The Charge Relaxation in Semiconductors and in Elements of Microelectronics

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Abstract **– The analysis of existing theoretical models for the description of relaxation processes in semiconductors and semiconductor barrier structures has been carried out. The criteria allowing the use of transport models of nonequilibrium charge carriers in a relaxation or recombination semiconductors have been formulated. It is shown that a space charge region (SCR) of semiconductor barrier structure under reverse bias can be considered as a relaxation semiconductor in which the relaxation time of charge carriers is determined by the span time while the base maintains the properties of a recombination semiconductor where the electric field is absent.**

Key words**: electrical conductivity, Maxwell relaxation, recombination, relaxation time, screening length, drift length, ballisticity length.**

I. INTRODUCTION

Relaxation processes features of charge in semiconductors and barrier structures based on them are of considerable interest as they determine the frequency properties of semiconductor devices and integrated circuits.

According to the modern scientific view [1-4], there are relaxation and recombination semiconductors. The division is based on whether the lifetime of charge carriers τ_0, determining the diffusion length of minority carriers exceeds or not the majority nonequilibrium charge carriers (the dielectric relaxation) time τ_d.

Recombination semiconductors are those for which $\tau_0 > \tau_d$. Widely used low-resistance germanium and silicon could be adduced as clear examples. Relaxation semiconductors are those for which $\tau_0 < \tau_d$. Examples of such substances include some high resistivity semiconductors such as organic semiconductors (e.g. anthracene) and disordered (amorphous) semiconductors (e.g. chalcogenide glass) characterized by small lifetime of minority nonequilibrium charge carriers.

The aim of this work is to analysis the impact of charge carriers concentration changes peculiarities on the relaxation and recombination semiconductors characteristics, as well as barrier structures based on them.

II. RELAXATION DETERMINED BY THE MINORITY NONEQUILIBRIUM CHARGE CARRIERS LIFETIME

The lifetime of minority carriers is the predominant factor in recombination semiconductors under non-equilibrium conditions.

Dielectric relaxation occurs so quickly compared to other time-dependent processes that can be considered instantaneous assuming $\tau_0 > \tau_d$ [5]. The dielectric relaxation time, or the so-called Maxwell time is defined as

$$\tau_{м} = \tau_d = \varepsilon\varepsilon_0 / \sigma, \qquad (1)$$

where *ε* is a relative dielectric constant which determines a degree of the Coulomb interaction of charges in a semiconductor (i.e. dielectric medium); ε_0 is an electric constant which equals to $8.85 \cdot 10^{-12}$ F/m, σ is the electrical conductivity which is a measure of concentration and mobility of available free charge carriers, ρ is electrical resistivity.

It is obvious that the higher τ_d ($\tau_м$) is the more time is required for occurred volumetric charge relaxation. For conventional semiconductors τ_d is of the order of 10^{-14} – 10^{-12} s, and τ_0, as a rule, exceeds 10^{-9} s. Concentration Δn minority carrier (electron) injection in a semiconductor leads to a change in the position of Fermi E_{Fn} quasilevel for which

$$n = n_0 + \Delta n = N_c \exp\left[-\left(E_c - E_{Fn}\right)/kT\right], \qquad (2)$$

where n_0 is an equilibrium electron density, N_c is an effective density of allowed energy states in the conduction band, E_c is energy corresponding to the bottom of the conduction band of the semiconductor, k is a Boltzmann constant, T is an absolute temperature.

On accomplishing the injection there will be a very quick response of majority carriers (holes) tending to neutralize the excess of electrons Δn and striving to keep neutrality (see figure). The processes of relaxation and recombination return the system to equilibrium.

Field created by the minority carriers excess charge — $q\Delta n$, will attract the number of majority carriers Δp *(*from the inner circle) sufficient to completely neutralize the excess harge. The characteristic time of this process is the relaxation time τ_d. At the end of the relaxation process, a semiconductor is in a neutral state again. An equilibrium state results from recombination letting within a certain time period Δn reduction to the level where equilibrium restores according to the law of mass.

The characteristic time of this process is the lifetime of minority carriers τ_0. When in equilibrium, Fermi E_{Fn} and E_{Fp} quasi levels coincide, forming a single Fermi level E_{F0}. It determines the equilibrium concentrations of electrons n_0 and holes p_0.

Local value of Δp must rise to neutralize Δn in a non-equilibrium system and E_{Fp} is included in the equation analogous to (2):

$$p = p_0 + \Delta p = N_v \exp\left[-\left(E_{Fp} - E_v\right)/kT\right], \qquad (3)$$

where N_v is an effective density of states in a valence band, E_v is energy corresponding to the semiconductor valence band ceiling.

