Potential distribution over temperature sensors of p-n junction diodes with arbitrary doping of the base region

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Abstract. In p-n-junction temperature sensors connected in the forwardbiased, the temperature dependence of the built-in potential is important, while in the reverse biased p-n-junction temperature sensors, it is necessary to study the temperature dependence of the built-in potential and space-charge region width.For this case, as well as for homogeneous and gradient alloyed cases, the temperature dependence of built-in potential and space-charge region widthare studied and mathematical analysis is presented for these cases.Based on these mathematical analysis, the results are obtained for cases where the base region of p-n-junction temperature sensors is doped at different concentrations with a homogeneous or inhomogeneous distributions of impurities. It is well known that in conventional temperature sensors, when the main current transport mechanism is determined by generation-recombination processes in space charge region, the dependence of the space charge region width on the temperature can affect the linearity of temperature response curve of sensor, it is desirable to increase the doping rate of the base region to weaken this effect, or it is necessary to use p-n junction.

1 Introduction

Temperature sensors, which are designed to convert the measured temperature value into an electrical signal, are widely used in various fields today and the demand for them is increasing gradually.

In general, temperature sensors can be used as a stand-alone component for temperature measurement or as a component to compensate for its temperature dependence as part of a complex system whose characteristics depend on temperature.

In mass production conditions, the productions of temperature sensors with repeatable and stable parameters are important with reducing the cost of testing and calibrating temperature sensors, and at the same time significantly decreasing production costs.

In this regard, p-n junction semiconductor temperature sensors, which are capable of efficient production using serial production technologies and integrated circuits, are superior to all other devices.

Besides, p-n junction semiconductor temperature sensors have a linear relationship over a wide temperature range (as far as 600K [1, 2]). In p-n junction semiconductor temperature sensors, including in semiconductor diodes [3] and in transistors [4], the temperature is measured by recording the temperature dependence of the voltage drop across the p-n junction biased in the forward direction through which the stabilized DC current flows. The main advantages of them are relatively high linearity of volt-temperature curve, high response to change of temperature, small size and low cost.

The disadvantages of these temperature sensors are relatively high consumption and requirement of a stabilized current source with a small drift in order to ensure high accuracy.

The power consumed by the temperature sensor can be reduced by using p-n junction semiconductor diodes biased in reverse direction to measure the temperature.

In particular, in [5], a reverse current is taken as a temperature measurement parameter and a temperature sensor operating in the reverse direction is suggested. The drawbacks of such a temperature sensor are: the nonlinearity of the temperature response curve, the relatively narrow range of temperature sensitivity and the dependence of the accuracy on the stability of the external power supply. In [6], a diode temperature sensor is suggested which operates in reverse voltage and based on the temperature dependence of the charge and discharge processes of the barrier capacitance of p-n-junction, in which the discharge rate of the diode’s barrier capacitance is used as a temperature measurement and is determined by direct or indirect measurement parameter of the reverse current. Another low-power temperature sensor based on a p-n junction semiconductor diode temperature sensor which is capable of biasing in the reverse direction is presented in [7]. The device consists of a temperature-sensitive diode based on a p-n junction connected in the reverse direction and consists of a voltage source connected to the cathode and anode electrodes. This device includes the fact that the p-n junction connected in the reverse direction has a barrier capacity and its value depends on a certain extent on the temperature that can be used to measure the temperature. An example of the disadvantage of these temperature sensors is that they require a complex signal processing system, which leads to increase in power consumption, and the measurement accuracy depends on the source stability and the independence of the reference capacitance value.

Therefore, for the first time, new diode temperature sensor has been proposed in which the voltage of full depletion of the base area is used as a temperature measurement parameter, which eliminates the need for a stabilized power supply that allows reducing power consumption and ensuring high measurement accuracy.

Thus, it can be seen from the above that while the temperature dependence of the built-in potential in p-n junction temperature sensors biased in forward direction is important, in p-n junction temperature sensors biased in reverse direction it is necessary to study the temperature dependence of width of space charge region. For this case, as well as for homogeneous doped and linear doped cases, the temperature dependence of built-in potential and width of space charge region were studied.

