Radiation resistant BJT-based Temperature Sensor for IoT Sensor Nodes

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***Abstract* — The possibility of using a BJT with linear transfer function as a radiation resistant temperature sensor for low power IoT sensor nodes is experimentally investigated. For this reason, the effect of neutron, electron and gamma radiation on the temperature dependence of the forward voltage on the emitter p-n-junction of the BJT in the low-current mode at two-terminal connection, when the base is shorted with the collector, has been investigated. The voltage decreases linearly from 0.8 to 0.4 V in the temperature range from –40 °C to +100 °C. The transfer function remains stable after irradiation by a neutron beam of up to a total fluence 10^{14} n/cm^2. It has been experimentally established that the value of temperature sensitivity remains unchanged after the higher levels of radiation exposure for transistors with a narrow base region and with a lower doping level of base.**

Keywords* — *temperature sensor; radiation resistance; bipolar junction transistor; low-current mode; two-terminal connection; neutron irradiation; temperature sensitivity.

I. Introduction

When implementing the concept of the Internet of things (IoT), measurement tools play a special role, because they fill the computing environment with numerical information. This caused a rapid growth in the number of new designs and technologies for manufacturing low-energy reliable sensors of various physical quantities that operate under various severe conditions. In our previous work [1] special designs of frequency transduceers of temperature, illuminance, magnetic field, radiation as low power sensors for the IoT network were considered.

Advanced CMOS technologies allowed to develop and to introduce into an industry of fully-integrated with the IoT the low-power microcircuits of smart temperature sensors on resistive temperature detectors (RTD) [2], on MOSFET sensitive elements [3], on BJT sensors [4]. However, the influence of ionizing radiation on such sensors remains insufficiently studied.

At the same time, it is well known that even small ionizing radiation dose significantly changes the electrical parameters of MOS structures, but temperature sensors must reliably work near the cores of nuclear reactors, in the top of atmosphere, in outer space, in elementary particle accelerators where the radiation levels are sufficiently large.

The object of the work – is to study the possibility of using the semiconductor temperature sensitive elements, in particular BJT temperature detectors, as the working elements for IoT sensor units in places with an increased radiation background.

II. Semiconductor temperature sensitive elements

Semiconductor elements, such as diodes, field effect transistors (FET) and bipolar junction transistors (BJT), have obtained a wide application as thermosensitive elements in the measuring telecommunications networks in various areas of science, industry and daily life, since the traditional wire-wound type Pt100 have a large dimension and it consume a lot of energy.

The simplest in manufacturing are thermally sensitive diodes [5], for which the reverse current of the p-n-junction is the most sensitive variable parameter during temperature changes [6]. But the reverse current of the diode is very unstable, not only with radiation exposure, but it also degrades with time. The last circumstance is due to the fact that an important component of the reverse current of the p-n-junction is the leakage current through the surface conduction channels, which are broadened with time due to oxidation of surface, adsorption of various gases, etc. [7].

MOSFET temperature sensors have a great sensitivity, moreover, MOSFETs are already integrated into the CMOS chips of end nodes of IoT. However, when the ionizing radiation acts on the MOS structure, the radiation-generated charge carriers form an excess positive charge, since the mobility of holes of silicon oxide is nine orders of magnitude lower than the mobility of electrons. This charge accumulates at the dielectric-semiconductor interface, since the potential traps for the holes are basically just near the oxide-semiconductor interface, where the most nonequilibrium part of the system is due to a violation of stoichiometry. Obviously, the effect of this accumulated positive charge on the conductivity of the transistor channel is stronger the closer the charge to the surface of the semiconductor is located. Thus, the radiation-generated excess positive charge in the dielectric layer exerts a more significant influence on the conductivity of

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the MIS transistor channel than the radiation-induced defect formation in the channel of the transistor itself. This accumulated positive charge substantially changes the concentration of the main charge carriers in the channel, and is manifested in a change in the threshold voltage of the gate shutoff, which leads to a change in the saturation current of the MOSFET, even with small radiation fluxes [8], which are insufficient to create structural defects in the channel. To compensate for these changes, special technological or design solutions are required.

The BJT has a greater thermal sensitivity than the diode, especially in two-terminal connection of transistor, when the emitter-collector circuit is connected, and the base terminal is open. As an information parameter, it is possible to choice a current through a transistor, which at such a connection is defined as

$$I = \beta I_{KR} \,. \tag{1}$$

Here, both the collector reverse current I_{KR} and the current gain of common-emitter circuit β depend on the temperature T. However, despite the high thermal sensitivity, the stability of the current (1) under external influences deteriorates, as instability of the collector current ΔI_{KR} is added to the instability of the current gain coefficient $\Delta\beta$. It is well known that the current gain depends on the lifetime of the carriers injected into the base, and the lifetime of the nonequilibrium charge carriers decreases substantially under the action of ionizing radiation.

