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Accurate Temperature Measurement for Renewable Energy Applications: A Reverse Biased Silicon Diode Temperature Sensor Approach

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Abstract. A novel silicon diode temperature sensor (DTS) incorporating a fully depleted base region has been developed specifically for applications in renewable energy. The sensor employs the voltage across the fully depleted base as the principal parameter for temperature measurement. Upon application of a defined reverse bias (U_o), complete depletion of the base region of the silicon diode is achieved. This condition ensures that the measurement potential, derived from the increasing operational voltage, remains stable and varies solely in response to changes in temperature. Comprehensive characterization of the temperature response curve (TRC) from 93 K to 300 K revealed a high degree of linearity with a sensitivity of +2.26 mV/K. However, it is important to clarify that DTS is capable of operating effectively over a much broader range from 70 K to 500 K. To our knowledge, this study documents the first occurrence of a linear TRC in a reverse-biased diode temperature sensor, which could significantly improve the operational efficiency and reliability of renewable energy systems under a range of harsh and fluctuating environmental conditions.

Key words. Silicon, diode temperature sensor, reverse-biased diode, renewable energy applications, temperature response curve, sensitivity.

1. Introduction

Accurate temperature measurement is becoming increasingly important in the context of developing renewable energy applications [1-3]. Recently, these applications have received even more incentives due to the widespread implementation of the "Internet of Things" (IoT) and smart technologies. The reliability and efficiency of these systems directly depend on the ability to precisely control and regulate temperature parameters, making diode temperature sensors (DTS) an integral part of these technologies. Traditional DTS with forward-biased p-n junctions have several disadvantages, such as high energy consumption and low accuracy, which can lead to reduced efficiency and reliability of renewable energy systems [4].

This paper proposes a new type of silicon DTS that uses a reverse-biased p-n junction with a fully depleted base region for temperature measurement. This approach significantly reduces energy consumption, which is crucial for devices operating in conditions with limited energy access or in remote locations. The key advantages of the proposed technology are the linearity of the temperature characteristic and the elimination of the self-heating problem, which ensure high measurement accuracy even over a wide range of operating temperatures typical for renewable energy sources. Furthermore, the proposed DTS shows low sensitivity to changes in bias parameters, enhancing the efficiency and reliability of systems based on renewable energy sources. This research offers solutions specifically adapted for the harsh and variable operating conditions often encountered in this field.

2. Methodology and Results

A. Design of proposed diode temperature sensor

The simplified design and fabrication steps for the proposed diode temperature sensor are outlined as follows (Figure 1):

Initially, a phosphorus-doped n-type epitaxial layer with a carrier concentration of $5\cdot10^{15}$ cm^{-3} is grown on a boron-doped p-type silicon substrate. This substrate, which has a carrier concentration of $3\cdot10^{16}$ cm^{-3}, is oriented on the (100) plane. The dimensions of the substrate and epitaxial layer are 230 ± 20 μm and 3.2 ± 0.1 μm, respectively.

In the second step, a highly doped p^{++}-type diffusion region is created at the peripheral branches of the structure through boron diffusion. Additional boron diffusion into selected areas of the n-type epitaxial layer leads to the formation of an intensely doped p^{+}-type region with a carrier concentration of $3\cdot10^{18}$ cm^{-3}. The depth and length of this p^{+}-type region are 2.0 ± 0.1 μm and 2.5 ± 0.1 μm, respectively, and it is electrically connected to the p-type substrate via a p^{++}-type diffusion region also located at the structure's periphery.

Subsequently, two heavily doped n^{++}-type regions, each 2.5 ± 0.1 μm thick, are formed through phosphorus diffusion, with a separation of 20 μm between them. The final step involves forming contacts to these regions by sputtering aluminum layers, each 0.5 μm thick.