2 Methods

Firstly, for the equilibrium state, for a situation where no external voltage is applied, the current-transport processes in the p-n junction are considered. Therefore:

$$I_p(x) = q\left[-\mu_p p(x)E(x) + D_p \frac{dp(x)}{dx}\right] = 0 \quad (1)$$

From here:

$$\frac{\mu_p}{D_p}E(x) = \frac{1}{p(x)}\frac{dp(x)}{dx} \quad (2)$$

Considering$E(x) = -\frac{dV(x)}{dx}$and the Einstein equation $\left(\frac{\mu_p}{D_p} = \frac{q}{kT}\right)$, (3)

From here:

$$-\frac{q}{kT}\int_{V_p(W_p)}^{V_n(W_n)} dV = \int_{P_p(W_p)}^{P_n(W_n)} \frac{dp}{p} \quad (4)$$

Solving the integrals in Equation (4), the following is obtained:

$$-\frac{q}{kT}\left[V_n(W_n) - V_P(W_p)\right] = ln\frac{P_n(W_n)}{P_p(W_p)} \quad (5)$$

Consequently, taking into account hat $\mathrm{U_{bi}} = \mathrm{V_n(W_n) - V_p(W_P)}$, for the built-in potential the following is determined:

$$U_{\mathrm{bi}} = \frac{kT}{q} ln\frac{P_p(W_p)}{P_n(W_n)} \quad (6)$$

Similarly, since there is no electron current, it is possible to determine the following for the built-in potential:

$$U_{\mathrm{bi}} = \frac{kT}{q} ln\frac{n_n(W_n)}{n_p(W_p)} \quad (7)$$

Given that the Equation (6) and Equation (7) are mutually equivalent and $p_n n_n = p_p n_p = n_i^2$, the following general equation for the built-in potential is obtained:

$$U_{\mathrm{bi}} = \frac{kT}{q} ln\frac{N_A(W_p)N_D(W_n)}{n_i^2} \quad (8)$$

The condition of electro neutrality gives the following equation:

$$N_a W_p = \int_0^{W_n} N_D(x)dx \quad (9)$$

For the corresponding regions of the structure, the Poisson equation can be written as follows:

$$\frac{d^2V(x)}{dx^2} = \frac{q}{\varepsilon}N_a, \quad -W_p < x < 0 \quad (10)$$

$$\frac{d^2V(x)}{dx^2} = -\frac{q}{\varepsilon}N_D(x), \qquad 0 < x < W_n \quad (11)$$

from here, it is possible to define the following equation for the p-type region:

$$E(x) = -\frac{dV(x)}{dx} = -\frac{q}{\varepsilon\varepsilon_0} N_a x - Const \qquad (12)$$

From this, in order to determine the integral constant, we use $E\left(x = -W_p\right) = 0$ and obtain:

$$E\left(x = -W_p\right) = \frac{q}{\varepsilon\varepsilon_0} N_a W_p - Const = 0$$

$$Const = \frac{q}{\varepsilon\varepsilon_0} N_a W_p \qquad (13)$$

Thus:

$$E(x) = -\frac{q}{\varepsilon\varepsilon_0} N_a x - \frac{q}{\varepsilon} N_a W_p \qquad (14)$$

By integrating the Equation (14) again, it is possible to determine the distribution of the potential along the x-axis for the p-type region:

$$V(x) = \frac{qN_a x^2}{2\varepsilon\varepsilon_0} + \frac{qN_A W_p x}{\varepsilon\varepsilon_0} + \frac{qN_A W_p^2}{2\varepsilon\varepsilon_0} + V_p\left(-W_p\right) \qquad (15)$$

In the same way, for n-type region it is possible to obtain:

$$E(x) = \frac{q}{\varepsilon\varepsilon_0} \int_0^x N_D(x)dx - \frac{q}{\varepsilon\varepsilon_0} \int_0^{W_n} N_D(x)dx \qquad (16)$$

$$V(x) = -\frac{q}{\varepsilon\varepsilon_0} \int_0^x dx \int_0^x N_D(x)dx + \frac{q}{\varepsilon\varepsilon_0} x \int_0^{W_n} N_D(x)dx - \frac{q}{\varepsilon\varepsilon_0} \int_0^{W_N} dx \int_0^x N_D(x)dx + V_n(W_n) \qquad (17)$$