To improve the stability of a thermally sensitive transistor, the forward current of the p-n-junction can be used as the information parameter, which is determined mainly by the injection of charge carriers and depends very little on external factors. But for this, the thickness of the transistor base W must be less than the diffusion length of the injected carriers L, and near the base contact, the rate of recombination of the injected carriers should be high. For a conventional diode, these conditions are technologically difficult to implement, and for BJT they are easily realized if only the emitter emitter-to-base junction of the transistor is used. To do this, the collector terminal must be shorted with the base contact.

The thermosensitive parameter for such a connection is the forward voltage on the emitter p-n-junction, which is defined as:

$$U = \frac{E_g}{q} - \frac{kT}{q}\ln\left(\frac{CT^{4-\alpha}}{nWI}\right), \tag{2}$$

where E_g – energy gap of the semiconductor, q – elementary charge, n – concentration of the electrons in the p+-n-junction base, the remaining coefficients k, α and C include all constants that doesn't depend on temperature [6].

To reduce power consumption, the low current mode is used

$$nWI << CT^{4-\alpha}, \tag{3}$$

Under condition (3), the value of the logarithm in (2) depends only slightly on the temperature, and the dependence of the forward voltage on the emitter junction on the temperature (2) is practically linear.

III. Experiment Results

For experimental studies, production batches of silicon planar BJT p-n-p-type with different base thicknesses and different doping levels of the base region were used. Two-terminal connection was simply obtained by short-circuiting the collector's and base's contacts of the transistor.

Fig. 1 shows the dependence of the forward voltage on the emitter p-n-junction of the BJT on the temperature with power supply from a current generator of 100 μA. The characteristic is linear over the whole measurement temperature range.

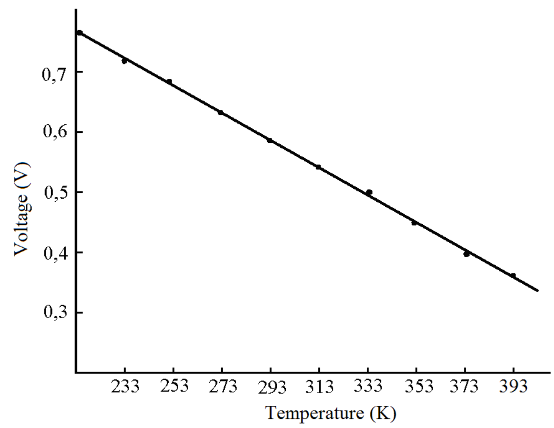

Fig. 1. The dependence of the forward voltage on the emitter p-n-junction of the BJT on the temperature at a current value of 100 μA

Sensor sensitivity $\Delta U/\Delta T$ in the temperature range from 213 K to 393 K is –2.234 mV/deg.

In order to increase the sensitivity of this temperature sensor, it is possible to use in series connection of several transistors.

To obtain a thermal sensor with a positive temperature coefficient output slope, a bridge circuit of two resistors and two transistors connected in the opposite bridge branches can be used [9].

The effect of irradiation of transistors by neutron flux, electron stream and gamma quanta on the magnitude of voltage on the emitter p-n-junction U and the current gain coefficient of common-emitter circuit β was investigated. As one would expect, the irradiation by neutron flux, as an effect of action by heavier particles is impacted the greatest influence on these parameters. Fig. 2 shows the dependences of U and β on the neutron fluence with an energy of 2 MeV.

As can be seen from the Fig. 2, a noticeable decrease of the value β begins at fluences of $5\cdot10^{12}$ n/cm^2, but of the value U –

at fluences larger than 10^{14} n/cm^2. Thus, the thermal sensor based on the dependence of the direct voltage (2) on the emitter p-n-junction $U = f(T)$ is more resistant to the action of ionizing radiation than the thermal sensor based on the dependence of the collector current (1) on the temperature $I = f(T)$.

