Study of temperature coefficient of resistance of n-InSb films on i-GaAs (100) substrate and produce temperature sensor of them

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Abstract. In present work, the explosive thermal evaporation was used to form n-InSb films on i-GaAs (100) substrates. The investigation results of crystal state, microstructure, phase and elemental composition, electrical properties of n-InSb films deposited at the substrate temperature of 420−480 °C are presented. It is shown that heteroepitaxial n-InSb films form in the deposition temperature of 420 °C. At a substrate temperature of 430–440 °C, the surface is inhomogeneous; precipitates oriented differently in the substrate plane are clearly observed. At a substrate temperature of 480 °C, the phase composition of the film is a superpositionof n-InSb and Inphases, and the SEM image of the sample shows that the sample is a i-GaAs substrate with InSb formations distributed over the surface. The resulting n-InSb films at a deposition temperature of 430°C have the best temperature coefficient of resistance (−1.25±0.02) $\%\cdot deg^{-1}$.Temperature sensor based on n-InSb-i-GaAs show performance in a wide temperature range (–80…+150 °C) and at liquid nitrogen temperature and can be used in the space industry and low-temperature electronics, as well as in the automotive and aircraft industries.

Key words:n-InSb-i-GaAs, vacuum deposition, crystal structure, electrical properties, temperature sensor.

Introduction

Indium antimonide (InSb) is a narrow-bandstraight-gap semiconductor of the $A^{III}B^{V}$ group with an energy gap of 0.18 eV at 300 K, which has a record high electron mobility. Due to its properties, InSb is widely used in the field of microelectronics. Based on InSb, highly sensitive photocells, Hall sensors, magnetoresistors and optical filters are manufactured. InSb is also used in infrared detectors, including thermal imaging (Balvanovich, 1981).

Methods of deposition of semiconductor films make it possible to give them various types of structural perfection, from polycrystalline to epitaxial structure, depending on the deposition conditions and the structure of the substrate. The first work on the preparation of InSb films on various types of substrates appeared in the mid-1950s. The research results of this period are presented, for example, in works (Francombe and Johnson, 1972; Gunther, 1967;Paparoditis, 1967). High-quality epitaxial InSb films on single-crystal substrates are formed by molecular beam epitaxy (Joyce et al, 1989;Zhang et al., 2004). Another way to form InSb films is the three-temperature method(Gulyaev and Shitnikov, 2015). In addition, InSb films are formed by electron beam evaporation (Ivanov and Smirnov, 2015; Rahul et al, 2011).

The deposition of InSb films on GaAs by explosive thermal evaporation makes it possible to achieve high values of the film deposition rate. However, the epitaxial growth of thin InSb films on GaAs during explosive thermal evaporation is a rather complicated process, depending on the substrate temperature, the temperature of the powder evaporator, the size of the powder, its purity, and the rate of powder supply to the evaporator. The substrate temperature is the most important parameter that determines the mechanism of condensation, the form of growth, and the degree of phase and structural homogeneity of thin films. At too low temperatures, the deposited atoms have low mobility, as a result, of which complete crystallization of the growing film does not occur. With an increase in the substrate temperature, the mobility of the elements increases, but a too high substrate temperature can lead to reverse evaporation of the deposited surfaces from the surface, which will change the stoichiometric composition of the film (Balvanovich, 1981; Oszwaldowskia et al., 2004; Taher, 2018).

Previously, the authors found heteroepitaxial InSb films are formedby the method of explosive thermal evaporation of n-InSb powder at the temperature of the i-GaAs (100) substrate in the range of 375−420 °C. Investigates of the electrical properties have shown that the formed heteroepitaxial n-InSb films on semi-insulating i-GaAs (100) make it possible to use them as highly sensitive miniature Hall sensors(Uglov et al., 2021).

At the same time, one of the possible areas of practical application of InSb films is also thermometry with temperature sensors. Temperature sensors are used in remote and centralized temperature measurement and control systems, electric heating devices, thermal control devices, etc.