Thus, from the Equation (8) to Equation (17), the following can be found:

$$V(0) - V\left(-W_p\right) = \frac{qN_A W_p^2}{2\varepsilon\varepsilon_0} \qquad (18)$$

$$V(W_n) - V(0) = -\frac{2q}{\varepsilon\varepsilon_0} \int_0^{W_n} dx \int_0^x N_D(x)dx + \frac{q}{\varepsilon\varepsilon_0} W_n \int_0^{W_n} N_D(x)dx + \frac{q}{\varepsilon\varepsilon_0} \int_0^{W_n} dx \int_0^x N_D(x)dx = \\ -\frac{q}{\varepsilon\varepsilon_0} \int_0^{W_n} dx \int_0^x N_D(x)dx + \frac{q}{\varepsilon\varepsilon_0} W_n \int_0^{W_n} N_D(x)dx \qquad (19)$$

So, for the built-in potential, the following equation is obtained:

$$U_{\mathrm{bi}} = V(W_n) - V\left(-W_p\right) = -\frac{q}{\varepsilon\varepsilon_0} \int_0^{W_n} dx \int_0^x N_D(x)dx + \frac{q}{\varepsilon\varepsilon_0} W_n \int_0^{W_n} N_D(x)dx + \frac{qN_A W_p^2}{2\varepsilon\varepsilon_0} \qquad (20)$$

Using the condition of electroneutrality of the charge (Equation (9)), W_p can be altered by W_n:

$$W_p = \frac{1}{N_a} \int_0^{W_n} N_D x\, dx \qquad (21)$$

Considering the Equation (21), it is possible to write Equation (20) as follows:

$$U_{\mathrm{bi}} = -\frac{q}{\varepsilon\varepsilon_0} \int_0^{W_n} dx \int_0^x N_D(x)dx + \frac{q}{\varepsilon\varepsilon_0} W_n \int_0^{W_n} N_D(x)\, dx + \frac{q\left[\int_0^{W_n} N_D(x)dx\right]^2}{2\varepsilon\varepsilon_0 N_A} \qquad (22)$$

Thus, by solving equations (8) and (22) together, it is possible to determine $\mathrm{U_{bi}}$ and $\mathrm{W_n}$ for p-n-junctions with arbitrary distributions of impurities in the base region.

A Case Where the Distribution of Impurities in The Base Area is a Homogeneous**.** To study the distribution of potentials along the p-n junction, first consider the case where the base area has a homogeneous constant concentration, which is $\mathrm{N_D(x) = N_D}$.

For this case, the potential distribution across the n-type region $(0 < x < W_n)$can be written using (22) as follows:

$$V(x) = -\frac{q}{\varepsilon\varepsilon_0}\int_0^x dx\int_0^x N_D dx + \frac{q}{\varepsilon\varepsilon_0}x\int_0^{W_n} N_D dx - \frac{q}{\varepsilon\varepsilon_0}\int_0^{W_n} dx\int_0^x N_D dx + V_n(W_n) =$$
$$-\frac{q}{\varepsilon\varepsilon_0}N_D\int_0^X xdx + \frac{q}{\varepsilon\varepsilon_0}N_D x W_n - \frac{q}{\varepsilon\varepsilon_0}N_D\int_0^{W_n} xdx + V_n(W_n) = -\frac{qN_D x^2}{2\varepsilon\varepsilon_0} + \frac{qxN_D W_n}{\varepsilon\varepsilon_0} - \frac{qN_D W_n^2}{2\varepsilon\varepsilon_0} + V_n(W_n)$$
(23)

Similarly, the potential distribution across the p–type region $\left(-\mathrm{W_p} < \mathrm{x} < 0\right)$is given by:

$$V(x) = \frac{qN_a x^2}{2\varepsilon\varepsilon_0} + \frac{qN_a W_p x}{\varepsilon\varepsilon_0} + \frac{qN_a W_p^2}{2\varepsilon\varepsilon_0} + V\left(-W_p\right) \qquad (24$$

where: $\mathrm{W_n}$ and $W_p$are the width of the parts of space charge region in the n-type and p-type region of structure.