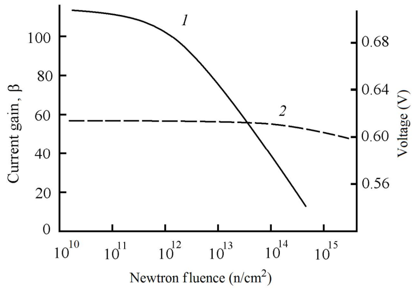

Fig. 2. The dependences of current gain of common-emitter circuit β (1) and voltage on the emitter p-n-junction U (2) on the neutron fluence

When the samples are irradiated by electrons with energy of 5 MeV, the value of U is stable up to the fluenses of $5{\cdot}10^{14}$ el/cm^2. When the samples are irradiated with γ-quanta of 1.25 MeV, forward voltage begins to slowly decrease at doses greater than 10^9 R. This is two orders of magnitude higher than for silicon diode temperature sensors [10].

Annealing of the samples to recovery the parameters of the transistors after irradiation was carried out. As shown by experiments, a complete recovery of U occurs at temperatures $T > 410$ K, whereas for complete recovery of β it is necessary to anneal at $T > 620$ K.

Experimental studies of radiation effect on forward voltage at the emitter p-n-junction and on the temperature sensitivity of transistors with different base thickness and concentration of doping impurity in the base were carried out. The same type transistors were used from different production batches with a base thickness from 0.88 μm to 2.1 μm and with a concentration of impurity in the base region from $7{\cdot}10^{17}$ cm^{-3} to $2{\cdot}10^{19}$ cm^{-3}. It was found that transistors with a narrow base and a lower base doping level maintain a stable value of temperature sensitivity at higher levels of radiation exposure.

The deterioration of the electrical characteristics of silicon devices during irradiation is due mainly to the effect of removing the intrinsic charge carriers and the degradation of the lifetime of nonequilibrium charge carriers. In Fig. 3 compares the changes in the effective concentration of the main charge carriers, the lifetime of nonequilibrium charge carriers and their mobility after neutron irradiation with different doses.

The concentration of the majority charge carriers n/n_0 decreases most rapidly (curve *3*). However, such degradation is manifested only for the fluenses of ~ 10^{14} n/cm^2, whereas the decrease in the lifetime of nonequilibrium charge carriers is already affected by fluenses ~ 10^{11}-10^{12} n/cm^2 (curves *1* and *2*). For large values of the lifetime before irradiation τ_0, such degradation begins with smaller irradiation streams (curve *1*). The mobility is less sensitive to the action of radiation, and its decrease begins with large irradiation fluenses ~ 10^{15} n/cm^2 (curve *4*).

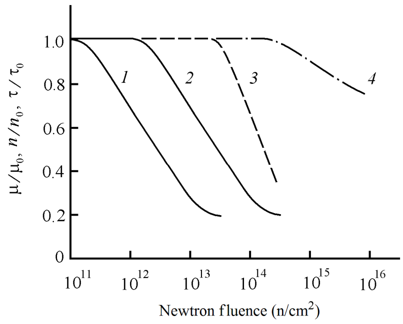

Fig. 3. The changes of the relative values of the n-type silicon parameters after the irradiation of neutrons with an energy of ~ 10 keV: *1*, *2* – the lifetime of nonequilibrium charge carriers τ / τ_0; *3* – the concentrations of the majority charge carriers n / n_0; *4* – mobility μ / μ_0. The value of the lifetime before irradiation is τ_0, s: *1* – 10^{-6}, *2* – 10^{-9}.

IV. Discussion of Experimental Results

Silicon is a semiconductor with a relatively small energy band gap and with a comparatively large threshold energy of defect formation. The main radiation-induced process in such semiconductors is the bulk mechanism of damage of the crystalline structure as a result of the displacement of atoms.

During the action of radiation on the semiconductor, vacancies and interstitial atoms are firstly formed (primary structural defects). Then, primary defects migrate through the semiconductor, as a result the various types of defect complexes are formed: A- and E-centers, divacancies, etc., which create deep acceptor levels in the band gap. The appearance of such complexes leads to changes of basic electrophysical parameters of the semiconductor.

The decreasing of the concentration of the majority charge carriers in n-silicon after irradiation is mainly due to the appearance of E-centers, each of which removes two electrons from the conductivity band of n-silicon: one at the appearance of a new acceptor level, and one at the capture by a vacancy atom of the donor impurity.

The decreasing of the mobility of charge carriers is mainly due to the appearance of additional scattering centers in the form of A-centers that have a value of scattering cross section of the same order as the other scattering centers. The formation of the E-center does not affect the value of mobility, since it occurs simultaneously with the disappearance of the donor scattering center.

