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TEMPERATURE RESPONSE CURVE OF SILICON DIODE TEMPERATURE SENSORS

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In this paper the results of the development of a semi-analytical model of the temperature response curve of silicon temperature diode sensors for the case of an arbitrary current transport mechanism, and a physical model that allows for high-precision determination of the temperature response curve for the case of diffusion-dominated current transport are presented. The results obtained using calculations based on this model were compared with experimental data, which showed their correspondence over the entire temperature range.
Keywords: *Diode temperature sensor; Temperature response curve; Silicon; $p-n$ junction; Saturation Current; Built-in potential*
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INTRODUCTION

Currently, temperature sensors are effectively used in various fields of technology, such as personal computers, mobile phones, vehicles, medical devices, industrial installations, power plants, and many others. In recent years, with the widespread adoption of concepts such as the "Internet of Things" and "smart technologies," various sensors, including temperature sensors, have been utilized even more actively [1]-[6]. Additionally, temperature sensors are also used as a key component of other types of sensors, such as pressure sensors, humidity sensors, mass flow gas sensors, bolometers, and many others [7]-[9].

To meet the new demands arising from all these applications, research is being conducted on the development of new temperature sensors based on various principles and made from different materials [10]-[16]. However, in order to take temperature sensor technology to the next level and establish large-scale production, it is necessary to study the impact of technological and structural parameters on their working principles. In other words, it is essential to answer the question of how sensitive sensor parameters are to processes at each stage of their manufacturing technology. The most effective way to achieve this is through modeling.

First and foremost, for the correct interpretation of the sensor's working principle, it is crucial to create a model that closely reflects reality. That is, such a model should not require precise data on material properties but should accurately reflect the primary physical characteristics of the sensor. During the design phase, it is more important to correctly describe how relative changes in input variables affect the sensor's operation than to precisely calculate absolute values.

Thus, the main objective of this work is to develop an optimal physical model for silicon diode temperature sensors.

RESEARCH METHODOLOGY

In this section, a physical model of silicon diode temperature sensors is proposed, allowing the determination of the temperature dependence of sensitivity for any current transport mechanism through the sensor.

As is well known, the process of current flow in diodes based on a $p-n$ junction can generally be expressed as follows:

$$I = I_s\left[exp\left(\frac{qV}{nkT}\right)-1\right], \tag{1}$$

where: I_S is the saturation current, q is the charge of an electron, V is the voltage applied to the diode's $p-n$ junction, k is Boltzmann's constant, T is the absolute temperature, and n is the ideality factor.

We introduce the following notation:

$$I_S^* = I_s exp\left(\frac{qV_k}{nkT}\right), \tag{2}$$

where: V_k is the built-in potential.

Considering equation (2), equation (1) can be rewritten as:

$$I = I_S^*\left\{exp\left(-\frac{q(V_k-V)}{kT}\right) - exp\left(-\frac{qV_k}{kT}\right)\right\} \tag{3}$$

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At room temperature, $V_k \gg \frac{kT}{q}$, since $V_k \sim 0.6 \div 0.8\ V$ and $\frac{kT}{q} \approx 0.026$ V, so the second term in equation (3) can be neglected. Under forward bias and with the voltage equal to V_k, the first term inside the brackets in equation (3) will be equal to 1, and the current through the diode will be I_S^*. Thus, the physical meaning of I_S^* is the saturation current under forward bias, while I_s represents the saturation current under reverse bias. These cases are graphically illustrated in Fig. 1, showing the dynamics of charge carrier movement in the $p-n$ junction.