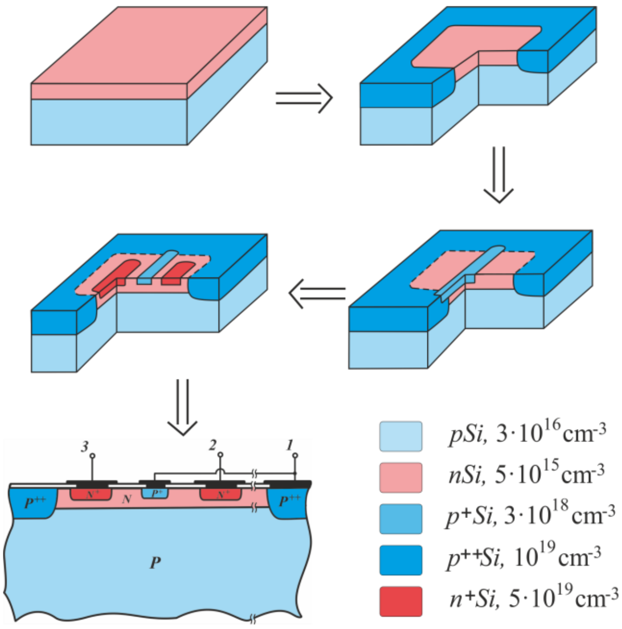

Fig. 1. Proposed diode temperature sensor and its fabrication steps.

The completed structure features two rectifying junctions: an n-p$^+$ junction and a p-n junction. These junctions, with the p$^+$-type region (top emitter) being short-circuited to the p-type region (bottom emitter), are configured in parallel. The top junction is characterized by a linearly graded profile, whereas the bottom junction is abrupt. The total die size is 0.045 cm x 0.045 cm, with the bottom junction covering an area of 2.36×10^{-4} cm^2 and the top one 0.2×10^{-4} cm^2.

B. Results and Discussion

Figure 2a illustrates the typical relationship between the measuring potential (U_{13}), taken from pins 1 and 3, and the reverse biasing voltage (U_{12}) applied from an external source to pins 1 and 2, as observed in experimental diodes. Initially, at low voltages, the measuring potential equates to the reverse biasing voltage. However, when the voltages exceed the critical reverse biasing voltage U_o, the measuring potential stabilizes at a value that remains essentially unchanged unless there is a corresponding change in temperature.

The dynamics of this behavior are elucidated by examining the changes in the depletion regions within the n-p$^+$ and p-n junctions of the device, depicted through structural diagrams from Figures 2b to 2e at various bias voltages:

$U_{bias} = 0$: Initially, in the absence of any bias voltage (Figure 2b), the structure maintains a quasi-neutral base region of a certain length.

$0 < U_{bias} < U_o$: As the reverse bias voltage increases (Figure 2c), the quasi-neutral base region's length decreases, primarily due to the expansion of the depletion region at the n-p$^+$ junction. Nevertheless, it remains sufficient to maintain electrical continuity between pins 2 and 3 through the n$^+$-n-n$^+$-junctions, resulting in the measuring potential (U_{13}) equating to the bias voltage (U_{12}), as indicated in the linear growth section (designated as "c") in Figure 2a.

$U_{bias} = U_o$: Upon reaching the voltage U_o, the depletion regions of both n-p$^+$ and p-n junctions converge, completely depleting the quasi-neutral base region, and disconnecting pins 2 and 3 (Figure 2d).

$U_{bias} > U_o$: At reverse bias voltages exceeding the depletion voltage U_o of the base region (Figure 2e), the depletion regions extend only towards pin 2, leaving pins 2 and 3 disconnected. Consequently, the measuring potential, derived from pins 1 and 3, stabilizes at a constant value, represented in the saturation section of Figure 2a (designated as "e").

An increase in temperature reduces the initial widths of the depletion regions, thereby elevating the depletion voltage of the base region, which explains the temperature sensitivity observed in Figure 3a.