Using $U_{\mathrm{bi}} = V_n(W_n) - V\left(-W_p\right)$, the built-in potentials can be written in the following form:

$$U_{\mathrm{bi}} = -\frac{qN_D W_n^2}{2\varepsilon\varepsilon_0} + \frac{qN_D W_n^2}{\varepsilon\varepsilon_0} + \frac{qN_D^2 W_n^2}{2\varepsilon\varepsilon_0 N_a} = \frac{qN_d W_n^2}{2\varepsilon\varepsilon_0} + \frac{qN_D^2 W_n^2}{2\varepsilon\varepsilon_0 N_a} \qquad (25)$$

At the same time, given that $\mathrm{N_D W_n = N_A W_p}$ under the electroneutrality condition, the built-in potentials for the p–n junction can be summarized as follows:

$$U_{\mathrm{bi}} = \frac{qN_D W_n^2}{2\varepsilon\varepsilon_0} + \frac{qN_A W_p^2}{2\varepsilon\varepsilon_0} = \frac{q}{2\varepsilon\varepsilon_0}\left(N_D W_n^2 + N_{\mathrm{A}} W_p^2\right) = \frac{qN_D W_n}{2\varepsilon\varepsilon_0}\left(W_n + W_p\right) = \frac{qN_D W_n W_{p-n}}{2\varepsilon\varepsilon_0} \qquad (26)$$

It is also known that for the built-in potentials, the following equation can also be used:

$$\mathrm{U_{bi}} = \frac{\mathrm{kT}}{\mathrm{q}}\ln\frac{\mathrm{N_A N_D}}{\mathrm{n_i^2}} \qquad (27)$$

Using Equation (26) and Equation (27), $W_n$can be expressed as follows:

$$\mathrm{W_n} = \sqrt{\frac{2\varepsilon\varepsilon_0\mathrm{kT}}{\mathrm{q^2 N_D}}\ln\frac{\mathrm{N_A N_D}}{\mathrm{n_i^2}}} \qquad (28)$$

2.1 A Case Where The Concentration of Impurities in The Base Region is a Linear (With Constant Gradient) Variable.

Now consider the potential distribution across the p–n junction for a case where the base concentration is non-homogeneous and the impurity concentration varies with a known gradient (a), where $N_D(x) = N_{Do} + ax$. For this case, the potential distribution across the n-type region$(0 < x < W_n)$can be written using Equation (17) as follows:

$$V(x) = -\frac{q}{\varepsilon\varepsilon_0}\int_0^x dx \int_0^x (N_{D0} + ax)dx + \frac{q}{\varepsilon\varepsilon_0}\int_0^{W_n}(N_{D0} + ax)dx - \frac{q}{\varepsilon\varepsilon_0}\int_0^{W_n} dx \int_0^x (N_{D0} + ax)dx + V_n(W_n) = -\frac{q}{\varepsilon\varepsilon_0}\left(\frac{N_{D0}x^2}{2} + \frac{ax^3}{6}\right) + \frac{q}{\varepsilon\varepsilon_0}\left(N_{D0}W_n + \frac{aW_n^2}{2}\right) - \frac{q}{\varepsilon\varepsilon_0}\left(\frac{N_{D0}W_n^2}{2} + \frac{aW_n^3}{\pi}\right) + V_n(W_n) \quad (29)$$

Similarly, the potential distribution across the p-type region$\left(-\mathrm{W_p} < \mathrm{x} < 0\ \right)$ is given by:

$$V(x) = \frac{qN_a x^2}{2\varepsilon\varepsilon_0} + \frac{qN_a W_p x}{\varepsilon\varepsilon_0} + \frac{qN_a W_p^2}{2\varepsilon\varepsilon_0} + V(-W_p) \quad (30)$$

where, $\mathrm{W_n}$ and $W_p$are thewidth of the parts of space charge region in the n-type and p-type regions.