Usually, pure metals are used for the manufacture of temperature sensors. However, the value of the temperature coefficient of resistance of the applied metal temperature sensors such as Pt, Au and Cu, which are used in high precision and stable temperature sensors, is a small value of 0.4 %·deg.$^{-1}$. Such temperature sensors are inconvenient to manufacture and hardly amenable to miniaturization (Balvanovich, 1981). Semiconductor materials have a higher temperature coefficient of resistance. The use of semiconductor materials improves measurement accuracy and allows the use of simpler secondary instruments. Semiconductor single crystals have a perfect structure, have a insignificantly number of defects, which ensures stable behavior of devices based on them. For the manufacture of semiconductor monocrystalline temperature sensors, germanium (Cohen et al., 1966), silicon (Ammer et al., 1979), their solid solutions, silicon carbide, and compounds of the $A^{III}B^{V}$ group are most often used. For example, temperature sensors for low temperature measurements were developed from gallium antimonide (Amirhanova, 1971) and gallium arsenide (Logvinenko et al., 1974). Compared to monocrystalline devices, thin-film devices have better surface-to-volume ratios for efficient thermal exchange with the environment. This is especially beneficial for the production of high-speed temperature sensors.

It is supposed that InSb films are a promising material for the manufacture of temperature sensors, since they are of great importance for the electron mobility near room temperature. This is the reason for the very large change in the electrical resistance of InSb films with increasing temperature (Balvanovich, 1981).

The aim of this work is to establish the regularities of changes in the electrical properties, particularly the temperature coefficient of resistance of n-InSb films deposited by explosive thermal evaporation on i-GaAs (100) substrates, depending on their phase and elemental composition, crystal structure and microstructure, which is determined by the deposition temperature.

Materials and experimental details

The n-InSb films are obtained by explosive thermal evaporation of high purity InSb powder onto (100) oriented i-GaAs substrates. The procedure of explosive thermal evaporation is following. The powdered material from the vibrating feeder device is continuously supplied onto the evaporator where it is heated to a temperature that allows instant evaporation of particles of material, followed by condensation on the substrate surface (Maissel and Glang, 1970).The carriers concentration of InSb powder is $n = 10^{15}$–10^{16} cm^{-3}. The films were deposited in vacuum 5×10^{-3} Pa. The temperature of the substrate holder with the i-GaAs plate was varied by means of a heater in the range from (420±2.5) up to (480±2.5) °C. The thickness of the films is about (2.00±0.05) μm.

Crystal state of the obtained films was investigated by the X-ray diffraction (XRD) analysis with CuK_{α} radiation using a Rigaku Ultima IV diffractometer.The microstructure and element composition of the deposited films were analyzed by means on a scanning electron microscope (SEM) LEO 1455 VP, including use energy dispersive X-ray analysis (EDX). The roughness of the film surface was estimated using a Solver P47 Proatomic force microscope.

The electrical properties of filmswere investigated using a four-contact method on rectangular samples (Kuchis, 1974). Hall measurements were performed in a magnetic field of (0.44±0.01) T. The electric current value was (10.0±0.1) mA. The estimated error in measuring the concentration and mobility of charge carriers does not exceed 7 %.The temperature coefficient of resistance was calculated according to(Macklen, 1983).

Result and discussions

According to XRD analysis at a substrate temperature of 420 °C, heteroepitaxial films are deposited on i-GaAs substrates with (100) orientation by explosive thermal evaporation of high-purity n-InSb powder (Uglov et al., 2021). The epitaxial growth is confirmed by the X-ray diffraction pattern, which shows the InSb (400) diffraction reflection of considerable intensity. The plane(400) shows complete dominance in all XRD patterns; however, with an increase in the substrate temperature, the intensity of this peak decreases and the appearance of additional InSb reflections from the (111), (220), (311) planes is observed. To quantify this effect, the texture coefficient (TC) for the 400 peak was calculatedas follows (Barret and Massalski, 1980):

$$TC_{hkl} = \frac{I_{hkl}/I_{0hkl}}{\frac{1}{N}\sum I_{hkl}/I_{0hkl}}$$

The intensity I_{hkl} is determined by normalizing to the maximum value. I_{0hkl} is the standard intensity for InSb powders indicated in the ICSD-PDF2 database. In our case, we take the intensity of reflections from planes with indices (400) as the maximum; the number of selected reflections is N=4. To determine the texture coefficient, the following reflections were chosen: 23.77° (111), 39.31° (220), 46.46° (311), and 56.78° (400). For randomly distributed powders the TC values for all peaks is 1; in the case of textured film, the TC of the preferential orientation increases reaching a maximum value of N only when no other peaks are present in the XRD pattern (Fanni et al., 2014).The results are presented in Table 1. Note that the phase composition of the films deposited at the temperature of 420−460 °C is an n-InSb compound. However, at the substrate temperature of 480 °C, the phase composition of the film is a superposition of the InSb and In phases. This indicates that antimony evaporates from the films at this temperature.