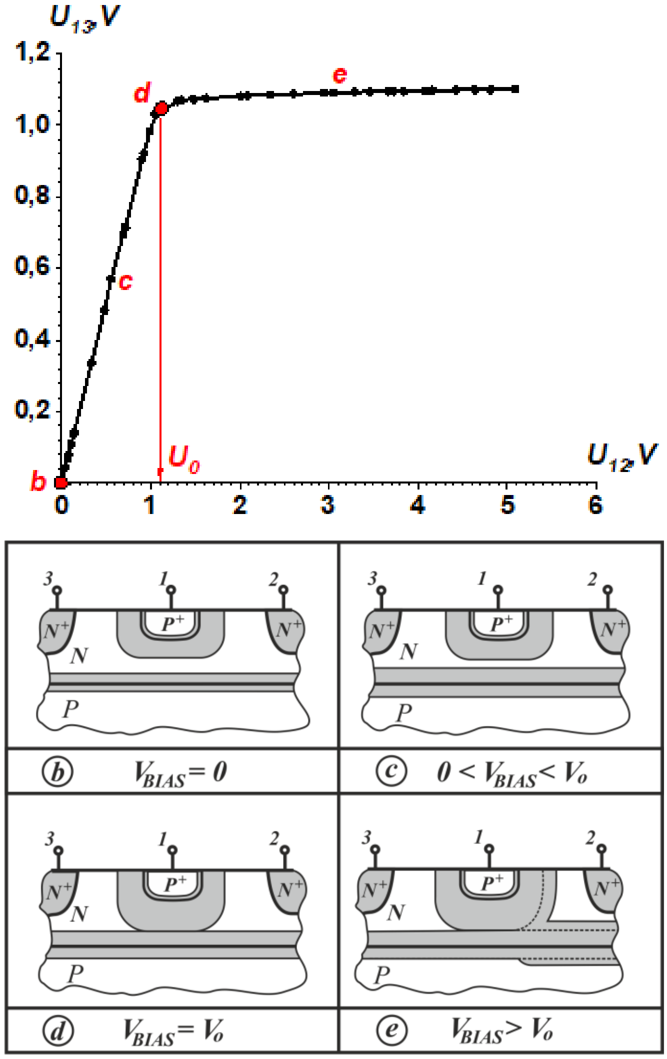

Fig. 2. Typical measured output voltage (U_{13}) versus bias voltage (U_{12}) characteristics of proposed diode temperature sensors (a) and the structural diagrams (b-e) of the device under study at various bias voltages

The temperature dependence of the depletion voltage of the base region (U_o) was investigated across a broad temperature range from 93 K to 300 K, as depicted in Figure 3b. In contrast to the behavior under forward bias, the voltage U_o exhibits a linear increase with temperature, closely adhering to the equation

$U_o=0.42349+0.00226 \cdot T$ with a coefficient of determination $R^2=0.99982$.

Consequently, the temperature sensitivity of the voltage U_o throughout this temperature range is determined to be +2.26 mV/K.

In the proposed diode temperature sensor featuring a depleted base region, the fully depleted voltage of the base region, measured between pins 1 and 3 (refer to Figure 1), serves as a temperature-dependent measurement parameter. Concurrently, an external voltage that biases the junction in the reverse direction is applied to pins 1 and 2. By solving the Poisson equation and considering the presence of two junctions within the structure (p-n and p^+-n junctions), the following expression for the depletion voltage of the base region is derived:

$$V_0 = \frac{qN_d L^2}{8\varepsilon\varepsilon_0} - \frac{V_{bi1}+V_{bi2}}{2} + \frac{\varepsilon\varepsilon_0 (V_{bi1}-V_{bi2})^2}{2qN_d L^2} =$$

$$= \frac{qN_d L^2}{8\varepsilon\varepsilon_0} - \frac{E_G}{q} + \frac{kT}{q} ln \frac{N_c N_v}{N_d \sqrt{N_{A1} N_{A2}}} + \frac{\varepsilon\varepsilon_0 (kT)^2}{2q^3 N_d L^2} ln^2 \frac{N_{A2}}{N_{A1}} \quad (1)$$

where L – technological thickness of base region; E_g – bandgap at temperature T; V_{bi1},V_{bi2} – built-in potentials of p-n- and p^+-n-junctions of structure; N_d – concentration of donors in base region; N_{A1}, N_{A2} – concentration of acceptors in p- и p^+-regions of structure, respectively.