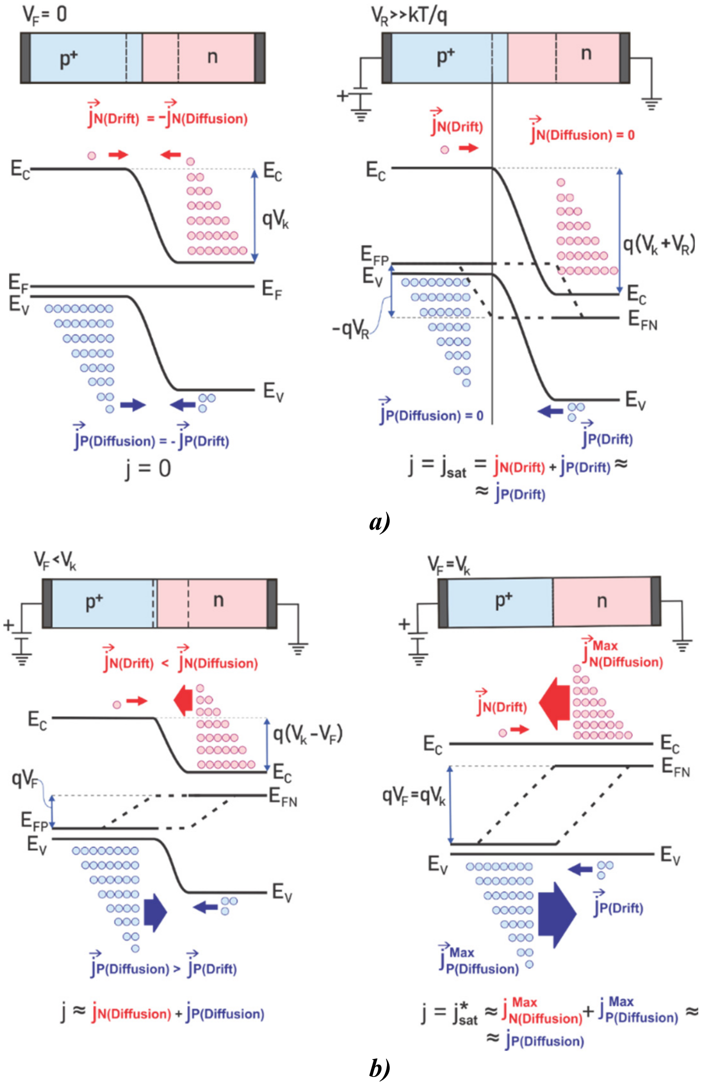

Figure 1. Dynamics of charge carrier movement in a $p-n$ junction:
a) drift and diffusion currents under reverse bias, and *b)* forward bias

From Figure 1a, under reverse bias, the electron concentration in the p –region is equal to n_i^2/N_A, where N_A is the acceptor concentration, which, in the first approximation, does not depend on temperature, while n_i (the intrinsic carrier concentration) is temperature-dependent. As the temperature increases, the concentration of minority charge carriers rises, indicating that the reverse saturation current I_S depends on temperature. From Fig. 1b, under forward bias, the electron concentration in the n –region depends on the doping level N_D and does not change with temperature. Therefore, it can be concluded that I_S^*, in the first approximation, is temperature-independent for any current transport mechanism.

Thus, I_S^* defines the saturation current under forward bias and does not depend on temperature, while I_S is the saturation current under reverse bias and is highly temperature-dependent.

From equation (1), the voltage across the $p-n$ junction can be determined as:

$$V = V_k - \frac{nkT}{q} ln\frac{I_S^*}{I} + \frac{nkT}{q} ln\left(1 + \frac{I_S}{I}\right) \quad (4)$$

To eliminate the term I_S^*, which depends on technological parameters, we can use the voltage $V(T_0)$ determined at a reference temperature T_0:

$$V(T_0) = V_k(T_0) - \frac{nkT_0}{q} ln\frac{I_S^*}{I} + \frac{nkT_0}{q} ln\left(1 + \frac{I_S(T_0)}{I}\right) \quad (5)$$

Substituting the term $ln\frac{I_S^*}{I}$, determined from equation (5), into equation (4), we can derive the following equation:

$$V(T) = V_k(T) - \frac{T}{T_0}\left(V_k(T_0) - V(T_0; I)\right) + \frac{nkT}{q} ln\left(\frac{I+I_S(T)}{I+I_S(T_0)}\right) \quad (6)$$

This expression, being a semi-empirical model, allows for the determination of the temperature response curve of diode sensors for any current transport mechanism.

