



INVESTIGATION OF ELECTRICAL AND STRAIN-RESISTIVE PROPERTIES OF FILM-BASED SENSITIVE ELEMENTS FROM BISMUTH-ANTIMONY TELLURIDES

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Annotation This study is devoted to the investigation of the electrophysical and strain-sensitive properties of polycrystalline film-sensitive elements based on bismuth-antimony tellurides. The work examines the influence of deposition parameters, particularly the deposition rate, on the resistivity and strain-sensitivity coefficient of films grown on polyimide substrates.

The results show that increasing the deposition rate from 10 nm/s to 40 nm/s leads to a decrease in the resistivity of the films. Meanwhile, the strain-sensitivity coefficient demonstrates non-linear behavior, reaching a maximum at a deposition rate of 20 nm/s. The amplitude of this maximum is determined by the evaporation temperature, indicating the critical role of thermal and deposition conditions in shaping the film's properties.

The findings highlight the potential of bismuth-antimony telluride films as sensitive elements for thermoelectric and strain-sensitive applications. This study provides a foundation for optimizing the fabrication process to achieve reproducible and high-performance materials for use in energy-efficient technologies, strain sensors, and flexible electronic devices.

Keywords. film sensing elements, bismuth and antimony tellurides, strain gauges, strain gauge, thermal deposition, electrical conductivity, resistivity, gauge factor, substrate temperature, evaporation temperature, deposition rate

Introduction

The Bi-Sb-Te ternary compound with variable composition is widely recognized as one of the most promising materials for use in semiconductor film strain gauges, which serve as highly effective tools for studying the stress state of machine-building structures. The primary advantages of film strain gauges include their compact size, high strain sensitivity, and the ability to modify their mechanical and electrical properties across a wide range—capabilities that are not achievable with traditional metal resistors.

To date, the electrical and tensorial properties of film-sensitive elements based on the Bi-Sb-Te system with variable composition have been extensively studied. However, the findings are often contradictory and fail to provide a comprehensive understanding of the mechanisms underlying the exceptionally high strain sensitivity ($\sim 10^4$ and higher) observed in these films.

The conditions under which the sensitive layer is deposited, as well as the mechanisms of its growth on various substrates, play a critical role in determining the phase and chemical composition, microstructure, and, consequently, the structurally sensitive, electrophysical, and tensometric properties of the material. Therefore, further investigation into the influence of condensation parameters and substrate interactions is essential for optimizing the performance and understanding the fundamental properties of these film-sensitive elements.

Materials and Methods

The study of the electrical properties of semiconductor films based on antimony-bismuth tellurides is intricately linked to exploring their electronic and strain-sensitive characteristics. These properties are critical for understanding the behavior of semiconductor materials in advanced applications. A variety of methods were employed in this study, including measurements of electrical conductivity and thermoelectric power, as well as determining the optical properties—such as transparency, absorption, and refractive indices—of the films using spectroscopy

across the infrared (IR), visible, and ultraviolet (UV) spectral regions. Additionally, thermally stimulated conductivity measurements were performed to evaluate defect concentrations in the material and their impact on electrical conductivity.

The investigation of the electrophysical properties of antimony-bismuth telluride semiconductor films holds significant relevance for fields such as electronics, optoelectronics, and photovoltaics. The findings from these studies can guide the development of new materials and devices, while also optimizing existing technologies for improved performance and reliability.

The primary technique for producing film strain gauges involved the thermal deposition of semiconductor materials in a vacuum environment through a mask of predetermined dimensions onto a neutral dielectric substrate. Using this method, film strain-sensing elements composed of Bi, Te, Bi_2Te_3 , Sb_2Te_3 , and related compounds were fabricated. This approach ensures precise control over the film's composition and geometry.

When a polycrystalline film of antimony-bismuth telluride is subjected to mechanical stress, deformation of its crystal lattice occurs, leading to changes in atomic spacing. This alteration affects the electrical and strain-sensitive properties of the films, making them highly responsive to external mechanical influences. These characteristics are significantly influenced by factors such as:

- Composition of the evaporated and condensed molecular beams.
- Evaporation method and substrate temperature (T_s).
- Evaporation temperature (T_e) and deposition rate (v).
- Film thickness (h), heat treatment conditions, and other microscopic technological parameters.

Substrate temperature (T_s) was measured using a chromel-alumel thermocouple, and the evaporation process was monitored visually to ensure consistency. Film thickness, which ranged between 50 and 150 nm, was controlled by the evaporation time, while the deposition rate was determined by the evaporator

temperature. The high atomic number of the material minimized electron scattering from the substrate, enhancing measurement accuracy.

The electrical conductivity and strain sensitivity of the films were characterized using specific resistivity (ρ) and the strain gauge coefficient (K). These properties are particularly sensitive to deformation cycles, making it essential to evaluate the influence of deposition parameters (v , T_s) on ρ and K.

To simulate mechanical deformation, the test samples were affixed to an elastic beam and subjected to controlled bending. The deformation was applied using an adjustable eccentric mounted on a motor shaft, allowing precise strain transfer to the sample. The relative deformation reached up to $\varepsilon = 10^{-3}$, with multiple deformation cycles performed on the same sample to assess reproducibility.

The strain sensitivity coefficient (K) was calculated using the following formula:

$$K = \frac{\Delta R}{R \cdot \varepsilon}$$

where ΔR is the change in resistance, R is the initial resistance, and ε is the relative deformation. The accuracy of K determination was primarily affected by the measurement precision of relative deformation (ε) and resistance change ($\Delta R/R$). The maximum measurement error did not exceed 3%.