Table 1. Calculated texture coefficient for n-InSb films deposited at different substrate temperature

Температура осаждения, °C	TC_{400}
420	4
430	3.99
440	3.92
460	3.52
480	3.47

For a detailed study of the microstructure and elemental composition of n-InSb films, depending on the deposition temperature, the SEM was used. Fig. 1 displays scanning electron images of the surface of n-InSb films at a deposition temperature of 420−460 °C.

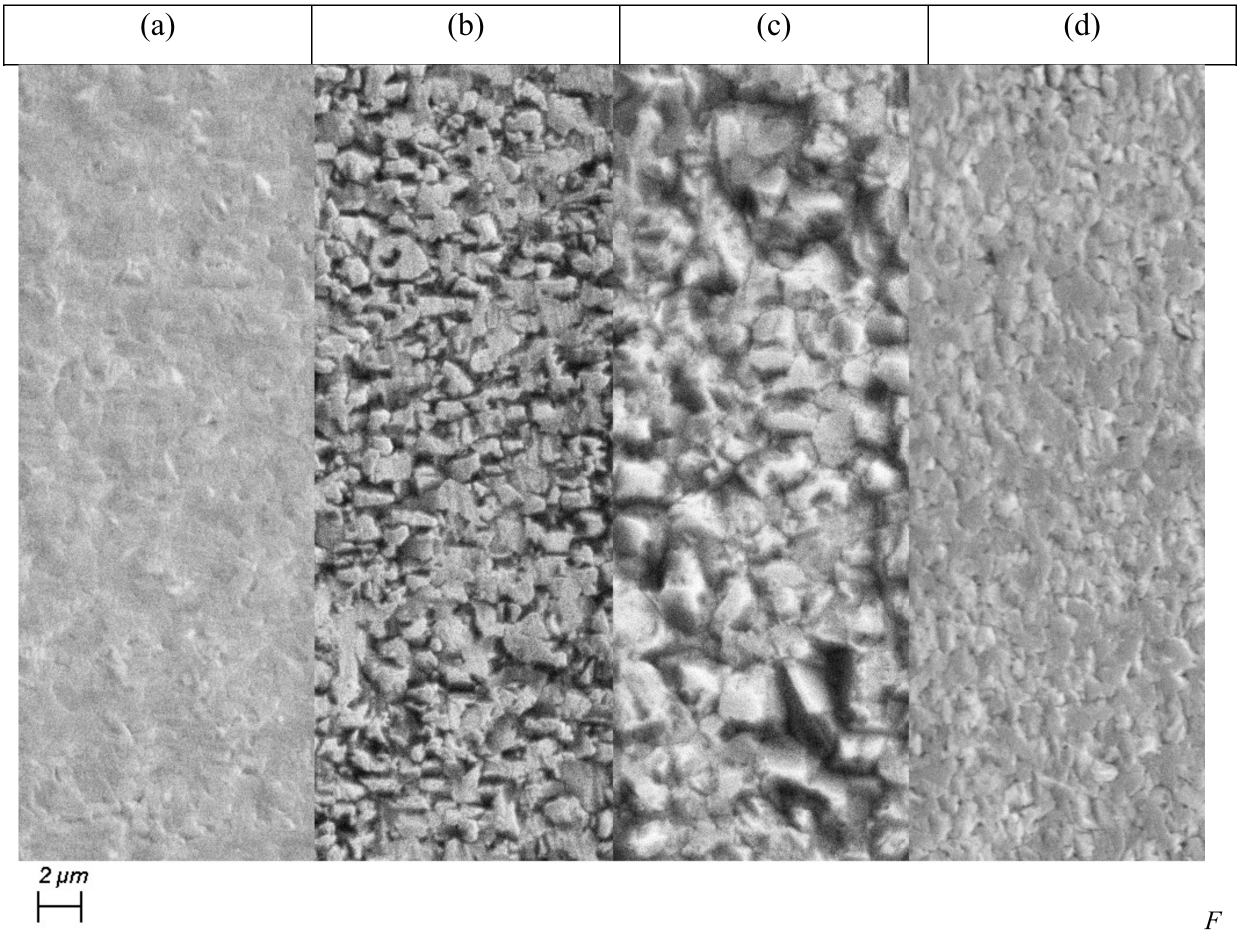


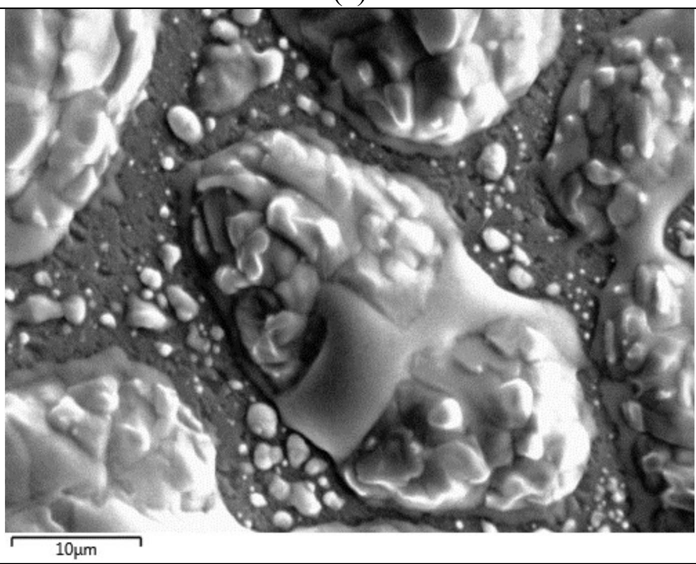
Figure 1. Scanning electronic images of the surface of n-InSb films obtained by explosive thermal evaporation at deposition temperatures: (a) 420 ° C, (b) 430 ° C, (c) 440 ° C, (d) 460 ° C

Scanning electron microscopy showed that at a deposition temperature of 420°C, the film surface is uniform (Fig. 1a). The surface roughness of the film deposited at the substrate temperature of 420 °C is R_a = 5.10 nm.The surface of films deposited at a substrate temperature of 430 and 440°C is inhomogeneous; precipitates oriented in different ways in the substrate plane are clearly observed. Theprecipitatessizeofthedepositedn-InSbfilmsincreaseswithanincreaseofthesubstratetemperaturefrom 430 °Cupto 440 °C. At the same time, the film roughness increases due to a change in the size of precipitates due to the merging of smaller precipitates (Taher, 2018). The surface roughness of the film deposited at the substrate temperature of 440 °C is R_a = 7.67 nm.With a further increase in the deposition temperature, the surface becomes smooth, and intergranular boundaries are clearly visible.

Comparison of XRD and SEM analysis data demonstrates a correlation.The change in the texture (Table 1) resulting from an increased deposition temperature has an influence on the microstructure (Fig. 1) of the prepared n-InSb films.

At a substrate temperature of 480°C, significant changes in the microstructure and morphology of the sample surface occur. The SEM image of the sample shows that the sample is ai-GaAs substrate with InSb formations distributed over the surface (Fig. 2a).In order to verify the existence of the indium incorporation in n-InSb film, we carried out a detailed study on elements distribution by EDX (Fig. 2b-e).

(a)



(b)	(c)

