Modeling of radiation effects at the physical and technological level in the IET CAD

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Abstract: The article considers the issues of energy distribution and use management by means of modeling changes in the electrophysical characteristics of semico nductor structures under the influence of static radiation. The change in the main electrical parameters of transistor structures is given, such as, change in the concentration of the main charge carriers, change in specific resistance, change in the mobility of charge carriers, change in threshold voltage, change in the lifetime of charge carriers. Also in the article within the framework of changing other parameters of transistors the following calculations are carried out: change in the slope of the drain-gate characteristic, change in the leakage current in the drain circuit, thermal generation current, surface leakage current, change in input resistance.

1 Introduction

Stable radiation defects arising under the influence of displacement effects introduce a wide range of energy levels into the bandgap of a semiconductor or dielectric, which can be recombination centers, trap centers, and scattering centers [1].

The presence of levels introduced by radiation defects into the bandgap affects the electrophysical parameters of semiconductors, the most significant of which are the concentration of the main charge carriers, the mobility of charge carriers, resistivity and the lifetime of charge carriers. The listed characteristics of semiconductors are macroscopic by definition, so the scope of their application is limited to cases of equilibrium energy release.

When deep centers are introduced into the forbidden zone, some of the charge carriers are captured by them. When calculating the change in concentration, it should be borne in mind that along with the capture of free carriers at the levels of defects, the dopant atom binds to the vacancy (formation of an E-center), as a result of which the efficiency of the defect as a capture center increases (in the limit it doubles). Therefore, the change in the concentration of carriers in the presence of radiation defects (in accordance with Fermi statistics) can be recorded as [2-4]

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$$n_F = n_0 - F_N \sum_j \frac{A_{tj}}{1 + g_j \exp\left(\frac{E_{tj} - E_F}{kT}\right)} - F_N \sum_{j^*} A_{tj^*}\,, \tag{1}$$

where n0, n_F are the concentrations of carriers before and after irradiation; A_{tj} is the efficiency of introducing the jth center with the energy level E_{tj} (macroscopic section of formation); g_j is the ratio of the statistical weights of the unoccupied state to the occupied state, equal to 2 for the levels under consideration. Summation by indices with an asterisk goes according to the levels that include donors.

In practical calculations, the change in concentration is approximated by the formula

$$n_F = n_0 \exp\left(-\frac{R_0 F_N}{n_0}\right), \tag{2}$$

which is applicable up to concentrations n_F comparable to one’s own.

$R_0 = -\left.\frac{\Delta n_F}{\Delta F_N}\right|_{F_n=0}$ There is an initial rate of removal of carriers, determined by the spectrum of radiation defects.

When disordered regions are formed in the semiconductor volume, their contribution to the removal of carriers can be obtained from an estimate of the total charge of the disordered region [5]

$$R_{0r} \approx \frac{4}{3}\pi r_1^3 \left(aN_r + N_r^*\right) N\sigma_{e_{dr}}\,, \tag{3}$$

where *Nr* is the concentration of radiation defects in the disordered region (including those that include an atom of the dopant *Nr**); *a* is the coefficient characterizing the proportion of ionized radiation defects in the disordered region (usually $a = 0.1 \div 0.2$).

Typical values of *R0* in Si and GaAs for different types of radiation are given in [6]. The concentration of charge carriers decreases most efficiently under high-energy proton irradiation, followed by neutrons, fast electrons, and 7-quanta. The dependence of the carrier removal rate on the concentration of dopant is weaker when irradiated with protons, neutrons, and high-energy electrons The formation of disvacancies and disordered regions prevails over the formation of defect complexes with impurity atoms [6].