To construct a complete analytical model in this work, we consider the diffusion mechanism ($n = 1$), which is typically the dominant current transport mechanism in diode temperature sensors. It is known that for the diffusion mechanism, the saturation current I_s, the contact potential difference V_k, and the effective saturation current I_s^* are expressed as follows:

$$I_s = qAn_i^2\left(\frac{\left(\frac{kT}{q}\mu_p\right)}{L_pN_D} + \frac{\left(\frac{kT}{q}\mu_n\right)}{L_nN_A}\right) \quad (7)$$

$$V_k = \frac{E_g}{q} - \frac{kT}{q}\ln\left(\frac{N_VN_C}{N_AN_D}\right) \quad (8)$$

$$I_S^* = q\left(\frac{L_pN_A}{\tau_p} + \frac{L_nN_D}{\tau_n}\right) \quad (9)$$

Considering expressions (7)-(9), equation (4) can be represented as:

$$V(T) = \frac{E_g(T)}{q} - \frac{kT}{q}\ln\left(\frac{N_V(T)N_C(T)}{N_A(T)N_D(T)}\right) - \frac{kT}{q} ln\frac{q\left(\frac{L_p(T)N_A(T)}{\tau_p(T)} + \frac{L_n(T)N_D(T)}{\tau_n(T)}\right)}{I} + + \frac{kT}{q} ln\left(1 + \frac{qAn_i^2(T)}{I}\left(\frac{\left(\frac{kT}{q}\mu_p(T)\right)}{L_p(T)N_D(T)} + \frac{\left(\frac{kT}{q}\mu_n(T)\right)}{L_n(T)N_A(T)}\right)\right) \quad (10)$$

From this expression, it is clear that the voltage-temperature dependence in a forward-biased diode is determined by many variables. In particular, the primary temperature-dependent parameters are the lifetime of minority carriers τ, carrier mobility μ, and the bandgap E_g. Typically, in the first approximation, the temperature dependence of τ, μ and E_g is considered negligible, and only the temperature dependence of the intrinsic carrier concentration n_i in semiconductors is considered [17]-[19].

In this work, we aim to develop an analytical model of diode temperature sensors that considers the temperature dependence of all physical quantities (n_i, τ, μ, E_g, N_b). To achieve this, we used models from studies [20], [21] to determine carrier mobility and lifetime. It is known that in this model, the lifetime changes due to additional deep levels are not considered, and for such cases, the lifetime is assumed to be independent of or weakly dependent on temperature. For the temperature and doping dependence of the bandgap width, we used the model from study [22]. The proposed model also considers the temperature dependence of the ionized impurity concentration.

RESULTS AND DISCUSSION

This section presents the calculations performed based on the proposed model, their comparison with experimental results, and general conclusions. Figure 2 shows a comparison of the voltage dependence on temperature, calculated using the developed analytical model, with experimental data. From the figure, it can be seen that there is good agreement between the experimental data and the analytical calculations across almost the entire temperature range. However, it should be noted that this analytical model is applicable only when the diffusion mechanism of current transport is dominant. In cases where the experimental results do not align with the analytical model's predictions, it is recommended to use a semi-empirical model based on formula (5).

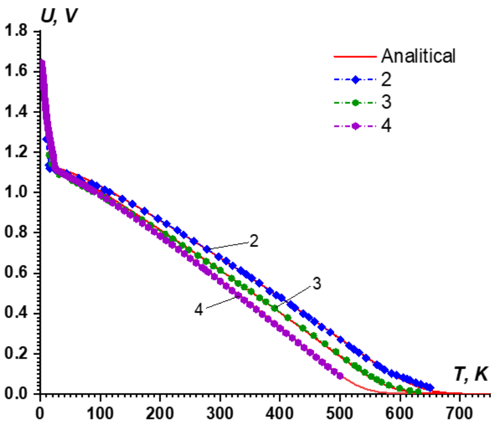

Figure 2. Temperature response curves for silicon diodes: 1 – analytical model (9); experimental data: 2, 3 – [23], 4 – [24].