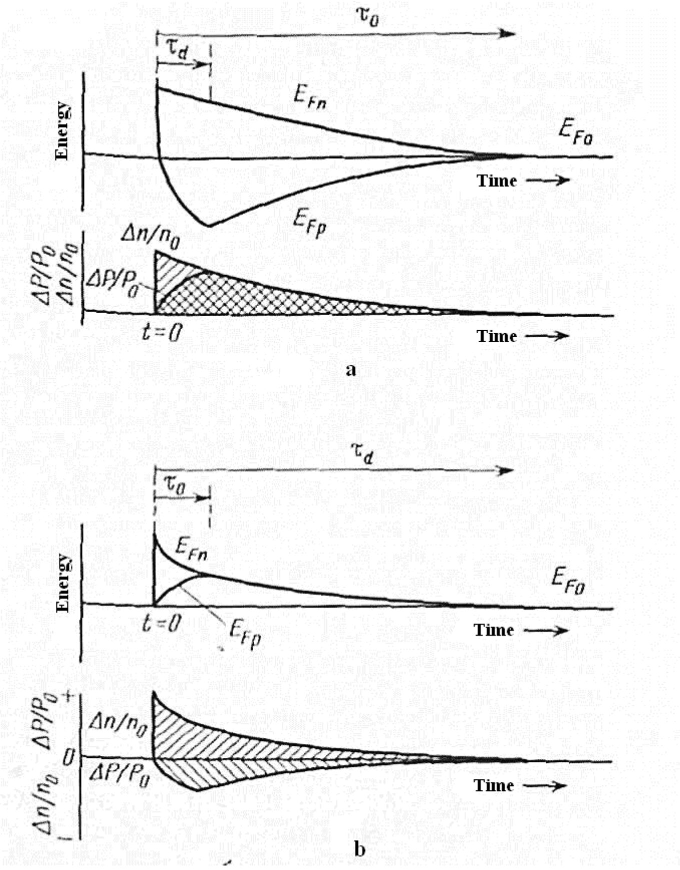

Fig.1. Change of Fermi quasilevel E_{Fn} and E_{Fp} and relative concentrations of the charge carriers after shot-term injection of excess minority carriers (electrons) Δn. a - recombination regime: $\tau_0 > \tau_{d;}$ *b* - relaxation regime: $\tau_0 < \tau_d$ [1].

For a given Δn the Δp and ΔE_{Fp} build up time equals the relaxation time τ_d. The values of Δn and Δp are decreasing in time as a result of recombination while E_{Fn} and E_{Fp} during the time τ_0 return to a single equilibrium level E_{F0}, as shown in fig. 1, part a.

III. THE CHANGE OF THE CHARGE DETERMINED BY THE DIELECTRIC RELAXATION TIME

For a relaxation regime when $\tau_0 < \tau_d$, the conductivity σ must be very low. Therefore, ratio (1) can be valid for substances with low mobility carriers and (or) low concentration of mobile charge carriers. For example, a semiconductor with a resistivity of $10^8\ \Omega\cdot$ cm is characterized by the relaxation time of the order of 10^{-4} s. Such magnitude generally exceeds the lifetime of minority carriers whose value for substances with high resistance is typically less than 10^{-8} s.

According to this classification, gold-doped silicon and germanium can turn into relaxation semiconductors at very low temperatures, when τ_0 becomes smaller than τ_d. Under the effect of a strong electric field, when the increment of the charge carrier drift velocity on a free path is comparable to the thermal velocity at the corresponding temperature, a concept of the minority carriers drift length is used: $L_E=\mu_n\tau_nE$, where μ_n and τ_n - mobility and lifetime of minority charge carriers, E is electric field gradient. The value of L_E may be up to 10^{-2} m.

For a recombination regime, neutrality condition is achieved long before Δn carriers excess vanishes, while in the relaxation mode, the situation is reversed. After injection of Δn excessive concentration of minority carriers into a relaxation semiconductor during a certain time interval τ_0 (equal to carriers' lifetime), take place a rapid restoration of thermodynamically equilibrium state as a result of decrease of local concentration of major carriers, and the mass action law comes into force.

Thus, at the moment when this process is completed the product *np* subjects to equation

$$pn=(n_0+\Delta n)(p_0+\Delta p)=n_i^2=p_0n_0\ , \qquad (4)$$

thus,

$$\Delta p=-p_0\Delta n/(n_0+\Delta n)\,. \qquad (5)$$

If the injection level is so high that $\Delta n > n_0$, then

$$\Delta p \rightarrow -p0\,. \qquad (6)$$

It means that in an extreme case all main movable carriers may disappear. In terms of the recombination mode the injection of minority carriers will contribute to the semiconductor resistance reduction, while in case of the relaxation mode, the injection of minority carriers may entail the semiconductor resistance increase. It is shown in equations (4) - (6).

This injection feature inherent to the relaxation mode is often referred to as "recombination injection of space charge" [4]. Generally, a layer depleted of major carriers is placed squarely at the contact injecting minority carriers, following a narrow recombination front (fig.1, part b). It is this layer depleted in the main carriers that is responsible for the current sublinear dependence on-voltage ($I \propto V^{1/2}$) as voltage rise increases a volumetric charge in the depletion layer thereby leading to an increase in the differential resistance. In some cases, it is even possible to form a region of negative differential resistance [1]. Concentration of the space charge slowly decreases in time τ_0, and the system reaches equilibrium (figure, part b).