2 Materials and Methods

Analysis of experimental data on silicon irradiation with neutrons of the fission spectrum made it possible to establish that, in the first approximation, the rates of removal of charge carriers do not depend on the methods of crystal growth and the type of dopants and are approximated by dependencies

$$R_{on} = n_0^{0,23} / k_n \quad \text{for n-Si;}$$

$$R_{op} = p_0^{0,23} / k_p \quad \text{for p-Si}$$

where in the range of concentrations of the main carriers 5 × 1013 < *p0* < 1017 $^{\text{cm-3}}$ and 1014 < *p0* < 5 × 1017, the coefficients *kn* = 387 and *kp* = 444.

For n-GaAs, an approximation is used

$R_{on} = n_0^{0,2} / k_n$, where *kn*=300.

The value of the mobility of charge carriers in a semiconductor is determined by two main mechanisms: scattering on acoustic phonons (*μe*) and scattering on ionized impurities (*μI*), so that the total mobility of the

$$\frac{1}{\mu} = \frac{1}{\mu_e} + \frac{1}{\mu_I}. \tag{4}$$

Therefore, when radiation defects are formed, the change in mobility will occur, first of all, due to the introduction of charged impurities. Therefore, for *an n-semiconductor, we can write that*

$$\frac{1}{\mu} = \frac{1}{\mu_e} + \frac{1}{\mu_{I0}} \left(1 + \frac{F_N}{N_{nI}} \sum_j \frac{A_{tj}}{1 + g_j \exp \frac{E_{tj} - E_F}{kT}} \right), \tag{5}$$

where *μI0* is the initial value of μ_I before irradiation; *NpI* is the concentration of ionized impurities.

Scattering on ionized impurities at room temperature is higher than scattering on phonons at *NnI* ≥ 10^{16} $^{\text{cm-3}}$. Therefore, the change in mobility due to point radiation defects will be observed at sufficiently high fluences (*FNe* ≥ 1017 $^{\text{cm-2}}$ for electrons with an energy of 1 MeV), at which it may also be necessary to take into account the scattering of carriers on non-ionized impurities [7].

With a particle energy sufficient to form disordered regions, a noticeable change in mobility occurs with much smaller fluences. Disordered regions affect mobility in two ways: geometrically, blocking the flow of carriers and thereby reducing the actual volume of the semiconductor, and electrically, being scattering centers. It should be borne in mind that due to the large size of the spatial charge region of disordered regions, which become commensurate with the free path length, the motion of free carriers in the field of the disordered region occurs diffusely. In this approximation, the initial change in mobility due to the influence of disordered areas can be represented as

$$\left(\frac{\Delta\mu}{\mu} \right)_r \cong \frac{1}{3} \frac{R_0 \psi_p^2}{N \varphi_T} \left[\frac{F_N}{\left(\sqrt[3]{a N_r / N - 1} \right)^2} \right]. \tag{6}$$

When silicon is irradiated with neutrons of the fission spectrum, the typical value *of Δμ/*$_{\mu F\, Nn}$ is 10-15 ÷ 10-16 cm2, and when *Ep* = 14 MeV increases to 10-14$^{\div 15\text{-}15}$ cm2. For GaAs irradiated by fission neutrons, the approximation Δμ/*μF*$_{Nn}$ ≈ 7.8 x 106 n0-0.64 $^{\text{is used}}$.

A decrease in the mobility and concentration of free charge carriers determines an increase in the resistivity of the semiconductor under irradiation. For radiations that mainly create point defects, the change in resistivity is primarily due to the removal of free carriers. Therefore

for N-semiconductor

$$p_{nF} = p_{n0} \exp\left(k_{\rho n} F_N \right);$$

For P-semiconductor

$$p_{pF} = p_{p0} \exp\left(k_{\rho p} F_N \right),$$

where *ppo, p_{ro}, p_{nF}, p_{pF}* are the resistivities n and p of the semiconductor before and after irradiation; *kpn, k_{pp}* are the coefficients of radiative change in resistivity.

