THE GaSb-CoGa$_{1.3}$ EUTECTIC COMPOSITE AS A PROMISING MATERIAL FOR TENSOMETRY

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Abstract

New small-size tensoresistors based on the GaSb-CoGa$_{1.3}$ semiconductor eutectic composite have been designed; they exhibit linear, nonhysteresis, and thermostable characteristics, stable parameters, and high reliability and operate in a temperatures range of 220-400 K. The improvement in the characteristics of the tensoresistors in comparison with GaSb and GaSb-FeGa$_{1.3}$ is attributed to an increase in the density of the metal inclusions and a decrease in their sizes.

1. Introduction

Tensoresistors with semiconductor sensing elements are characterized by high sensitivity, small overall sizes, technological effectiveness, and reliability. Stuck silicic tensoresistors and tensoelements based on SmS compounds are mostly used for designing semiconductor strain gauges [1, 2]. A strong and nonlinear temperature dependence of tensosensitivity and resistance is their essential drawback. Different circuit methods have been developed for the compensation for errors in the tensoelements working in a temperature range of 220 and 400 K. However, this has resulted in an increase in their cost and a limitation of the production volume. A reduction in the stability of the sensor characteristics in integral silicic tensoelements is also a disadvantage. These disadvantages confine the use of the semiconductor tensoresistors in the contemporary systems for monitoring and control of the technological processes.

Our studies of tensometric characteristics of the semiconductor eutectic composites based on III-V group elements and 3d transition metal showed that it is possible to create the tensoelements on their base with a small temperature error and a high linear transformation. They exhibit high reliability and stability; that is, they are free from the deficiencies inherent in silicic semiconductor sensing elements [3]. A distinctive property of these semiconductor eutectic composites is the presence of metal inclusions in the semiconductor matrix, which causes some specific features of tensometric characteristics in them. In these heterogeneous structures, there is a semiconductor-metal contact system; their deformation must lead to a change in the interface resistance. On the other hand, the interatomic interaction weakens and decreases the binding energy of valence electrons during the formation of these structures. This also has effect to the tenso characteristics in these composites. Furthermore, a eutectic alloy exhibits high mechanical properties caused by the presence of the second needle-shaped phase. They exhibit much greater plasticity and creep than its component.
Tensoresistors with the linear, hysteresis-free, and thermostable tenso characteristics based on GaSb-FeGa₁.₃ were prepared [3]. It was shown in [15] that the temperature coefficient of tensosensitivity decreases by 15% because of a change in the size and density of the metal inclusions in the GaSb-FeGa₁.₃ eutectic composite after alloying with cobalt atoms.

In our cycle studies on the preparation of tensoresistors with improved characteristics, which are based on eutectic composites consisting of GaSb and 3d transition metals, we selected the GaSb-CoGa₁.₃ eutectic composite which has metal inclusions with smaller sizes and higher density.

In our previous paper [4], we carried out thermography, XRD, and a microstructural study of the GaSb-CoGa₁.₃ eutectic composite. The initial and final temperatures of melting, melting heat, and entropy for the GaSb-CoGa₁.₃ eutectic composite were found to be 963 K, 1003 K, 31.768 J/g, and 6.019 kJ/K·mol, respectively. The oriented metallic needles were 0.5-2 μm in diameter, 5-20 μm in length and had a density of 20 x 10⁴ mm⁻². The EDX analysis revealed that the matrix contains Ga and Sb, while the metal inclusions contain Co, Ga, and small quantities of Sb.

The present work is focused on studying the tensoresistive properties of the GaSb-CoGa₁.₃ eutectic composite and preparing tensoresistors on its basis.

2. Experimental

The GaSb-CoGa₁.₃ eutectic composite was prepared as described in [6]. The GaSb semiconductor with a hole concentration of about 1.7 x 10¹⁷ cm⁻³ was made by alloying the related components in stoichiometric quantities with the subsequent 15-fold horizontal recrystallization refining. The GaSb-CoGa₁.₃ composite is synthesized by alloying the GaSb with 3.1 wt % Co and by a quantity of Ga corresponding to the formula of CoGa₁.₃.

The synthesis was conducted at a temperature of 900 K under vibration in a quartz ampoule evacuated to a 1.3-mPa pressure for 3 h. After that, the alloy was heated to a temperature of 1300 K; after full homogenization, it was withdrawn from the furnace and rapidly hardened. Immediately after that, the ingot underwent oriented re-crystallization by the vertical Bridgman method. To avoid ampoule vibration, which can disturb the “solid-melt” interface, the prepared sample was kept motionless with the movement of the freezing interface accomplished by lifting the furnace at a speed of 1 mm/min. After the oriented re-crystallization, 85-90% of the length of the ingot consisted of the GaSb-CoGa₁.₃ eutectic composite. The obtained composite was characterized by the uniform distribution of the CoGa₁.₃ metal inclusions in the GaSb matrix. The composite had p-type conductivity with a charge carrier concentration of about 1.8 x 10¹⁸ cm⁻³ at room temperature.