However, taking into account the equation $N_A = \left(N_{D0} + \frac{aW_N}{2}\right)\frac{W_n}{W_p}$under the condition of electroneutrality, the built-in potential for the p–n junction can be written in the following forms:

$$U_{\mathrm{bi}} = -\frac{q}{\varepsilon\varepsilon_0}\int_0^{W_n} dx \int_0^x (N_{D0} + ax)dx + \frac{q}{\varepsilon\varepsilon_0}W_n\int_0^{W_n}(N_{D0} + ax)dx + \frac{q}{2\varepsilon\varepsilon_0 N_A}\left[\int_0^{W_n}(N_{D0} + ax)dx\right]^2 = \frac{qN_{D0}}{2\varepsilon\varepsilon_0}W_n \cdot W_{p-n} + \frac{qaW_n^2}{\varepsilon\varepsilon_0}\left(\frac{W_n}{3} + \frac{W_p}{4}\right) \quad (31)$$

$$U_{\mathrm{bi}} = \frac{kT}{q} ln\frac{N_a \cdot (N_{D0} + aW_n)}{n_i^2} \quad (32)$$

Thus, by solving Equation (31) and Equation (32) together, it is possible to determine the built-in potential and the space charge region width for the cases where base region is doped by impurities with linear distributions.

3 Results and discussion

For samples with different levels of doping of the base region, the temperature dependence of the space charge region width of the p-n-junction is studied (Fig. 1). From these dependencies, we can see that with increasing temperature, the space charge region width of p-n-junction decreases, as well as the space charge region width decreases with temperature as the doping concentration of base region increases. It is well known that in conventional temperature sensors, when the main current transport mechanism is determined by generation-recombination processes in space charge region, the dependence of the space charge region width on the temperature can affect the linearity of temperature response curve of sensor, it is desirable to increase the doping rate of the base region to weaken this effect, or it is necessary to use p-i-n junction. In this case, the temperature sensitivity of the proposed temperature sensors with fully depleted base region does not depend on the space charge region width, and its temperature dependence does not matter at all.

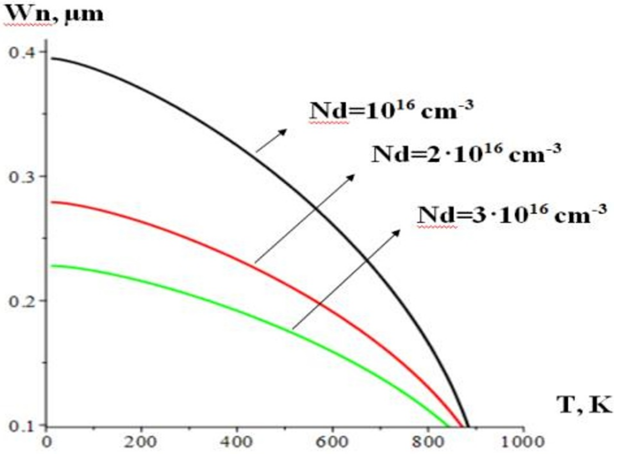


Fig. 1. Temperature dependence of the space charge region width of the p–n junction in homogeneous doped samples with different concentrations of impurities

The main parameter that determines the sensitivity of diode temperature sensors is the built-in potential of the p-n junction, and its temperature dependence has been studied (Fig. 2). From these dependencies, it can be seen that an increase in the doping level of the base region leads to a decrease in sensitivity, but an increase in the measuring range, while a decrease in the doping level of the base region leads to an increase in sensitivity and a decrease in the measuring range.

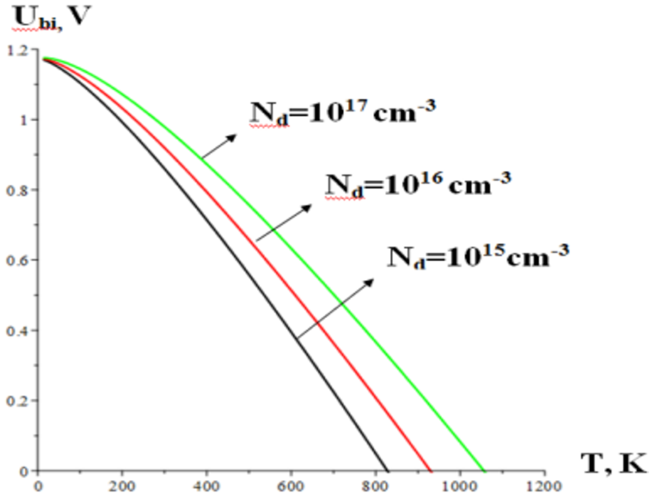


Fig. 2. Temperature dependence of the built-in potential of p–n junction in homogeneous doped samples with different concentrations of impurities

For the above-mentioned cases, the potential distribution in p-n junction is studied for cases where temperature is variable and the doping level of the base region is constant (Fig. 3), and for cases where temperature is constant and the doping level of the base region is variable (Fig. 4), as well as in cases where the external voltage was set (Fig. 5).