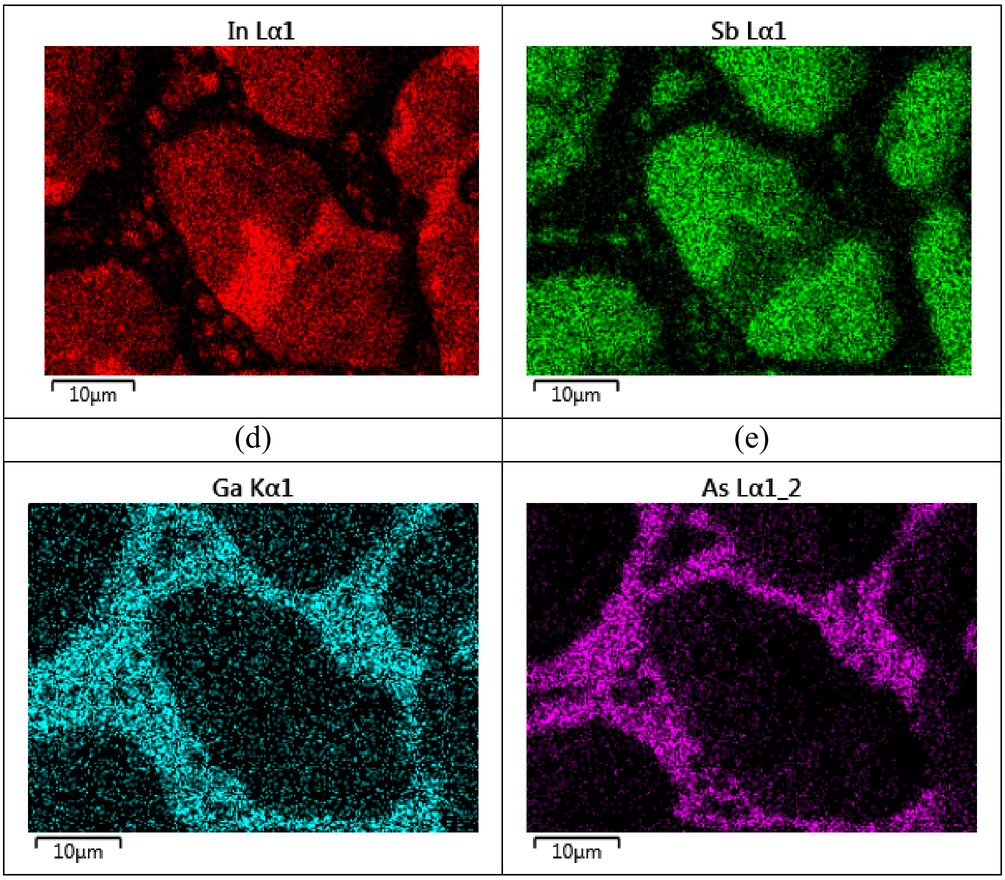


Figure. 2. Scanning electron microscopy image (a) and X-ray maps for (b) In Lα, (c) Sb Lα, (b) Ga Kα and (e) As Lα of n-InSb film deposited at the temperature of 480 °C

As shown by EDS mapping results in Fig.2(b-c), the accumulations of indium on the surface of indium antimonide formations were found. Table 2 presents the results of studying the elemental composition of n-InSb films depending on the substrate temperature.

Table 2. Relative atomic concentration (± 0.3 at.%) of In and Sb elements inn-InSb films deposited on i-GaAs (100) substrates

Depositiontemperature,°C	420		430		440		460		480	
Element	In	Sb	In	Sb	In	Sb	In	Sb	In	Sb
At.%	50,7	49,3	50,7	49,3	50,6	49,4	50,6	49,4	67,9	32,1

For n-InSb films deposited in the temperature range 420–460°C, the ratio of the atomic concentrations of In and Sb within the error is the same. At the substrate temperature of

480°C, the concentration of In exceeds Sb by a factor of two. The decrease in the content of Sb relative to In in the film with an increase in the deposition temperature is due to the higher value of the vacuum sublimation coefficient of antimony at a given substrate temperature. A similar effect of antimony evaporation from indium antimonide single crystals was observed when they were heated to temperatures of 490°C in a helium atmosphere (Abaeva et al., 1987).

Changes in the microstructure, elemental and phase composition of n-InSb films have a significant effect on their electrical properties. Table 3 presents the electrical properties of n-InSb films, such as electrical resistivity, temperature coefficient of resistance, electron mobility, depending on the substrate temperature during deposition.

Table3. Electrical properties of n-InSb films on i-GaAs (100) substrates formed by explosive thermal evaporation: electrical resistivity (ρ), temperature coefficient of resistance (α), carrier mobility (μ)

Depositiontemperature, °C	ρ, 10^{-5}Ω·m	α, %·deg.$^{-1}$	n, cm^{-3}	μ, cm^2/(V·s)
420	2.77	– 0.742±0.006	(1.22±0.08)×10^{17}	(18.5±1.3)×10^3
430	5.93	– 1.250±0.020	(8.32±0.58)×10^{16}	(12.6±0.9)×10^3
440	5.47	– 0.934±0.007	(9.95±0.69)×10^{16}	(11.5±0.8)×10^3
460	7.87	– 1.062±0.008	(8.03±0.56)×10^{16}	(9.8±0.9)×10^3
480	48.40	0.271±0.002	(2.75±0.19)×10^{18}	46.9±3.3

At the deposition temperature of 420 °C, the film electrical resistivity is 2.77×10^{-5} Ω·m, while at the deposition temperature of 460 °C electrical resistivity increases to 7.87×10^{-}

[5] Ω·m. The electrical resistivity increase is due to the decrease of the charge carriers mobility.