The preparation technology of the tensoresistors consists of several technological processes:
- the preparation of tensoelements;
- the creation of ohmic contacts;
- attaching of the tensoelement on the bending beams using a VL 931 glue;
- selection of resistance and temperature resistance coefficient.

To determine tensoresistive characteristics, rectangular beams with a size of 0.15 x 0.2 x 7 mm³ were cut from the grown crystals and then were prepared by polishing using conventional techniques and etching in CP-4 (HCl + HF + CH₃COOH – 2 : 11 : 2) with the subsequent washing in alcohol. The tin contacts attached on the beam were ohmic, mechanically
strong and reliable. It was found that the Ohm’s law holds true for the prepared contacts up to 30 mA in a range of 80 to 400 K.

The produced tenso elements were attached on the bending beams shown in Fig. 1 using a VL-931 glue as described in [3]. The thickness of the glue layer did not exceed 15 μm. The glue layer was dried at room temperature and underwent polymerization for 2 h at each temperature of 410 and 450 K. It is known that the characteristics of tensoresistors, such as tensosensitivity, creep, linearity, insulation resistance, temperature dependence of tensosensitivity, “zero drift” and their service lifetime, depend on the glue connection. The selection of the VL-931 glue is caused by its adhesion to metals. Furthermore, a film with even an insignificant thickness of glue is characterized by high dielectric qualities: flexibility and strength. The operating temperature of the glue is 80-400 K.

It is significant to note that the tensoresistive properties are mainly determined by the specific resistance of the eutectic composite, which depend on the mutual orientations of the metallic inclusions, and electrical current exhibits strong anisotropy. So, the deformation characteristics of tensoresistors in three different mutual directions of needles (x), electrical current (I), and plane (P) of substrate were investigated: I||x||P, I⊥x||P and I⊥x⊥P. The measurements were performed by the current perpendicular to the needles and the needles parallel to the plane of the tensoresistor substrate (I⊥x||P), owing to the tensoresistor that exhibits the greatest tensosensitivity coefficient [3]. Characterization of the tenso elements was carried out using the compensation method in a temperature range of 200-450 K and under deformation of up to $\varepsilon = 1.5 \times 10^{-3}$ rel. units.

![Fig. 1. Bending beam for the tensoelement.](image)

3. Results and discussion

The results of studying the strain characteristics of the tensoresistors based on the GaSb-CoGa eutectic composite at different temperatures are represented in Fig. 2. The figure shows that there is a linear dependence of $\Delta R/R_0$ (where, $\Delta R=R_T-R_0$, $R_T$ and $R_0$ are the resistance at the fixed and room temperature, respectively) on both tension and compression types of strain. The limit of linearity of the deformation characteristics for the GaSb-CoGa$_{1.3}$ tensoresistors is about 1.2 $\times 10^{-3}$ rel. units, which almost twice exceeds the value for GaSb [3, 6]. The linearity does not deviate with the variation in temperature. It was revealed that the temperature dependence of the tensosensitivity is free of hysteresis.

Figure 3 represents the comparative temperature dependences of tensosensitivity for the tensoresistors based on GaSb, GaSb-FeGa$_{1.3}$, GaSb-FeGa$_{1.3}$<Co>, and GaSb-CoGa$_{1.3}$. It is evident from the figure that the weakest temperature dependence of tensosensitivity is observed for the GaSb-CoGa$_{1.3}$ eutectic composite.
Fig. 2. Relative change in resistance versus strain at different temperatures for GaSb-CoGa$_{1.3}$.

The tensosensitivity (S) and the temperature coefficients of tensosensitivity ($\alpha$) were determined from the experimental data as $S = \frac{(\Delta R / R_0)}{\varepsilon}$, $\alpha = \frac{(\Delta S / S_0)}{\Delta T}$, $\Delta S = S_T - S_0$, and $\Delta T = T_T - T_0$, where $S_T$ and $S_0$ are coefficients of tensosensitivity at the fixed ($T_T$) and room temperature ($T_0$), respectively.

Fig. 3. Comparative temperature dependences of tensosensitivity for the tensoresistors based on GaSb, GaSb-FeGa$_{1.3}$, GaSb-FeGa$_{1.3}$<Co>, and GaSb-CoGa$_{1.3}$. The data for GaSb, GaSb-FeGa$_{1.3}$, and GaSb-FeGa$_{1.3}$<Co> are taken from [3, 5].