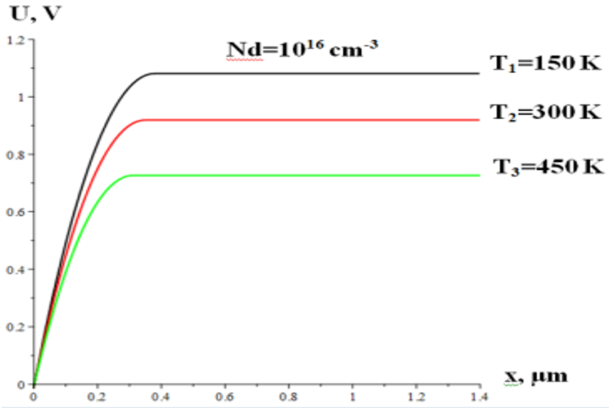


Fig. 3. Potential distribution along the p-n-junction at different temperatures for a case where the base region is doped by $10^{16}cm^{-3}$

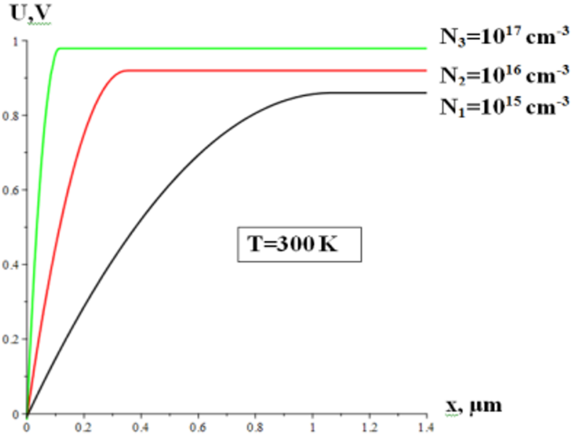


Fig. 4. Potential distribution along the p-n-junction at a temperature of 300 K for different levels of doping

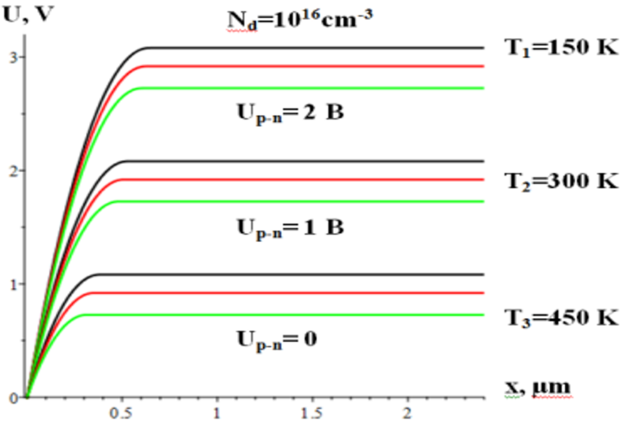
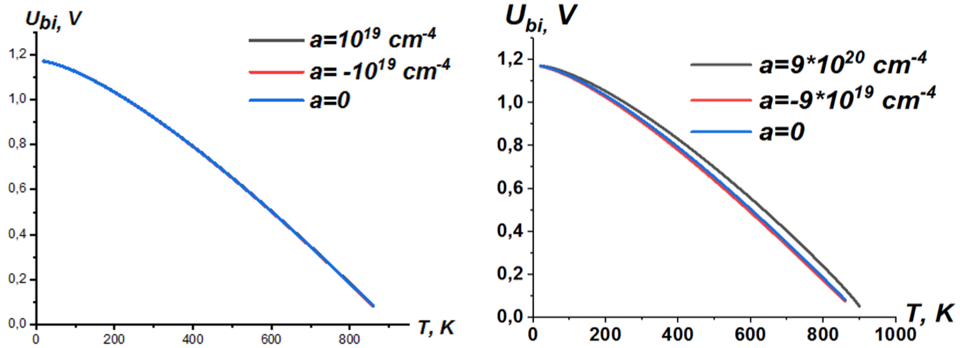