For neutrons of the fission spectrum

$$k_{\rho n} = 1/k_n n_0^{0,77}\ ;\ k_{\rho p} = 1/k_p p_0^{0,77}\ \text{ for Si;}$$

$$k_{\rho n} = 1/k_n n_0^{0,8}\ \text{for n-GaAs.}$$

When calculating the change in resistance from the action of high-energy neutrons, it is necessary to take into account the increasing influence of disordered regions on the mobility of carriers.

3 Research and results

The lifetime of charge carriers in semiconductors is influenced by two main types of recombination processes: interzone (direct) and through recombination centers (indirect). In non-degenerate semiconductors at low and medium injection (ionization) levels, the lifetime is almost entirely determined by indirect recombination through levels in the bandgap. The calculation of the effect of ionizing radiation that creates radiation defects on the lifetime of charge carriers requires, in general, taking into account the dependence of the recombination rate on the charge state of the centers, the degree of doping, and the level of injection, which is difficult to accomplish in the presence of more than two levels of recombination centers. However, as experiments and calculations show, the influence of a whole range of defects can be reflected with sufficient accuracy for practice by two (and in some cases one) dominant recombination levels [8,9].

The use of a single-level model leads to the formulas of the Shockley-Reed recombination statistics, according to which when the concentration of equilibrium charge carriers is significantly higher than the concentration of recombination centers, the lifetimes of electrons and holes are described by a single time constant

$$\tau_r = \frac{1}{N_{tr}}\left(\frac{1}{A_p}\frac{n_0+n_1+\Delta n}{n_0+p_0+\Delta n} + \frac{1}{A_n}\frac{p_0+p_1+\Delta n}{n_0+p_0+\Delta n}\right), \qquad (7)$$

where N_{tr} is the concentration of recombination centers; $A_n = \sigma_n \bar{v}_n$; $A_p = \sigma_p \bar{v}_p$ - constant capture of electrons and holes, respectively; $\bar{v}_n$ $\bar{v}_p$ - thermal velocities of electrons and holes; n1, p1 - equilibrium concentrations of electrons and holes, when the Fermi level coincides with the level of the recombination center.

At low levels of injection (ionization)

$$\tau_r = \tau_0 = \frac{1}{N_{tr}}\left(\frac{1}{A_p}\frac{n_0+n_1}{n_0+p_0} + \frac{1}{A_n}\frac{p_0+p_1}{n_0+p_0}\right). \qquad (8)$$

As the degree of doping increases, the width of the energy gap increases, with levels contributing to recombination. At high injection levels

$$\tau_r = \tau_\infty = \frac{1}{N_{tr}}\left(\frac{1}{A_p} + \frac{1}{A_n}\right) = \tau_{p0} + \tau_{no}\ , \qquad (9)$$

where $\tau_{n0} = 1/N_{tr}A_n$; $\tau_{p0} = 1/N_{tr}A_p$.

In this case, it can be considered that almost all the levels administered by radiation are recombinational.

The action of ionizing radiation, which creates radiation defects, leads to an increase in the concentration of recombination centers and, as a result, to a decrease in the lifetime of carriers. If the Shockley-Reed statistic is correct, the change in lifetime can be expressed by the

$$\Delta\left(\frac{1}{\tau_r}\right)=\frac{1}{\tau_r F}-\frac{1}{\tau_r}=$$
$$=\frac{A_{tr}F_N}{\dfrac{1}{A_p}\dfrac{n_0+n_1+\Delta n}{n_0+p_0+\Delta n}+\dfrac{1}{A_n}\dfrac{p_0+p_1+\Delta n}{n_0+p_0+\Delta n}}=K_\tau F_N \tag{10}$$

where τ_{rF} is the life time after irradiation; *Atr* is the efficiency of the introduction of recombination centers by irradiation; *Kτ is* the coefficient of radiative change in the lifetime of charge carriers [10].

