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Peculiarities of injection phenomena in heavily doped silicon structures and development of radiation-resistant diode temperature sensors

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Abstract. To explain the experimental behaviour of differential characteristics (ideality factor, differential resistance) before and after radiation influence, a theoretical model of injection current flow mechanisms for the silicon diode temperature sensors (DTSs) is proposed. The observed nonmonotonic dependencies of the ideality factor on the current are described well by the influence of generation-recombination and drift current components to the diffusion current of the minority carriers. The developed model allowed to find characteristic lifetimes of the minority carriers in the base and in the space-charge region of the diode structure with heavily doped base and emitter regions. Investigations of electrophysical and metrological characteristics of the DTSs allowed to reveal such operating regimes that are characterised by minimal influence of radiation on the device thermometric characteristics.

Keywords: radiation-resistance, diode temperature sensor, silicon diode structure.

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1. Introduction

The development of advanced semiconductor temperature sensors, in particular silicon ones, that are able to reliably operate under radiation environment above 1 Mrad is an actual task for extreme electronics [1]. Silicon diode temperature sensors (DTSs) are distinguished by a wide measured temperature range and high sensitivity, stability and reproducibility, high interchangeability [2]. However, widely represented on the market these DTSs continued not be suitable for applications under radiation conditions, as their thermometric characteristics underwent considerable temperature shift from 3 K to 18 K within actual for practical applications range of 77–350 K already at the dose of 10^6 rad [3].

The formation of thermometric characteristics of DTSs is determined by physical processes to occur in them. Therefore, the development of DTSs with predictable behaviour of their main characteristics under irradiation conditions and determination of optimal operation regimes are impossible without study of the current flow mechanisms in the device and their connection to constructive-technological parameters of semiconductor structures.

The present work is devoted to experimental and theoretical investigations of peculiarities of injection phenomena in heavily doped *p-n* silicon structures under influence of irradiation with the purpose of development of radiation-resistant DTSs.

2. Samples and experimental methods

The DTSs investigated in this work have been developed by the industrial technology of manufacturing of diode chips on the base of heavily doped silicon structures. The concentration of boron in the test structures and in the base region of diodes is $\sim 2.10^{17}$ cm^{-3} and of phosphorous in the emitter region is $\sim 10^{20}$ cm^{-3}.

The measurements of the conductivity, the Hall effect of test structures, the current-voltage characteristics (CVCs) of DTSs in the current interval of 10^{-11}–10^{-2} A have been carried out in the range of temperatures 77–400 K before and after irradiation. The silicon structures have been irradiated by γ-quantum Co^{60} in the set MRX-γ-25 M with the dose rate of gamma radiation of 200 rad/s at the temperature 320 K.

The measurements of the temperature response curves (TRCs) have been carried out on the metrological stand

UGT-A in the range of excitation current from 0.1 μA to 100 μA. An accuracy of the excitation current keeping was ±0.05 %. A calibration accuracy of the DTSs is 0.03 K.

3. Experimental results

From the experimental CVCs measured before and after irradiation, the ideality factor m has been extracted by

$$m = (q/k_BT)(dU/d\ln I), \qquad (1)$$

where I is the direct current, U is the voltage drop across the diode structure, k_B is the Boltzmann constant, q is the electron charge, T is the absolute temperature.

In Fig. 1, we present the dependencies of the ideality factor m on the current I at the temperatures 220 K and 330 K for pre- and post-irradiation DTSs. The following peculiarities in the behaviour of the ideality factor can be pointed out:

a). All the dependencies $m(I)$ corresponding to the measurements before and after irradiation have a characteristic minimum. The value of the characteristic current in the minimum, $I_{\min}$, is increased with the irradiation dose D from $I_{\min} \approx 10^{-6}$ A ($D = 0$) to $I_{\min} \approx 10^{-5}$ A ($D = 10^7$ rad). The respective minimum value of the ideality factor $m_{\min}$ in the pre-irradiation dependence $m(I)$ is less than that corresponding to the post-irradiation one.

b). With increasing I, the dependencies $m(I)$ have approximately linear character. The slope of such the dependence is rather larger for the pre-irradiation measurements in comparison with the post-irradiation ones. The intersection point C of these dependencies corresponds to the current $I \approx 10^{-4}$ A. In the vicinity of the point C, the ideality factor and differential resistance are least influenced by the irradiation.