Fig. 5. The potential distribution across the p–n junction at different temperatures for cases where an external voltage is applied to the p–n junction

The temperature dependence of the built-in potential for p-n junctions with positive and negative gradients is studied (Fig. 6-a and 6-b). In this study, a decrease in temperature sensitivity is observed at positive values of the gradient and an increase at negative values.



a *b*

Fig. 6. Dependence of the built-in potential of p-n junctions on temperature for cases where the base concentration is non-homogeneous and the impurity concentration varies with a known gradient: a– $\pm10^{19}$cm^{-4}, b– $+9\cdot10^{20}$cm^{-4}, $-9\cdot10^{19}$ cm^{-4}

4 Conclusions

As noted above, the width of the space charge region of a p–n junction with a positive and negative impurity gradient in the base region depends on temperature (Fig. 7). A small change in the width of the space charge region is observed at large values of the gradient. Figure 8 considers the temperature dependence of the built-in potential of a p–n junction with a positive impurity gradient in the base region showing that the temperature sensitivity increases with decreasing gradient.

On fig. 9, contrary to fig 7, it does not matter when the width of the space charge region of p–n junction with a positive gradient is related to temperature. Since with a significant increase in temperature, it can be seen that the width of the space charge region of the p–n junction is practically stable.

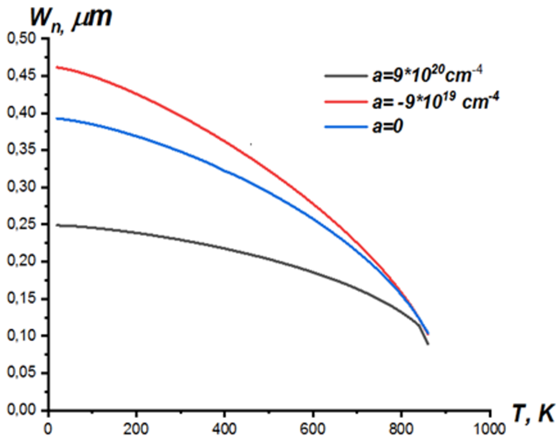


Fig. 7. Temperature dependence of the space charge region width of the p–n junction with positive and negative gradients of impurities in base region

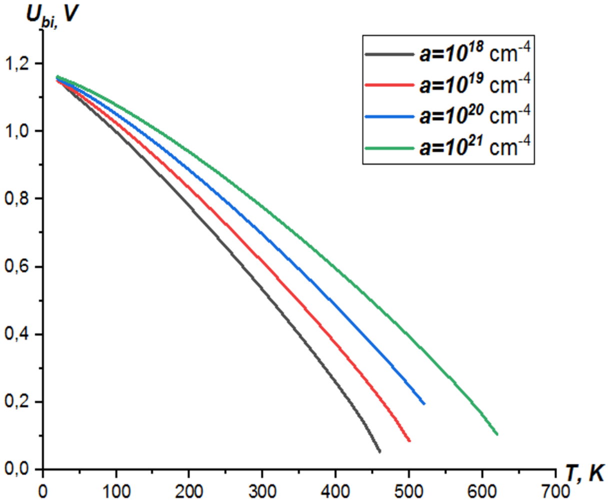


Fig. 8. Temperature dependence of the built-in potential of p-n junction with a various positive gradient of impurities in base region

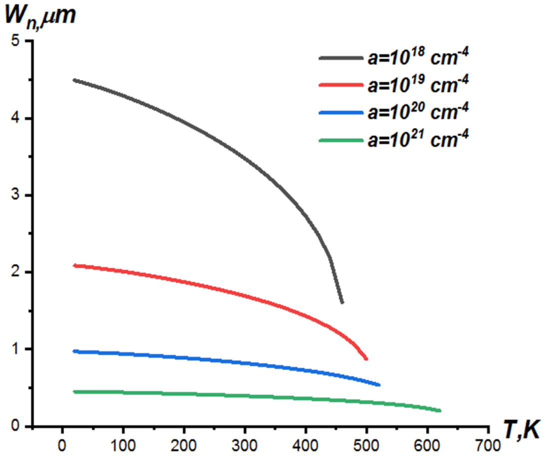


Fig. 9. Temperature dependence of the space charge region width of the p-n junction with a various positive gradient of impurities in base region

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