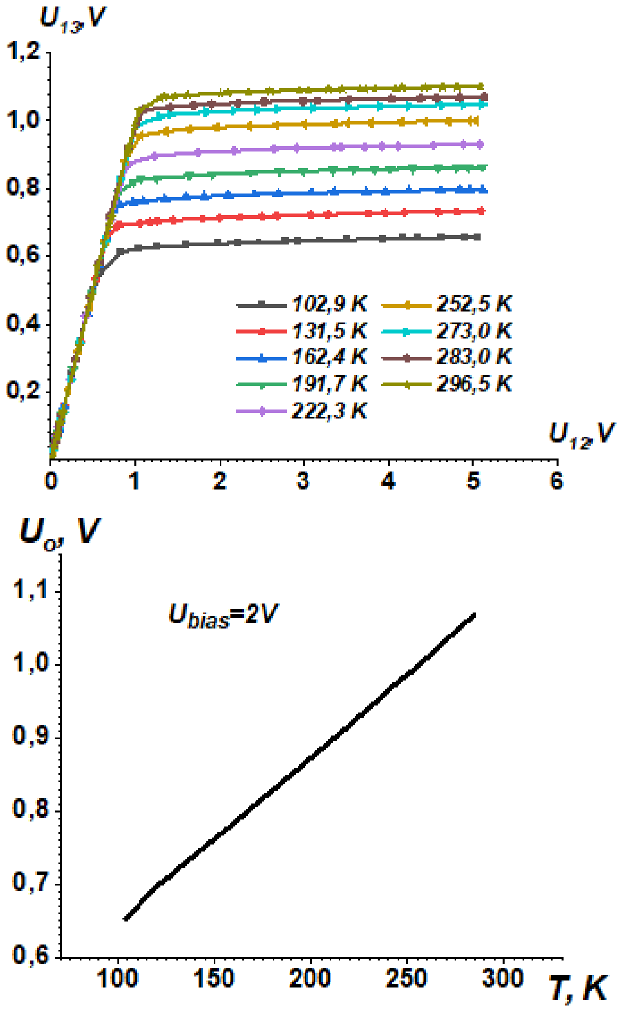

Fig. 3. Typical measured output voltage (U_{13}) versus bias voltage (U_{12}) characteristics at different temperatures (a) and the temperature response curve (TRC) of proposed diode temperature sensor

As indicated by equation (1), the depletion voltage of the base region, measured between pins 1 and 3, is constituted by several terms but solely depends on the material parameters of the structure. This independence from the power source parameters ensures that measurements are not influenced by the noise commonly present in the power circuit, thereby enhancing accuracy and linearity as depicted in Figure 3.

Unlike traditional diode temperature sensors where the temperature sensitivity typically exhibits a negative sign, the proposed sensor demonstrates positive temperature sensitivity, as corroborated by the experimental results shown in Figure 3b.

Moreover, the characteristic whereby the voltage decreases with decreasing temperature renders these sensors particularly suitable for cryogenic applications. This delineation of the sensor's attributes, grounded in empirical evidence, underscores its potential advantages over conventional diode temperature sensors.

As is evident from Equation (1), the depletion voltage of the base region is a sum of several thresholds and depends only on the material parameters of the structure. It is not susceptible to noise that may occur in the circuit with the power source of the structure. Unlike conventional diode temperature sensors, this provides high repeatability and measurement accuracy (Fig. 4).

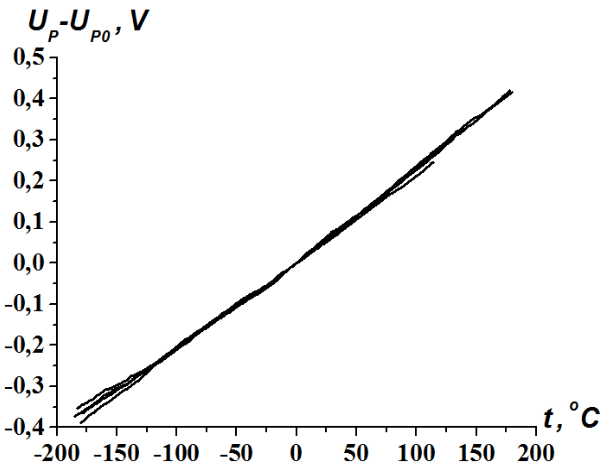

Fig. 4. The temperature response curves (TRCs) of 10 proposed diode temperature sensor samples