The lifetime of nonequilibrium charge carriers is very sensitive to the appearance of new recombination A-centers. The value of effective capture cross-section of nonequilibrium charge carriers of such generation-recombination levels is two orders of magnitude greater than the capture cross section of direct band-band recombination. Therefore, the degradation of the lifetime of charge carriers in silicon begins at lower irradiation doses than the concentrations of the majority charge carriers and their mobility (see Fig. 3, curves *1* and *2*).

To estimate the influence of radiation on the electrical parameters of the transistor, we rewrite expression (2) for the voltage on the emitter p-n-junction for the case of a thin base of a bipolar transistor at a forward current density j [6] as:

$$U = \frac{kT}{q}\ln\left(\frac{jWN}{kT\mu_p n_i^2}\right), \qquad (3)$$

where W – thickness of the base; N – effective concentration of the type-setting impurity in the base region (concentration of the majority carriers); μ_p – hole mobility; n_i – concentration of intrinsic charge carriers in the base.

From expression (3), one can well see that the determining parameter in the radiation-stimulated changing of voltage on the emitter p-n-junction of the transistor U is the majority carriers concentration n (or type-setting impurity N) in the base. Therefore, the voltage U begins to decrease due to a decreasing of the concentration n at the fluences 10^{14} n/cm^2 (Fig. 3, curve *3*). Decreasing of the mobility (Fig. 3, curve *4*) partly compensates the voltage variation at fluences $5\cdot10^{14}$ n/cm^2, therefore the voltage on the emitter p-n junction U is less sensitive to radiation (Fig. 2, curve *2*) than the coefficient β. Thus, the voltage degradation at the emitter p-n junction U is associated with the formation of E-centers under radiation exposure.

The inverse value of the transistor current gain coefficient in common-emitter circuit is determined, basically, by recombination losses in the base of the transistor, in its emitter and on the base surface [6]:

$$\frac{1}{\beta} = \frac{J_\mathrm{b}}{J_\mathrm{k}} \approx \frac{qW^2}{2kT\mu_p^\mathrm{b}\tau_p^\mathrm{b}} + \frac{\sqrt{q}\rho_\mathrm{e}W}{\rho_\mathrm{b}\sqrt{kT\mu_p^\mathrm{e}\tau_p^\mathrm{e}}} + \frac{qsS_\mathrm{sur}W}{SkT\mu_p}, \qquad (4)$$

where ρ_e, ρ_b – resistivity of the emitter and the base; μ_p^e and τ_p^e – mobility and lifetime of holes in the emitter; μ_p^b and τ_p^b – mobility and lifetime of holes in the base; s – rate of surface recombination; S_{sur} – surface area at which recombination occurs.

As can be seen (4), the lifetime of holes τ is the determining parameter in the radiation-induced change of the current gain coefficient β. Therefore, the degradation of β (Fig. 2, curve *1*) begins with the decreasing of τ (Fig. 3, curve *1*) at considerably smaller radiation fluenses ($5\cdot10^{12}$ n/cm^2) than is observed for U (10^{14} n/cm^2). The sharp decreasing of the coefficient β during the irradiation is due to its strong dependence on τ. Thus, the degradation of the coefficient β is associated with the formation of A-centers under radiation exposure.

The relation between the radiative degradation of the voltage U and the coefficient β with the formation of E- and A-centers in the semiconductor is confirmed by experiments on restoring the initial values of the voltage U and the coefficient β upon the annealing of previously irradiated transistors. It is known [6] that the annealing of E-centers in silicon occurs at temperatures of 400-420 K, and the annealing temperature of the gain coefficient β is 610-650 K. The complete restoration of the voltage U occurs at temperatures T> 410 K, while for a complete recovery of the coefficient the annealing at T> 620 K should be performed.

These data make it possible to assert that, in fact, the degradation of the forward voltage on the emitter p-n junction U under radiation exposure occurs due to the formation of E-centers, whereas the change in the gain coefficient β is due to the appearance of A-centers.

V. Conclusions

Thus, as radiation resistant temperature sensors, it is more preferable to use BJT sensors than MOSFET sensors or diode sensors.

To increase the stability of the temperature sensor under external influences, the base of the transistor must be shorted with the collector, and as an information parameter, it is necessary to use a forward voltage on the emitter p-n-junction.

Temperature sensitivity of transistors with small base thickness and low doping level of the base region remains stable at high levels of radiation exposure.

Such BJT temperature detectors operate in low-current mode and can therefore be used as economical radiation-proof thermosensors for IoT sensor nodes when operating in radiation environments.

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