In Fig. 2, we show the temperature shift ΔT of the TRC due to the influence of irradiation for DTSs for the excitation current of 100 μA. As seen, the value of ΔT does not exceed 0.03 K for the dose 10^6 rad and 0.5 K for the dose 10^7 rad.

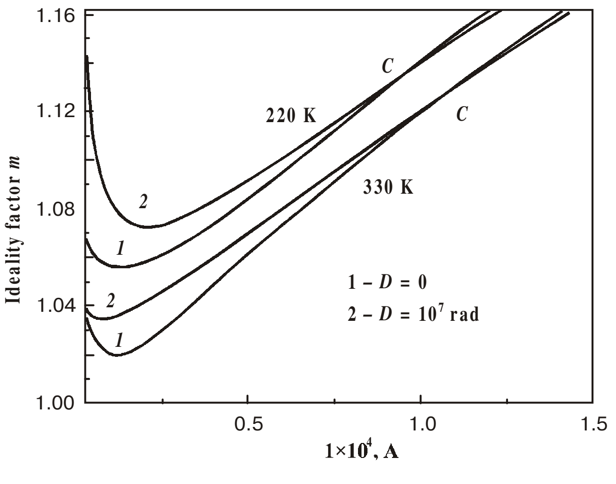

Fig. 1. Current dependencies of the ideality factor m before and after gamma irradiation dose $D = 10^7$ rad at the temperatures of 220 and 330 K.

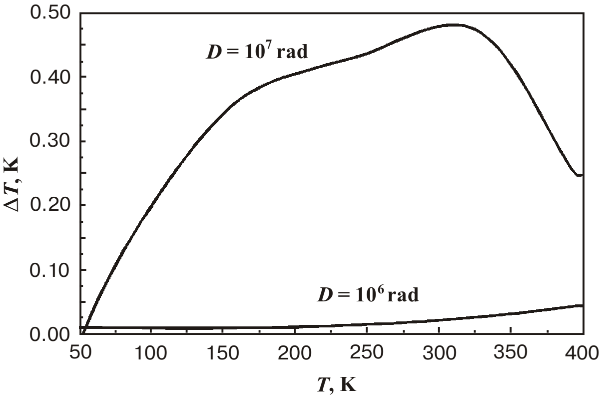

Fig. 2. Temperature shift ΔT as a function of temperature T due to gamma irradiation doses from Co^{60} source. The excitation current is of 100 μA.

In the next section we develop a simple theoretical model to explain the observed peculiarities of the ideality factor. On the base of this model such operating regimes of the DTSs are predicted that are least influenced by irradiation.

4. Theory

The established in the experiment proximity of $m(I)$ to unity testifies that the dominant carrier transport mechanism in the forward biased diode structure under study is the diffusion current of the minority carriers [4]

$$I_D = I_{DS} \exp(qU_0/k_BT), \qquad (2)$$

where I_{DS} is the diffusion saturation current, U_0 is the voltage drop across the space-charge region of the junction.

The observed deviation of CVC from the ideal behaviour in the considered range of temperatures and currents may be explained with taking into account two different carrier transport mechanisms. The first one is the generation-recombination current [4], that can become essential with decreasing excitation current,

$$I_R = I_{RS} \exp(qU_0/2k_BT), \qquad (3)$$

where I_{RS} is the respective saturation current. Another carrier transport mechanism that can become essential with increasing the excitation current is the current inherent in a pre-high injection regime [5]. These three current flow mechanisms must simultaneously be included in the theoretical model used for explanation of the experiment and analysis of radiation resistance of the DTSs.