Research on the effects of radiation exposure on temperature sensors has shown that radiation significantly alters the current transport processes in experimental samples. Specifically, these processes change (the ideality factor increases from 1.04 to 1.5, indicating a shift from a diffusion to a recombination mechanism in the space charge region), and the diode's saturation current increases by several orders of magnitude. It should be noted that such changes in the current transport processes are critical for traditional temperature sensors, which operate based on recording the direct voltage drop at a constant forward current. Furthermore, radiation does not affect the distribution of ionized impurities in the space charge region, and therefore, its impact on the depletion voltage is practically negligible. Thus, preliminary studies confirm that the proposed temperature sensors is more resistant to electron radiation exposure compared to traditional ones.

3. Conclusion

In this study, we have developed a novel silicon diode temperature sensor (DTS) utilizing a fully depleted base region, specifically designed for applications in renewable energy systems. The sensor operates by employing the voltage across the fully depleted base as the primary parameter for temperature measurement. Upon applying a defined reverse bias (U_o), the base region of the silicon diode becomes completely depleted, ensuring that the measurement potential remains stable and varies exclusively in response to temperature changes. This approach significantly enhances the operational efficiency and reliability of renewable energy systems under fluctuating and harsh environmental conditions.

A. Key Findings

Temperature Response Curve (TRC): Extensive characterization of the TRC from 93 K to 300 K revealed a high degree of linearity. This linear behavior is unprecedented in reverse-biased diode temperature sensors, offering significant improvements in measurement accuracy and stability.
Stability and Sensitivity: The proposed DTS demonstrates excellent stability in the measurement potential once the base region is fully depleted. This stability ensures that the sensor is not affected by variations in bias parameters, enhancing its reliability in real-world applications. Additionally, the positive temperature sensitivity of +2.26 mV/K makes the sensor particularly suitable for cryogenic applications.
Energy Efficiency: The reverse-biased configuration of the sensor significantly reduces energy consumption, making it ideal for devices operating in environments with limited energy access or in remote locations. This feature is crucial for the efficient operation of renewable energy systems.

B. Implications and Future Work

The development of this new type of silicon DTS addresses several limitations of traditional forward-biased diode temperature sensors, such as high energy consumption and low accuracy. The linear temperature response curve and the elimination of self-heating issues ensure high measurement accuracy even over a wide range of operating temperatures typical for renewable energy sources.
Applications in Renewable Energy:
- Solar Power Systems: Ideal for monitoring temperatures in solar panels, our sensor optimizes efficiency and prevents equipment failures. It is particularly useful in concentrated solar power (CSP) systems for managing higher temperatures.
- Wind Turbines: The sensor's effectiveness at lower temperatures is advantageous for monitoring critical components, such as gearboxes and generators, in cold climates, thereby helping to prevent equipment failures.
- Geothermal Energy: With its high-temperature capabilities, our sensor is well-suited for geothermal energy production, enhancing both efficiency and safety.
- Micro Energy Harvesting for IoT Devices: The sensor is also applicable in small power generators used as energy sources for Internet of Things devices, providing reliable temperature monitoring to ensure operational efficiency and device safety.

Advantages for Renewable Energy Applications:
- Enhanced Durability: Demonstrates increased resistance to radiation effects, including neutron and electron irradiation, making it more reliable in harsh environments.
- Advanced Materials: Incorporates advanced materials like silicon carbide, broadening the operational temperature range and improving durability and reliability under harsh conditions.
- Ease of Integration and Cost Efficiency: Designed for seamless integration, our sensor can be easily adopted into existing systems, providing a cost-effective solution for widespread deployment in renewable energy applications.

Future work could focus on further optimizing the design for specific applications, such as integrating the sensor into existing renewable energy systems to enhance their performance. Additionally, exploring the potential of this technology in other fields, such as automotive and aerospace industries, where precise temperature measurement is critical, could provide valuable insights and applications.
In conclusion, the proposed diode temperature sensor offers a promising solution for accurate and reliable temperature measurement in renewable energy systems, contributing to the advancement of sustainable energy technologies.

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