Field domains (or local potential perturbations) accounting for a pulse injection of minority carriers can move under the influence of applied electric field. These fluctuations in a relaxation mode will move in the same direction as the majority carriers because the excess of minority carriers decreases rapidly due to recombination process, but concentration of majority carriers is changing slowly in the direction of neutrality status. In terms of recombination regime, neutral local perturbations of the carriers' concentration will move in the same direction as a minority carrier.

In [1, 2] the analysis of relaxation organic and amorphous semiconductors properties has been carried out, as well as the comparison of their characteristics.

IV. Features of the Relaxation Charge Processes in the Semiconductor Barrier Structures

A number of theoretical and experimental works devoted to the study of relaxation processes in physical barrier layers, are based on the charge relaxation theory developed by Shockley and Reed [6]. This theory gives a number of assumptions that distort the physical meaning of the phenomenon. In particular, the theory does not take into account that in SCR is completely absent the processes of generation and recombination of carriers due to the presence of a strong electric field providing the dominance of drift over other processes.

The approach to the description of relaxation charge processes in semiconductors and semiconductor barrier structures was proposed in the works of R. Brage et al. [7]. The main features of this approach are based on modeling of nonlinear electrohydrodynamic waves of free charge carriers propagation, amplification and generation and the investigation of the possibilities of their application in electronic devices for signal processing.

The authors of this model show that in the layers of low-alloy doped semiconductors with their thickness lower than the ballistic length $L_б=\tau_{сп}(2h\omega_0/ m^*)^{1/2}$, but higher than the Debye of free charge carriers screening length and with a gradient of their concentration available the external field excites carrier waves with frequencies higher than the frequency of the Maxwell relaxation, but lower than the diffusion frequency of charge carriers. Here $\tau_{сп} = 10^{-13}- 10^{-12}$ s - is optical phonons spontaneous emission time; ω_0 – is limit frequency; *h*- is the Planck constant, *m** is the carrier effective mass [7]. Our calculations showed that the ballisticity length $L_b = 10^{-3} - 10^{-2}$ m, i.e. practically it coincides with the length of the drift L_E, but it is much longer than the Debye screening length.

Severe conditions described above and the analogue conditions with practical absence of free charge carriers are implemented in physical barrier structures space charge region (SCR). Activation-drift model developed and justified by P. T. Oreshkin and co-authors [8-10] is based on the consideration of two joint statistical events i.e. charge carriers of the semiconductor barrier structure (Schottky barriers and asymmetric p-n junctions) emission from deep levels (DL) and their drift in the SCR under reverse bias. Accordingly, the product of probabilities of these events gives the total probability of activation-drift phenomena [8, 9].

In contrast to previously proposed mechanisms, the described above exposure allows us to take into account not only the activation, but the drift component of the relaxation process as well. In [9] cogent explanations alongside with experimental results are shown to justify the developed model. The characteristic length of relaxation processes exceeds the value of the Debye length shielding in SCR where free charge carriers are practically absent and the processes of capture do not determine the physical mechanism of the process.

Thus, SCR of barrier structure under reverse bias can be considered as a relaxation semiconductor in which the relaxation time of charge carriers is determined by the span time while the properties of recombination semiconductor are maintained by the base (where electric field is absent).

Ratio of the time of the activation of the charge carrier with DL in the SCR under reverse biased barrier structure and the time-of-flight into the base were among the main subjects for discussion during the model testing. Some authors believed that the charge carriers' time-of-flight in the SCR could be neglected in comparison with the activation time. However, third-party authors' and our own experimental results have confirmed that the carriers in the SCR flight time is determined by the Maxwell relaxation time and the time-of-flight can be comparable with the total relaxation time [10].

In accordance with the concepts [2-4] of relaxation charge theory in the high-resistance materials (or device regions) the above said is believed to be equitable.

V. Conclusion

The paper presents a theoretical models analysis allowing to define parameters, characteristics and peculiarities of nonequilibrium charge carriers concentration changes in relaxation and recombination semiconductors and barrier structures based on them.

The mechanisms of conductivity processes are observed. The conductivity is determined by the lifetime of minority nonequilibrium charge carriers or by the time of dielectric relaxation. In future it seems to be perspective to discuss the processes in SCR barrier structures from the point of view of distribution, amplification and generation of nonlinear electrohydrodynamic waves of free charge carriers and to investigate the possibilities of their application.

The results of research allow to conclude that the activation-drift transfer mechanism of charge carriers refers to the most common physical processes. The following step to be undertaken is theoretical and experimental justification of application of above concepts to the description and practical implementation of other relaxation processes which occur in barrier structures.

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