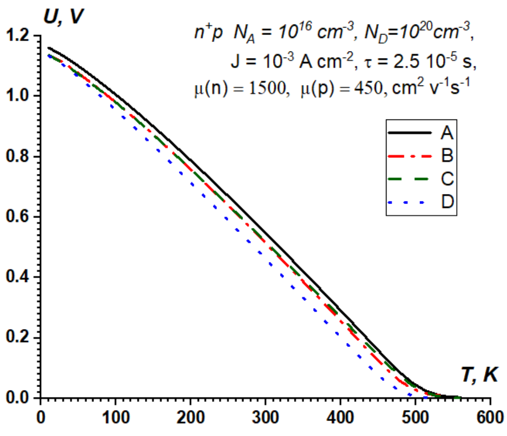

Figure 3. Temperature response curves for *Cases A, B, C,* and *D*.

Thus, using the analytical model that describes the temperature dependence of the voltage across a forward-biased diode, calculations were performed for the following cases: when only the temperature dependence of n_i, was considered, while the temperature dependence of the parameters N_b, τ, μ, and E_g was not considered (*Case A*); when the temperature dependences of n_i, N_b and E_g were considered, but the temperature dependences of τ and μ were not (*Case B*); when the temperature dependences of n_i, N_b, E_g and μ, were considered, but the temperature dependence of τ was not (*Case C*); and when the temperature dependences of all parameters were considered (*Case D*) (Figure 3).

Figure 3 illustrates the differences between these cases, showing that ignoring parameters such as the concentration of partially ionized impurities, bandgap width, carrier mobility, and carrier lifetime is not always appropriate. Furthermore, it can be observed that in *Case D*, the temperature sensitivity curve is steeper compared to the other cases. This indicates higher temperature sensitivity for this case.

CONCLUSIONS

In this work, a semi-empirical model of the operation of a $p^+ - n$ diode was developed, showing the behavior of the structure without considering the ideality factor, i.e., assuming independence of the processes in the diode from current transport effects in the structure. Additionally, a complete model of a working diode was built, which considers the effects of incomplete impurity ionization, narrowing of the bandgap, total mobility of free carriers and lattice mobility, as well as the deviation of carrier lifetime depending on temperature. The consideration of the models mentioned above allowed for the graphical determination of the electro-physical and structural parameters in the form of temperature response curves.

Considering all parameters that play a crucial role in determining the diode's performance limits, the proposed complete model was studied based on four cases (*A, B, C, D*). Depending on the application areas, the optimal cases were identified. Determining the optimal variant by selecting materials and technological parameters during the production process is important for improving product quality and ensuring the reliability of manufacturing processes. The smaller the model error, the faster and more reliably the optimal variant can be determined and the correct operation of the diode evaluated.

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ХАРАКТЕРИСТИКА ТЕМПЕРАТУРНОГО ВІДГУКУ КРЕМНІЄВИХ ДІОДНИХ ДАТЧИКІВ ТЕМПЕРАТУРИ

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У цій роботі представлено результати розробки напіваналітичної моделі температурної відгукової характеристики кремнієвих діодних температурних датчиків для випадку довільного механізму перенесення струму, а також фізичної моделі, яка дозволяє з високою точністю визначати температурну відгукову характеристику для випадку дифузійно домінованого перенесення струму. Отримані результати, розраховані на основі цієї моделі, були порівняні з експериментальними даними, що показало їх відповідність у всьому діапазоні температур.

Ключові слова: *діодний температурний датчик; температурна характеристика відгуку; кремній; p-n перехід; струм насичення; вбудований потенціал*