Accurate calculation *of Kτ* is difficult in many practical cases, so this coefficient is more often determined by the results of tests of test structures. The injection dependence *Kτ,* in accordance with expression (10), is most often represented as

$$K_\tau=K_{\tau 0}\frac{1+\Delta}{1+\dfrac{K_{\tau_0}}{K_{\tau_\infty}}\Delta}\ , \tag{11}$$

where K_{τ_o} , K_{τ_∞} are the coefficients of radiative change in lifetime at low and high levels of injection (ionization), respectively; Δ = Δn/(n0-p0) is the coefficient of injection (ionization).

For doped semiconductors, as a rule, K_{τ_o} > K_{τ_∞} , as a result of which *Kτ* decreases with an increase in the level of injection. In this case, the ratio K_{τ_o} / K_{τ_∞} is approximately ten and decreases with an increase in the degree of doping of the semiconductor. It should be noted that in K_{τ_∞} a number of cases it becomes necessary to take into account direct recombination of a zone - a zone, the probability of which increases with an increase in the concentration of non-equilibrium carriers [11-13].

In neutron irradiation, disordered regions play the main role in recombination, and the Kτ coefficients depend mainly on the type of conductivity and concentration of the main carriers. Expressions for *Kτ* suitable for use at *EP* > 10 keV are as follows:

for n-Si

$$K_{\tau_n}=\frac{2{,}1+0{,}18\rho_{no}+9{,}0\cdot 10^{-5}\rho_{n0}^2}{1+1{,}4\cdot 10^{-2}\rho_{no}}\ ;$$

for *p-Si.*

$$K_{\tau_n}=\frac{1{,}4+8{,}6\cdot 10^{-2}\rho_{po}+1{,}2\cdot 10^{-3}\rho_{n0}^2}{1+3{,}8\cdot 10^{-2}\rho_{po}}\ ;$$

for n-GaAs

$$K_{\tau_n}\approx 4{,}7\cdot 10^{-14}n_0^{0{,}5}\ ;$$

for p-GaAs

$K_{\tau_p} \approx 4{,}7 \cdot 10^{-14} p_0^{0{,}5}$.

A distinctive feature of the effect of neutron radiation is the presence of a strong dependence of $K\tau$ on the level of injection, which is not subject to the Shockley-Reed statistics:

$$K_\tau = K_{\tau_\infty}\left(1 + \frac{K_{\tau_0}/K_{\tau_\infty} - 1}{1 + K_{\tau_0}/K_{\tau_\infty}\sqrt{c\Delta}}\right), \tag{12}$$

where c is the ratio of the capture rate of non-basic charge carriers to the capture rate of the main ones [14].

Usually, the ratio $K_{\tau_0}/K_{\tau_\infty}$ lies in the range of 10÷100 and is determined by the height of the barrier of the disordered area.

The surface leakage current is independent of the semiconductor material, but is a consequence of the difference between ns and no, which is caused by the accumulation of charge on the surface of the p-n junction [14, 15].

4 Conclusion

In passivated devices, the leakage current is strongly influenced by the charge formed in the volume of the dielectric. Silica film, which is most commonly used in planar semiconductor devices, is dominated by positive charge accumulation. This leads to a change in the surface concentration of charge carriers, the formation of surface conductive channels and the appearance of a surface leakage current. To reduce the value of charge in the volume of the dielectric, heat treatment in various atmospheres and doping of the dielectric with compensating impurities are used. During irradiation, both an increase and a decrease in leakage current are observed. The increase in the reverse current is due to the expansion of the p-n junction area due to the deformation caused by charge accumulation in the oxide and the increase in the surface recombination rate, and the decrease is caused by both the shielding of the near-surface region of the semiconductor by enriched (n-type substrate) or inversion (p-type substrate) layers.

Change in input resistance. When exposed to radiation, the input resistance of MOSFET decreases. The results of direct measurements of the input resistances of MOSFET with different dielectric materials when irradiated in the reactor by various fast neutron fluxes are presented in. It should be borne in mind that the fast neutron flux of $5 \cdot 10^9$ neutr/cm2 was accompanied by a dose of γ radiation of 1 Gy.

Thus, changes in the main electrical parameters of transistors are considered.

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