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RELATION BETWEEN THE CONCENTRATION OF NONEQUILIBRIUM ELECTRONS AND HOLES IN LONG SEMICONDUCTOR DIODES

Abstract. Analytical expressions are obtained for the dependence of the concentration of nonequilibrium current carriers on the parameters of deep impurities in compensated semiconductors, where the capture of carriers to deep impurity levels is taken into account. It is pointed out that the relationship between the concentration of nonequilibrium carriers is greatly complicated due to the variety of recombination processes and the generation of current carriers through multiply charged impurities. In this connection, below we analyze the dependences of nonequilibrium electrons and holes on the parameters of deep impurity centers.

Keywords: nonequilibrium current carriers, deep impurity centers, recombination and generation through multiply charged impurities.

At present, progress in the field of power semiconductor electronics is largely determined by the creation of devices with an optimal combination of electrical characteristics. The interrelation of various characteristics of devices, on the one hand, makes it difficult to carry out optimization calculations, and on the other hand, it requires an increase in the accuracy of theoretical calculations. From this point of view, the possibilities of some analytical calculations containing a number of significant simplifications (for example, the division of a semiconductor structure into regions of a strong field and quasi-neutral regions, the use of various approximations in solving the continuity equation, etc.) turn out to be clearly insufficient for an adequate description of the processes of charge carrier transport in multilayer semiconductor structures in a wide range of changes in external conditions (temperature, deformation, radiation) and parameters that determine the operating mode of the device (forward current density, voltage, etc.). Under these conditions, the only possible way out is the transition to exact approximations based on the solution of the fundamental system of equations of a semiconductor device by difference methods. Such approximations make it possible to take into account the complex profiles of the distribution of various electrophysical parameters over the thickness of the semiconductor structure. A large volume of literature devoted to the numerical simulation of semiconductor structures published in recent years indicates the promise of this direction [1; 2].

The current-voltage characteristic (CVC) S – of the type in three-layer structures in a diode connection, the base of which is made of a compensated semiconductor, is described not only by a mechanism due to a nonlinear increase in the conductivity

of the semiconductor thickness (base) depending on the current, but also by mechanisms due to an increase [3; 4]: the rate of thermal generation of carriers due to the heating of the thickness of the semiconductor by the flowing current; injection coefficient $p-n$-transition with increasing current; carrier mobility in a strong electric field upon scattering by ionized impurities [5]; lifetime with increasing carrier concentration (τ – mechanism) [6].

It is easy to verify that the proportion of the above mechanisms in the formation of negative resistance in diodes from semiconductors with deep impurity levels is determined by the dependence of nonequilibrium electrons and holes. This is due to the fact that in diodes, the base thickness of which is much larger than the diffusion length, the distribution of injected carriers depends on nature, in particular, on the degree of impurity charge. Therefore, the influence of the electric field on the distribution of nonequilibrium carriers in the base of the diode changes sharply with an increase in the injection level. But, in a purely intrinsic semiconductor, the field does not affect the distribution of current carriers at all.

In compensated semiconductors, due to the capture of carriers to deep impurity levels, the relationship between the concentration of nonequilibrium carriers is greatly complicated due to the variety of recombination processes and the generation of current carriers through multiply charged impurities. In this connection, we will analyze below the dependences of the concentration of nonequilibrium electrons and holes on the parameters of deep impurity centers.

Gold atoms in silicon can be in minus, zero, and plus charge states. The acceptor and donor levels are located above the valence band by 0.62 and 0.35 eV, respectively [7]. To determine the relationship between the concentrations of electrons and holes and the recombination rate, we assume that the transition processes occur according to the following scheme

$$Au+ \rightleftarrows A^-; \mathrm{Au}^+ + e \rightleftarrows Au,\ Au + h \rightleftarrows Au^+;$$
$$Au^- + h \rightleftarrows Au, \qquad (1)$$

where e (h) are electrons (holes).

These processes of recharging gold atoms by carriers are characterized by some probabilities W_{0-}, W_{+0}, W_{0+}, W_{-0}, which are equal to the capture cross sections of the corresponding processes, multiply by the average thermal velocity of an electron or hole and by the total concentration of gold atoms. Thermal generation and carrier recombination through the band gap are not taken into account. Expressions (1) lead to the following kinetic equations for charged gold atoms

$$\frac{dNf_-}{dt} = f_0 W_{0-}(n+n_0) - f_- W_{-0}(p+p_0) - \mathrm{A} f_- N + B f_0 N,$$
$$\frac{dNf_+}{dt} = f_0 W_{0+}(p+p_0) - f_+ W_{+0}(n+n_0) - C f_+ N + D f_0 N. \qquad (2)$$

Here, N, $n(n_0)$ and p (p_0) are the concentrations of gold, non-equilibrium (equilibrium) electrons and holes, $f_{-1,}$ f_0 and f_+ are the fractions of minus-, zero- and plus-charged gold atoms.

