\tau_{gk}}\right) + I_{pd} \qquad (20)$$

where G_s is surface generation; G_o-the full rate of generation of electron-hole pairs in the SCR; G_{sk} is the generation rate in the regional part of the SCR; I_{pd} - hole stream; W, W_k - thickness of the SCR and the edge of the SCR; τ_{go}, τ_{gk} are the generation lifetimes in the volume and in the regional part of the SCR, respectively.

The characteristic features of relation (20) are:

- the linear dependence of G on the non - equilibrium thickness of the SCR W in the case of the largest contribution to the generation rate in G of the SCR from the contact part of the SCR (G_o +G_{sk});
- the contribution of Gs is significant only at the initial moments of the relaxation process (for large W), because Sg decreases very strongly with increasing surface concentration of minority carriers p_s;
- the generation rate strongly depends on the temperature, decreases, as a rule, with its decrease proportionally $\exp\left(-\frac{E_g}{kT}\right)$.

The theory of thermal generation processes in MIS structures [4] gives a general expression for the flow of charge carriers, which includes the parameters of volume and surface generation centers, as well as the characteristics of contact SCRs and the diffusion process. Obviously, if we equate the experimentally determined rate of generation to the total flow of minority carriers into the near-surface layer of SCR:

$$G(t) = q(G_s+G_o+G_{sk}+I_{pd}) \qquad (21)$$

Or

$$\frac{qN_d\varepsilon_0\varepsilon_s C_d}{(C(t))^3}\frac{dC}{dt} = q\left\{n_i S_g + \left(1 - \frac{np}{n_i^2}\right)\left[\frac{n_i W}{\tau_{go}} + \frac{n_i W_k}{\tau_{gk}}\right] + I_{pd}\right\} \qquad (22)$$

then from the analysis and comparison of experimental and theoretical dependences it is possible to determine the dominant generation mechanisms, as well as evaluate the above generation-recombination parameters.

Consider accounting and separation of surface and volume generation components. The component of the I_{pd} flow, for example, for silicon-based structures, is usually negligible at room temperature. If we exclude the influence of the contact part of the SCR, then the component of the G_{sk} flow can also be neglected. Then the task is simplified and reduced to the separation of the generation rates through the surface levels $G_s(t)$ and through the volume centers in the SCR $G_o(t)$. The volumetric rate of generation in the SCR can be written as follows:

$$G_o = \frac{n_i \Delta W(t)}{\tau_{go}} = \frac{n_i\left[W(t) - W_\infty\right]}{\tau_{go}} = \frac{n_i \varepsilon_0 \varepsilon_s}{\tau_{go} C_d}\left[\frac{C_{ст}}{C(t)} - 1\right] \qquad (23)$$

where the equilibrium capacitance C_{st} and capacitance C(t) are related by the equilibrium SCR width W_∞ and the width W(t) by relations of the type:

$$\frac{1}{C} = \frac{1}{C_d} + \frac{1}{C_D} = \frac{1}{C_d} + \frac{W}{\varepsilon_0 \varepsilon_s} \qquad (24)$$

Thus, the final result for the total recombination rate in this case has the form:

$$G(t) = q(G_s + G_o) = -\frac{qN_d\varepsilon_0\varepsilon_s}{2C_d}\frac{d}{dt}\left[\frac{C_d}{C(t)}\right]^2 = qn_i S_g + \frac{qn_i\varepsilon_0\varepsilon_s}{\tau_{go}C_{ст}}\left[\frac{C_{ст}}{C(t)} - 1\right] \qquad (25)$$

or

$$-\frac{d}{dt}\left[\frac{C_d}{C(t)}\right]^2 = \frac{2C_d n_i S_g}{\varepsilon_0\varepsilon_s N_d} + \frac{2C_d n_i}{C_{ст} N_d \tau_{go}}\left[\frac{C_{ст}}{C(t)} - 1\right] \qquad (26)$$

differentiating expression (26) we obtain

$$\frac{1}{C^3}\frac{dC}{dt}=\frac{n_i S_g}{q\varepsilon_0\varepsilon_s N_d C_d}+\frac{n_i}{C_d N_d \tau_{go}}\left(\frac{C_{ст}}{C(t)}-1\right)\frac{1}{C_{ст}} \qquad (27)$$

The obtained expression describes the relaxation process of the MIS capacitance of the structure during the formation of the charge of the inversion layer after switching the bias voltage V_1 - V_2. This equation is a straight line equation in the coordinates:

$$x=\left(\frac{C_{ст}}{C(t)}-1\right)\frac{1}{C_{ст}}, \quad y=\frac{1}{C^3}\frac{dC}{dt} \qquad (28)$$

I.e. an equation of the form y=ax+b (Fig. 2).

The surface generation speed S_g and the lifetime of minority carriers τ_g are determined from the slope of the dependence a and the coefficient b determining the shift of the dependences along the axis $\frac{1}{C^3}\frac{dC}{dt}$. The coefficients *a* and *b* are determined using the least squares method.

RESULT AND DISCUSSION

The slope tangent is directly proportional to the lifetime of the main charge carriers in the semiconductor. The segment cut off on the axis "*y*" with "*x*" equal to zero allows you to determine the speed of surface generation of charge carriers (Figure 2).