For analysis of the CVCs in the pre-high injection regime we take into account redistribution of the applied voltage U between the space-charge region of the junction U_0 and the diode base U_∇ due to the appearance of the gradient electric field E_∇ [5]. Respectively, new features of the injection phenomenon in the diode structure should be considered, such as the drift component of the current due to the field E_∇; modification of the minority carrier distribution in the p-type base caused by the field E_∇ in comparison with that determined by the ideal diffusion carrier transport.

The minority carriers (electrons) injected into the diode base produce an excess negative charge that must be neutralised with an equal portion of a positive charge, as it is required by the charge neutrality condition: $n - n_{p0} = p - p_{p0}$. Here n, p are the electron and hole concentrations in the p-type base and n_{p0}, p_{p0} are their equilibrium values, respectively. Such regime is reached due to the majority carriers outgoing from the p^+-contact which nonuniform distribution in the base is kept with the electric field E_∇. At that, the diffusion and drift contributions to the majority carrier current density j_p are approximately counterbalanced:

$$j_p = q\mu_p pE - qD_p \frac{dp}{dx} = 0, \tag{4}$$

where μ_p and D_p are the hole mobility and diffusion coefficient. From this condition we obtain for the electric field $E_\nabla = (D_p / p\mu_p)(dp/dx)$ that results in a gradient voltage U_∇ across the base region

$$U_\nabla = \int_0^d E_\nabla(x)dx = \frac{D_p}{\mu_p} \ln \frac{p(d)}{p(0)} . \tag{5}$$

Here $p(0)$ and $p(d)$ are the hole concentrations at the space-charge region boundary on the base side ($x = x_p = 0$) and at the p^+-contact ($x = d$). Thereby, the voltage drop across the diode is

$$U = U_0 + U_\nabla \cdot \tag{6}$$

Now the minority carrier current density j_n includes, in contrast to the ideal case (2), both the drift and diffusion contributions

$$j_n = q\mu_n nE + qD_n \frac{dn}{dx} , \tag{7}$$

where μ_n and D_n are the electron mobility and diffusion coefficient. Using the Einstein relation $\mu_n = (q / k_B T)D_n$ and substituting for the electric field $E = E_\nabla$, the current density j_n can be written as

$$j_n = qD_{eff}(n)\frac{dn}{dx} . \tag{7a}$$

Note that it can be interpreted in terms of the nonlinear diffusion transport of electrons with the effective diffusion coefficient $D_{eff}(n)$ dependent on the electron concentration

$$D_{eff}(n) = D_n\left(1 + \frac{n}{n + p_{p0} - n_{p0}}\right). \tag{8}$$

The drift-diffusion current density through the n^+-p junction can be written as

$$j_{DD} = qD_{eff}[n(0)]\left(\frac{dn}{dx}\right)_{x=0} . \tag{9}$$

Below, we consider the case $n_{p0} << \Delta n << p_{p0}$. Then, the diffusion coefficient D_{eff} is reduced to

$$D_{eff} = D_n\left(1 + \frac{\Delta n}{p_{p0}}\right). \tag{10}$$

To obtain an expression for the CVC, we have found spatial distributions of the minority carrier concentration $n(x)$ in the base under the drift-diffusion transport and have calculated the derivative $(dn/dx)_{x=0}$ used in Eq.(9). Then using these results and the relation (6), the drift-diffusion current (9) can be put down as

$$I_{DD} = I_{DS}[1 - 2/3\alpha(U)]\exp(qU / k_B T) , \tag{11}$$

where we have introduced the small parameter $\alpha(U) \equiv (n_i^2 / p_{p0}^2)\exp(qU / k_B T) << 1$.