Coefficients A, B, C, and D characterizing the rate of thermal generation of carriers from impurity centers are determined from the principle of detailed equilibrium between levels and bands through the parameters of an equilibrium semiconductor $A = \frac{f_0^0 W_{0-} n_0}{N f_-^0}$, $B = \frac{f_-^0 W_{-0 p_0}}{N f_0^0}$, $C = \frac{f_0^0 W_{0+ p_0}}{N f_+^0}$, $D = \frac{f_+^0 W_{+_0 n_0}}{N f_0^0}$, where the index "0" means the equilibrium value of the considered parameters. Then, using the obvious equality from the solution of system (2), one can easily obtain the following relations

Using the obvious equality

$$f_0 + f_- + f_+ = 1,$$

from the solution of system (2) for the stationary case, we obtain

$$f_0 = \frac{1}{a};\ f_- = \frac{1}{a}\frac{n+n_0+\theta\delta p_0}{\theta(\mathrm{p}+\mathrm{p}_0)+\delta^{-1}n_0};$$
$$f_+ = \frac{1}{a}\frac{p+p_0+\beta^{-1}\alpha n_0}{\alpha(n+n_0)+\beta p_0}, \qquad (3)$$

here

$$a = 1 + \frac{n+n_0+\theta\delta p_0}{\theta(p+p_0)+\delta^{-1}n_0} + \frac{p+p_0+\beta^{-1}\alpha n_0}{\alpha(n+n_0)+\beta p_0},$$

$$\alpha = \frac{W_{+0}}{W_{0+}};\ \theta = \frac{W_{-0}}{W_{0-}};\ \beta = \frac{f_0^0}{f_+^0};\ \delta = \frac{f_-^0}{f_0^0}.$$

The relationship between the electron and hole concentrations is determined by solving the following Poisson equation $\frac{dE}{dx} =$

$$= -\frac{4\pi e}{\varepsilon}\left\{n - p - N\cdot f_-^0 + N\frac{n + n_0 + \theta\delta\cdot p_0}{\theta\cdot p + n + \theta(1+\delta)p_0 + (1+\delta^{-1})\cdot n_0}\right\}, \quad (4)$$

where the concentration of shallow donors is obviously equal to

$$N_d = N\left(f_-^0 - f_+^0\right) + n_0 - p_0. \quad (5)$$

If we use the inequality $\frac{1}{n+n_0}\frac{\varepsilon}{4\pi\varepsilon}\frac{dE}{dx} \ll 1$, i.e. quasi-neutrality conditions, then from expressions (4) and (5) for silicon n – type we obtain

$$n = -\frac{\left[p(\theta-1) + A - N(f_-^0+1)\right]}{2}\left[1 + \sqrt{1 + \frac{4\left[p\left(\theta\cdot p + \theta\cdot N\cdot f_-^0 + A\right) + N\left(-B + A\cdot f_-^0\right)\right]}{\left[p(\theta-1) + A - N\cdot f_-^0 + N\right]^2}}\right]. \quad (6)$$

A similar expression can be obtained for the case with one acceptor level. This is a consequence of the fact that in n – type silicon, the charge state of gold is practically not realized either in equilibrium ($f_+^0 = 0$ due to the proximity of the donor level to the valence band), or in the stationary state (due to the large electron capture cross section for this state of gold $\alpha \gg 1$) [7].

To simplify further calculations of the distribution of current carriers along the length of the base, it must be assumed that the following condition is satisfied

$$\frac{1}{\theta+1}\left|\frac{N(\theta f_-^0 - f_0^0)}{N\cdot f_0^0 + \theta(1+\delta)p_0 + (1+\delta^{-1})n_0}\right| \langle 1. \quad (7)$$

In this case, the compensation of low-resistance silicon n – type occurs due to the filling of the acceptor level of gold with electrons from small donor impurities, and since the acceptor level of gold is located slightly above the middle of the band gap, it will be less than half filled in compensated silicon ($\delta < 1$). Then the dependence of the concentration of electrons and holes is described by the expression

$$n = p\frac{p + N_1}{p + N_2}, \quad (8)$$

where $N_1 = \frac{\theta\cdot N\cdot f_-^0 + \theta(1+\delta)p_0 + (1+\delta^{-1})n_0}{\theta+1}$,

$$N_2 = \frac{\theta\cdot N\cdot f_0^0 + \theta(1+\delta)p_0 + (1+\delta^{-1})n_0}{\theta+1}.$$

In conclusion, we note that the rate of hole recombination, i.e. the total number of holes captured per unit volume per unit time is described by the following expression

$$R_p = \left(W_{-0}f_- + W_{0+f_0}\right)p. \quad (9)$$

In conclusion, we note the following. Substituting (8) into (9) have a simple physical meaning. At low hole concentrations, the quantities f_- and f_0 in Eqs. (2) and (9) can be replaced by their equilibrium values. In particular, at $n = \theta\delta p$ (9) takes the form $R_p = \left(f_-^0 W_{-0} + f_0^0 W_{0+}\right)p$. At hole concentrations satisfying $p > \frac{N}{1+\theta}$ the following condition, the impurity states of gold are recharged, and now there should be more electrons than holes, just by the amount of the formed uncompensated charge, and the recombination rate will be determined by the corresponding stationary values of the fractions of minus and zero-charged atoms of deep impurities in the equilibrium state. Thus, the difference between the electron and hole concentrations increases from the equilibrium electron concentration to $N\left(\theta f_-^0 - f_0^0\right)$. This means that in this case the nonequilibrium concentration of nonequilibrium electrons can exceed the concentration of equilibrium ones by several orders of magnitude. In this case, the lifetime of holes will change from $\tau_1 = \frac{1}{f_-^0 W_{-0} + f_0^0 W_{0+}}$ to $\tau_2 = \frac{\theta+1}{W_{-0} + \theta W_{0+}}$.

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