The average values of $S$ and $\alpha$ for GaSb-CoGa$_{1.3}$ at room temperature were calculated as $S = 24 \pm 5$ and $\alpha = 0.0008$ K$^{-1}$. These parameters for the GaSb, GaSb-FeGa$_{1.3}$, GaSb-FeGa$_{1.3}$<Co>, and GaSb-CoGa$_{1.3}$ eutectic composites are given in the table.

The decrease of value $\alpha$ for tensoresistors based on the GaSb-CoGa$_{1.3}$ eutectic composites in comparison with GaSb, GaSb-FeGa$_{1.3}$, and GaSb-FeGa$_{1.3}$<Co>, which is a significant result, is possibly attributed to the smaller sizes and the larger density of the metal inclusions.

However, it is noted in [3] that the decrease in the values of $\alpha$ for tensoresistors based on GaSb-FeGa$_{1.3}$ eutectic composites in comparison with GaSb was associated with the presence the additional deep impurity levels of 3d transition metals in the energy band of GaSb. The valence
band of GaSb, as well known, is degenerated at the center of the Brillouin zone and consists of light and heavy hole bands, and a third band that is split due to the spin–orbital interactions [8]. The crystal symmetry under the anisotropic strain deformation is broken; this results in the vanishing of degeneracy and the redistribution of holes between the subbands. The valence band tops corresponding to light and heavy holes are displaced with different value in opposite directions. A redistribution of the holes between the subzones occurs. A change in the concentration of light and heavy holes, which possesses different mobility and contributes differently to the conductivity, leads to a change in resistance even with retention of the hole concentration. This is also true for the impurities that form slightly doped levels in the band gap; however, when all impurity atoms are ionized at low temperatures, small changes in the ionization energy of the impurity under deformation do not change the charge carrier concentration. However, the present deep impurities under the deformation lead to a change in the charge carrier concentration in the semiconductor; it is rather considerable, therefore, it cannot be disregarded.

Characteristic parameters of the tensoresistors based on GaSb, GaSb-FeGa$_{1.3}$, GaSb-FeGa$_{1.3}$<Co>, and GaSb-CoGa$_{1.3}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GaSb</th>
<th>GaSb-FeGa$_{1.3}$</th>
<th>GaSb-FeGa$_{1.3}$&lt;Co&gt;</th>
<th>GaSb-CoGa$_{1.3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate strain, rel. units, x10$^3$</td>
<td>±0.6</td>
<td>±1.2</td>
<td>±1.2</td>
<td>±1.2</td>
</tr>
<tr>
<td>Coefficient of tensosensitivity</td>
<td>50±5</td>
<td>35±5</td>
<td>30±5</td>
<td>24±5</td>
</tr>
<tr>
<td>Temperature coefficient of tensosensitivity, K$^{-1}$</td>
<td>0.005</td>
<td>0.002</td>
<td>0.0017</td>
<td>0.0008</td>
</tr>
<tr>
<td>Temperature resistance coefficient, K$^{-1}$</td>
<td>0.004</td>
<td>0.0016</td>
<td>0.0013</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

It should be noted that all parameters of the indicated tensoresistors were measured after three or four cycles of heating, when their values were stabilized. Fatigue tests showed that these tensoresistors withstand more than 10$^6$ cycles of alternating-sign of strain with an amplitude of $\varepsilon = 1.2 \times 10^{-3}$ rel. units without breakdowns and crack formation and well withstand vibrations, overloads, and impact accelerations. The variation in the resistance and tensosensitivity of 12 pieces of tensoresistors did not exceed ~10%.

The technical characteristics of tensoresistors based on the GaSb-CoGa$_{1.3}$ semiconductor composite are given below.

Ultimate strain, rel. units.................................1.2x10$^{-3}$
Tensosensitivity at a temperature of 290 K..........................24±5;
Resistance at a temperature of 290 K, Ohm..........................50
Temperature coefficient of tensosensitivity, K$^{-1}$ ..............0.0008
Temperature resistance coefficient at 290 K ..........................0.0003
Nominal operating current, mA ................................10
Size of the tenso element, mm: ..............................................(0.1-0.2)x(0.15-0.2)x(5-7)
Operating temperature of gluing by with glue VL-931 ...... 220 ÷ 400 K
All the strain characteristics are linear and hysteresis-free.
3. Conclusions

Tensoresistors based on the GaSb-CoGa\textsubscript{1.3} eutectic composite with a tensosensitivity of 24±5 and a temperature coefficient of tensosensitivity of $\alpha = 0.0008$ K\textsuperscript{-1} have been prepared. They are hysteresis-free and exhibit linear characteristics under deformation of up to 1.2x10\textsuperscript{-3}. The significant decrease in the temperature coefficient of tensosensitivity of the GaSb-oGa\textsubscript{1.3} based tensoresistors in comparison with other composites based on GaSb is attributed to a higher density and smaller dimensions of the metal inclusions distributed in the semiconductor matrix.

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References