The total current through the diode can be obtained by combining the drift-diffusion current (11) and the generation-recombination current (3):

$$I = I_{DS}\left[1 - \frac{2}{3}\alpha(U)\right]\exp(qU / k_B T) + \\ + I_{RS}\left[1 - \frac{1}{3}\alpha(U)\right]\exp(qU / 2k_B T). \tag{12}$$

Then, using Eqs.(1) and (12), we arrive to explicit expression for the ideality factor m as a function of the excitation current

$$m(I) = 1 + \frac{I}{I_1} + \sqrt{\frac{I_2}{I}} . \tag{13}$$

Here, the characteristic currents $I_{1,2}$ are given by

$$I_1 = \frac{3p_{p0}^2 I_{DS}}{2n_i^2}, \qquad I_2 = \frac{I_{RS}^2}{4I_{DS}} . \tag{14}$$

The sum on the right-hand side of Eq.(13) is related to the ideal diffusion current, the pre-high injection current (the second term), and the generation-recombination current (the third term). The asymptotic behaviour of the ideality factor with increasing current is given by a linear dependence $m(I) \cong 1 + (I / I_1)$ with the characteristic slope

$$tg\varphi \propto 1/I_1 . \tag{15}$$

With decreasing current, an approximate dependence $m(I) \cong 1 + (I_2 / I)^{1/2}$ can be obtained. For $I \cong (I_1^2 I_2)^{1/3}$, both the last terms in (13) are of the same order of magnitude that leads to a minimum in the $m(I)$-dependence. It is easy to verify that at the minimum the ideality factor is

$$m_{\min} = 1 + \frac{1}{2}\left(\frac{3n_i I_{RS}}{p_{p0} I_{DS}}\right)^{2/3}, \tag{16}$$

with $I_{\min}$ being

$$I_{\min} = I_{DS}\left(\frac{3p_{p0}^2 I_{RS}}{8n_i^2 I_{DS}}\right)^{2/3}. \tag{17}$$

Thus, taking into account the above discussed three carrier transport mechanisms in the diode structure has allowed us to describe the observed nonmonotonic dependencies of the ideality factor on the excitation current.

5. Discussion

From the measurements of Hall effect on the test structures we have found that the carrier mobility within the investigated temperature range is least sensitive to the influence of gamma irradiation. The concentration of induced radiation defects does not exceed the value of $\sim 10^{15}$ cm^{-3} for the doze $D = 10^7$ rad. Because of a high level doping of the diode base, the concentration of induced radiation defects appears to be insufficient for appreciable influence to the carrier density and the basic carrier scattering mechanisms, which are responsible for formation of the carrier mobility in the considered temperature range. Therefore, in the diode structures under investigation within the limits of radiation doses used, the resistivity ρ is not a critical parameter to considerably affect the radiation resistance of the DTSs. Thus, we should consider the minority carrier lifetime τ as the basic critical parameter of radiation resistance of our diode structures.

We propose a new method to determine the carrier lifetime in the base τ_n and in the space-charge region τ_r from the investigated dependencies of $m(I)$. By substituting the explicit expressions [4] for the saturation currents $I_{DS} = [qSn_i^2 / N_A \mathrm{th}(d/L_n)](D_n/\tau_n)^{1/2}$ and $I_{RS} = qSWn_i / 2\tau_r$ in (16) and (17), the lifetimes τ_n and τ_r can be expressed as

$$\tau_n = \left(\frac{3}{2} qSp_{p0}\sqrt{D_n}\, tg\varphi\right)^2, \tag{18}$$

$$\tau_r = \frac{3W\sqrt{\tau_n}}{4\sqrt{2D_n}\,(\delta m_{\min})^{3/2}}, \tag{19}$$

where S is the effective junction area, W is the space-charge region width, $\delta m_{\min} = m_{\min} - 1$. Using the experimental values for $dm_{\min}$ and tgφ and electrophysical and design parameters for the DTSs, the lifetimes τ_n and τ_r have been calculated for the pre- and post-irradiation measurements in the investigated temperature range. The results are presented in Fig. 3. The obtained values for the pre-irradiation lifetime τ_n^0 agree well with available literature data on the minority carrier lifetime in the heavily doped silicon diffused layers [6].