The mobility of charge carriers decrease is due to the increase in the scattering of charge carriers on structural inhomogeneities(mainly intercrystalline boundaries).Note that at a substrate temperature of 480 °C, a decrease in the mobility of charge carriers and an inversion of the sign of the temperature coefficient of resistance are observed. This is due to the presence of the indium phase, whose metallic properties become decisive.

In practical terms, these results are promising for the creation of a temperature sensor. The main characteristic of the temperature sensor is the temperature coefficient of resistance α, so we to create the temperature sensor used the n-InSb film obtained at a substrate temperature of 430 °C (Table 3). To this end, after the deposition of the n-InSb film on i-GaAs, the topology of the sensitive element (meander) and metal contacts is photolithographically formed. To protect the sensitive film structure from the environment, it was covered with a protective layer.On Fig. 3 shows the temperature dependence of the temperature sensor resistance in the temperature range from–80 °C to +150 °C.

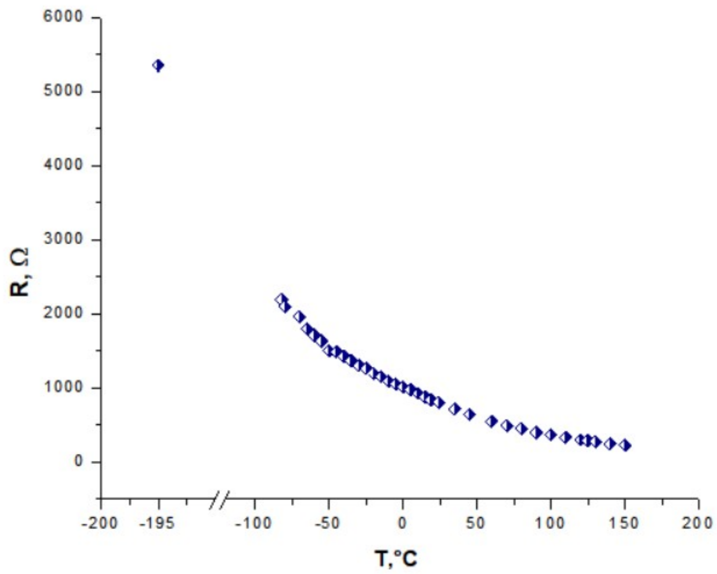


Figure 3. Temperature dependence of the resistance of the temperature sensor

It should be emphasized that the manufactured temperature sensor operates both at high temperatures (up to +150 °C) and at liquid nitrogen temperature.The electrical resistance decreases with temperature increase indicating a semiconducting behavior. It is not possible to talk about the temperature dependence of the resistance below –80 °C up to the temperature of liquid nitrogen. Based on the temperature dependence of the temperature sensor resistance, its main characteristics were determined. Temperature coefficient of resistance of temperature sensor α= (–1.23±0.02) %·deg.$^{-1}$. The topology of the sensitive element in the form of a meander makes it possible to increase the resistance of the temperature sensor to (804.10 ± 0.12) Ω and reduce its error in determining the temperature.

It is useful to compare the parameters of the obtained experimental temperature sensor with sensors available in production. Similar temperature sensors known today have a temperature coefficient of resistance up to 0.5%·deg.$^{-1}$(Baranochnikov, 2002).

Conclusions

InSb films can be the best material for the production of a wide range of sensors (Hall sensors, angular and linear displacement sensors, etc.). In the present investigation, we show that the same technology of n-InSb film on i-GaAs substrate preparation can be used for creation of temperature sensor elements. The results show that, by changing the substrate temperature, it is possible to influence the resistance of the n-InSb films.

During explosive thermal deposition in the temperature range of 420–440°C, n-InSb films of various degrees of crystalline perfection are formed on i-GaAs (100) semi-insulating substrates. At a deposition temperature of 430°C, n-InSb films have the highest value of the temperature coefficient of resistanceα (–1.23±0.02 $\%\cdot deg.^{-1}$).

Thus, our studies demonstrated that it is possible to produce the n-InSb-i-GaAs temperature sensor that can operate within the temperature range from –80 °C up to +150 °C. Temperature coefficient of resistance of the temperature sensor is α = (–1.23±0.02) $\%\cdot deg.^{-1}$.

The temperature sensor based on n-InSb-i-GaAs should find their applications, among others, in the spacecraft industries and in the low temperature electronics, as well as in the automotive, aircraft industry.

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