The described methodology offers a comprehensive approach to analyzing the strain-sensitive and electrical properties of antimony-bismuth telluride films. It enables a detailed understanding of how mechanical and technological factors influence the behavior of these materials, paving the way for their application in high-performance strain sensors, thermoelectric devices, and flexible electronics.

RESULT AND DISCUSSION

Figure 1 shows the results of studies on the effect of deposition rate v on the value of ρ and K of films grown on a polyimide substrate. These dependences show that with an increase in the deposition rate from 10 nm/s to 40 nm/s, the resistivity of the films decreases, and the value of the strain sensitivity coefficient passes

through a maximum at 20 nm/s, the amplitude of which is determined by the evaporation temperature (in this case, the deposition rate was changed by changing the evaporation temperature).

Note that a change in the mass of the initial sample, the temperature of the substrate, and the distance between the evaporator and the substrate at the same evaporation temperature led to a change in v , which affected the values of ρ and K .

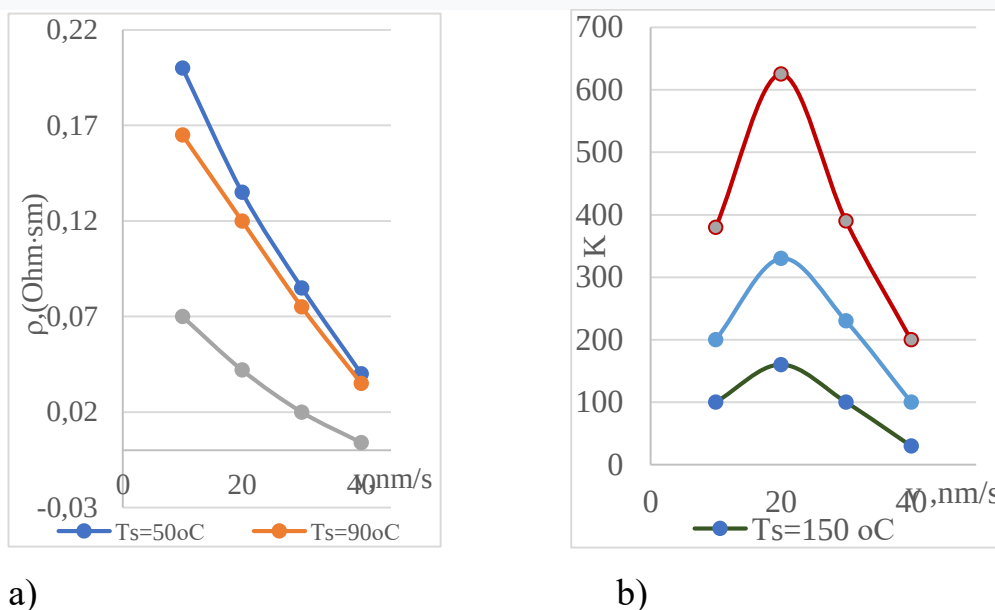


Fig.1. a) the dependence of resistivity and b) the strain gauge coefficient on the rate of deposition of the Bi-Sb-Te solid solution onto the polyimide substrate.

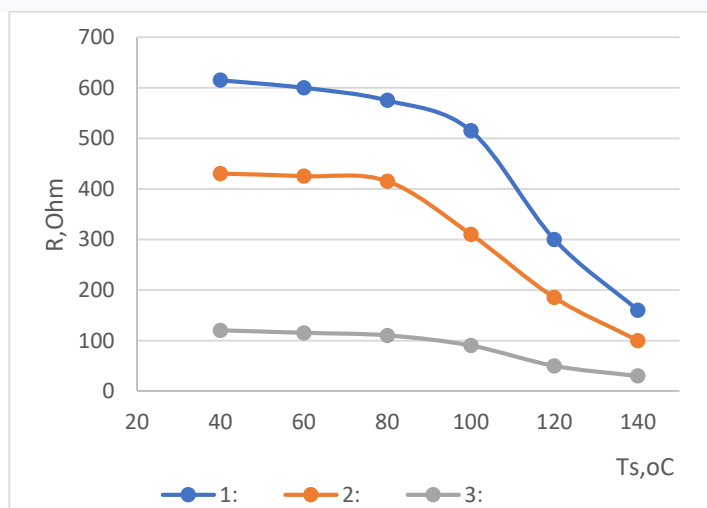


Fig. 2. Dependence of the resistance (curves 1-3) of the films on the substrate temperature T_s during deposition. Film sizes 8mm*1mm*6 microns. v : 10 nm/s (curve 1), 20 nm/s (curve 2) and 40 nm/s (curve 3).

Figure 2 shows the dependence of R for films 6 μm thick on T_s . It can be seen that at the same film thickness, its resistance sharply decreases at $T_s > 90^\circ\text{C}$. This decrease is accompanied by the appearance of a maximum at $T_s = 90 \dots 100^\circ\text{C}$ of independence $K(T_s)$.

CONCLUSION

The presented results show that the resistivity and strain sensitivity coefficient of the films obtained by evaporation of the Bi-Sb-Te solid solution depend on the film thickness, the substrate temperature during deposition, and the layer growth rate. By annealing the films after growth, their tensometric properties and parameter stability can be significantly improved. The optimal technological parameters for obtaining layers with high values of strain-electric properties have been found, which are as follows:

1. Deposition of a layer with a thickness of 5-6 μm at a deposition rate of 20 nm/s at a substrate temperature of $T_s = 90$.
2. Film annealing at 125 oC in air or in vacuum in tellurium vapor for 4-8 hours.

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