The irradiation reduces the minority carrier lifetime τ_n in the base only slightly, while the lifetime in the space-charge region τ_r^D after irradiation is less approximately in an order of magnitude in comparison with that τ_r^0 before irradiation. As in regime of pre-high injection the ideality factor (13) is determined mainly by the dependence $m(I) \cong 1 + I/I_1$, then according to definition of I_1 and I_{DS}, the characteristic slope of $m(I)$ (15) changes with variation of the lifetime τ_n as $tg\varphi \sim (\tau_n)^{1/2}$. Therefore, the slope after irradiation becomes lower than that before irradiation. On the other hand, according to (16) and definitions of I_{DS} and I_{RS}, the ideality factor at its minimum $m_{\min}$ varies as $\sim (\tau_n/\tau_r^2)^{1/3}$. Such combination of the lifetimes results in an increase of the value of $m_{\min}$ after irradiation. Therefore, the resulting combination of both changes in the slope and the ideality factor minimum after irradiation leads to the presence of the cross point C of the curves $m(I)$ for the pre- and post irradiation measurements (Fig. 1).

It is important to note that for operating regimes corresponding to a vicinity of the point C the ideality factor is least sensitive to influence of irradiation. It indicates that the dominant current flow mechanism in the DTSs has not undergone an essential modification. For the dominant diffusion carrier transport mechanism, the influence of radiation on the TRC (in the temperature equivalent ΔT) is determined by the influence on the saturation current I_{DS}, that is, on the lifetime, mobility, and concentration of carriers in the base. As was mentioned above, for the developed DTSs the changes in these three electrophysical parameters under irradiation are not considerable. At the same time, the observable more significant change in the lifetime τ_r in the space charge region of the diode cannot result in a noticeable modification of

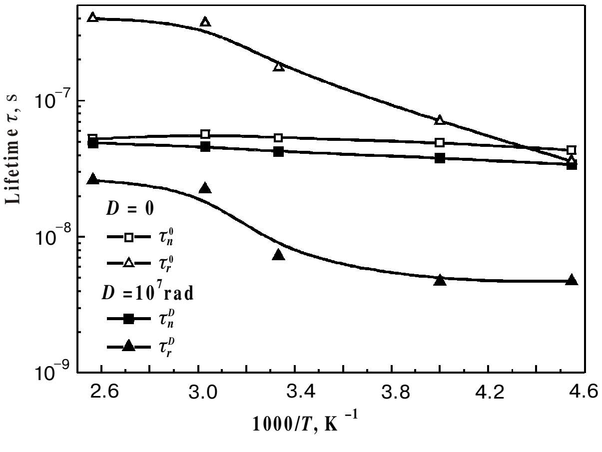

Fig. 3. Electron minority carrier lifetimes τ_r and τ_n calculated from the current dependencies of the ideality factor before and after irradiation at different temperatures.

the TRC as well, since the contribution of the generation-recombination current to the total current through the diode is small. This is the basic reason of radiation resistance of the developed DTSs reached in the investigated temperature range and the excitation current regime.

6. Conclusions

The developed theoretical analytical model taking into account peculiarities of injection current flow mechanisms for the DTSs explains well the experimental behaviour of differential characteristics (ideality factor, differential resistance) under radiation influence. The nonmonotonic current dependencies of the ideality factor are adequately described by the influence of the generation-recombination and drift current components in combination with the diffusion current of the minority carriers. The position of the minimum in the dependencies of $m(I)$ is determined by the competition of these two additional currents. The lifetimes of the minority carriers have been found separately in the base and in the space-charge region of the diode structure. The analysis of current flow mechanisms in the DTSs has allowed to reveal optimal operating regimes for the sensor which are characterised high radiation resistance. Such the regimes provide the temperature shift ΔT caused by gamma irradiation from Co^{60} with the doze up to 10^6 which does not exceed of 0.03 K. With increasing doze of the irradiation up to 10^7 rad, the value of ΔT does not exceed of 0.5 K that completely meets the requirements to temperature sensors for practically important cases.

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