From here:

$$S_g=\frac{C_d N_d \varepsilon_s \varepsilon_0 b}{n_i} \qquad (29)$$

$$\tau_g=\frac{n_i}{C_d N_d a} \qquad (30)$$

where C_d is the capacity of the oxide layer, defined as the capacity of the studied structures at enrichment voltages, N_d is the concentration of the donor impurity, ε_s is the dielectric constant of silicon, ε_0 is the dielectric constant, n_i is the intrinsic concentration of charge carriers in Si at a given temperature, and *a*-is the angle of inclination of the obtained dependencies, b is the point of their intersection with the axis $\frac{1}{C^3}\frac{dC}{dt}$.

Thus, this method allows one to determine the generation and recombination characteristics of GR P-D, by measuring the relaxation non - equilibrium capacitance in various modes (different temperature, switching voltage), it is possible to determine the parameters of the generation centers both in the SCR and on the GR P-D.

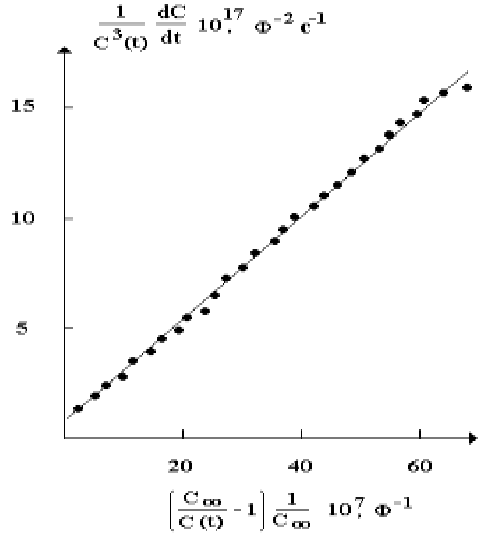

Fig. 2. The experimental values of C (t) for one of the TIR structures built using the expression (27).

By measuring the relaxation of the capacitance of the MIS structure (after switching the voltage $V_1 \rightarrow V_2$) at various temperatures, the temperature characteristics of the angle tangent can be used to determine the energy characteristics of the volume generation center in a semiconductor. In other words, according to the temperature dependence of the carrier lifetime, from the relation $\tau_g = \tau_0 \exp\left(\frac{E_g}{kT}\right)$, it is quite simple to find the depth of the energy level E_g through which the generation of charge carriers proceeds. The main parameter characterizing the speed of the structure is the rate of formation of the inversion layer at the semiconductor-insulator interface, with a pulse increase in the voltage applied to the structure. It should be noted that in [5, 6] it is assumed that the surface generation rate (the number of charge carriers generated per unit time by a surface unit) is a constant. It was shown in [7, 8] that, for an adequate description of the relaxation process of the capacitance of a MIS structure, after a pulse increase in the voltage applied to it, it is necessary to take into account the time dependence of the rate of surface generation of charge carriers. The time dependence of the surface generation speed S (t) can be due to the following reasons: the Coulomb interaction of mobile charge carriers in the forming charge of the inversion layer [9], the inhomogeneous distribution of surface charge density over the semiconductor band gap [7], and the presence of a tunneling current between the semiconductor and the dielectric [10] [11]. Moreover, it is known that the magnitude of the tunneling current depends little on temperature.

To establish the most probable reason for the time dependence of S (t) in MIS (Al-glass-Si) structures, using expressions (27), we experimentally measured the relaxation dependences of C (t) at various temperatures. Figure 3 shows the experimental relaxation dependences of the capacities of one of the structures under study, constructed in accordance with (27), in the coordinates 1/C3.dC/dt, (C/C-1). 1 Cst. The constructed dependences were measured in the dark, at a frequency of 150 kHz at a temperature of -20°C (dependence 1), at a temperature of -30°C (dependence 2) and at a temperature of -40°C (dependence 3) and at a temperature of -50°C (dependence 4), after increasing the voltage applied to the structures, from V_1 to V_2 (V_1 =8V, V_2 =20V). It can be seen from the above dependences that a change in temperature leads to a change in the slope of the time dependence S (t), without changing it qualitatively.

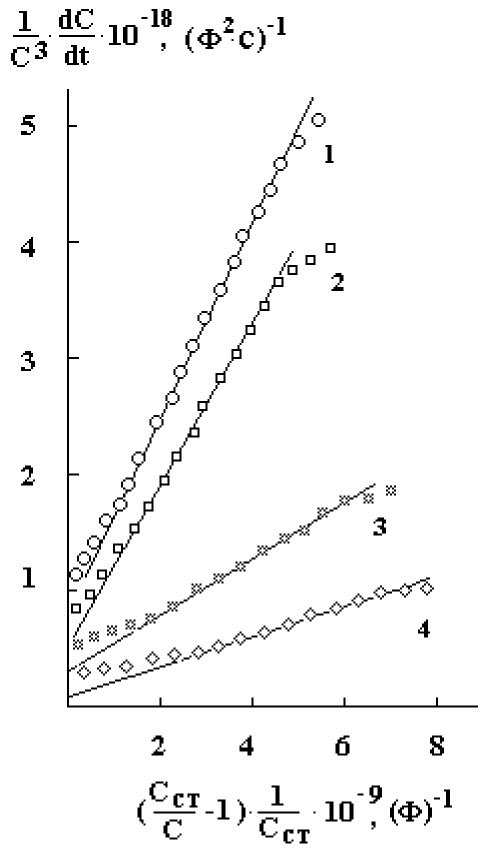

Fig. 3. Relaxation dependences of the capacitance at various temperatures

This behavior of the considered dependences indicates that in the measured structures, in the indicated temperature range and with the applied voltage values, the bulk contribution to the inversion charge formation rate is made by volume and surface generation.

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