



## Thermostable tensoresistors of Co doped GaSb–FeGa<sub>1,3</sub> eutectic composites

R.N. Rahimov<sup>a,\*</sup>, A.A. Khalilova<sup>a</sup>, D.H. Arasly<sup>a</sup>, M.I. Aliyev<sup>a</sup>,  
M. Tanoglu<sup>b</sup>, L. Ozyuzer<sup>c</sup>

<sup>a</sup> Institute of Physics of the Azerbaijan National Academy of Sciences, 33 H.Javid Avenue, Az-1143 Baku, Azerbaijan

<sup>b</sup> Izmir Institute of Technology, Department of Mechanical Engineering, TR-35430, Urla, Izmir, Turkey

<sup>c</sup> Izmir Institute of Technology, Department of Physics, Gulbahce Campus, TR-35430, Urla, Izmir, Turkey

### ARTICLE INFO

#### Article history:

Received 7 October 2007

Received in revised form 16 April 2008

Accepted 26 May 2008

Available online 14 June 2008

#### Keywords:

Eutectic composite

Microstructure

Tensoresistive effect

Strain sensitivity

Temperature coefficient of strain sensitivity

### ABSTRACT

The microstructure and tensoresistive properties of GaSb–FeGa<sub>1,3</sub> eutectic composites doped with 0.1% Co have been investigated. It was found that the Co impurity atoms mainly accumulate in the metallic inclusions. The length of the inclusions in GaSb–FeGa<sub>1,3</sub>(Co) was measured to be about half of those in undoped GaSb–FeGa<sub>1,3</sub> eutectics. The tensometric characteristics of gauges based on GaSb–FeGa<sub>1,3</sub>(Co) have been found to be more thermostable than undoped samples.

© 2008 Elsevier B.V. All rights reserved.

### 1. Introduction

Semiconductor tensoresistors have the potential for use in automated machinery devices and measurement systems such as flowmeters. For example, by employing these materials, it is possible to receive intense signals during flow experiments without preliminary signal amplification that would increase the cost of the devices. The main disadvantage of semiconductor tensoresistors is the high temperature coefficient of the strain sensitivity and the brittleness that creates some difficulties for their use at a wide range of temperatures and deformation intervals. This limits the design of strain gauge devices using semiconductor tensoresistors. Therefore, development of new thermostable semiconductor materials with lower temperature coefficients of strain sensitivity and less brittleness is critical for the applications mentioned above.

In previous studies, we showed that these properties can be improved by fabrication of strain gauges using semiconductor–metal eutectic composites [1]. The advantages of such composites is that the properties of semiconductors and metals combine, allowing for the ability to control their characteristics with electric and magnetic fields, temperature, pressure, and

various types of impurities. These eutectic composites also exhibit anisotropic properties in the presence of different directions of the electric current, heat flux, magnetic field, and metallic inclusions, which open wide prospects for their application in different areas of science and technology.

Within the microstructure of semiconductor–metal eutectic composites, the metal phase exists as needle-shaped inclusions that reduce the brittleness of the material and cause distinctive behavior in electron and phonon processes in addition to changing the deformation characteristics [1,2]. Some characteristics of the composites may be adjustable by varying the size and density of the metallic inclusions. It has been previously reported that the size and density of the inclusions may be controlled by changing the freezing rate during the application of microgravitation, centrifugation, and magnetic fields in the solidification process [3].

3d transition group (iron-group) elements form several deep levels in the band gap of III–V semiconductor compounds [4]. In previous studies [1], we showed that tensoresistors based on GaSb–FeGa<sub>1,3</sub> eutectic composites have thermostable deformation characteristics that are related to the deep impurity levels of iron atoms that are formed in the band gap of the GaSb matrix. It is expected that GaSb–FeGa<sub>1,3</sub> eutectic composites doped with Co atoms will create additional deep levels in the matrix that will result in higher stability of the strain characteristics as a function of temperature.

\* Corresponding author. Tel.: +994 124393315; fax: +994 124470456.  
E-mail address: [rashad@physics.ab.az](mailto:rashad@physics.ab.az) (R.N. Rahimov).

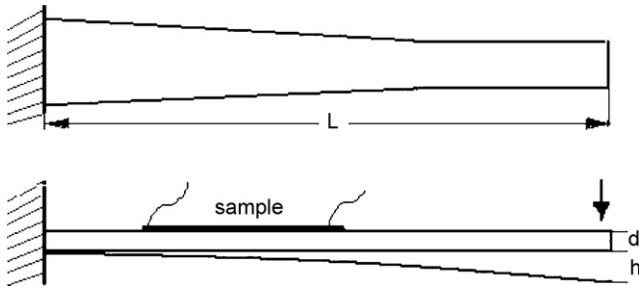


Fig. 1. Schematic representation of experimental setup for tensor resistivity measurements.

The present work focuses on the investigation of the influence of Co impurity atoms at 0.1% doping on the microstructure and the strain characteristics of GaSb–FeGa<sub>1.3</sub> eutectics.

## 2. Experimental

GaSb–FeGa<sub>1.3</sub> eutectic composites with and without Co doping were prepared by using the vertical Bridgman method as described in detail in ref. [2]. To avoid ampoule vibration that may disturb the solid–melt interface, the prepared sample was kept motionless with the movement of the freezing interface accomplished by lifting the furnace. The solidified interfaces were planar and oriented perpendicular to the transport direction on all ingot sections. The solidification rate was set to about 1 mm/min.

A Philips™ FEG scanning electron microscope (SEM) was employed to characterize the microstructure of the alloys. An energy dispersive X-ray spectroscopy (EDX) model EDAX™ was used to obtain quantitative information about the elemental composition of the samples. The accelerating voltage during the EDX analysis was 15 kV.

To determine the tensor resistive effect of the gauges, rectangular beams were cut from the grown crystals to obtain samples of the sensitive elements. Contacts were placed at the ends of the gauges, a minimum of 1 mm away from the ends. This tensor resistor on the base of GaSb–FeGa<sub>1.3</sub>(Co) composite was attached to the bending beam (as illustrated in Fig. 1) using VL-931 glue as described in a previous work [1]. Characterization of the strain gauge was carried out using the compensation method in the range of 200–400 K and with deformation up to  $2 \times 10^{-3}$  rel. unit. The measurements were performed with the current ( $I$ ) perpendicular to the needles ( $x$ ) and the needles parallel to the plane ( $P$ ) of the gauge substrate ( $I \perp x \parallel P$ ), owing to the strain gauges that exhibit the greatest strain sensitivity coefficient ( $S$ ) [1]. The relative deformation of the bending beams ( $\varepsilon$ ) was determined based on the following equation:

$$\varepsilon = \frac{hd}{L^2} \quad (1)$$

where  $d$  is the thickness of the beam,  $h$  the displacement of the beam on bending, and  $L$  is the working length of the beam.

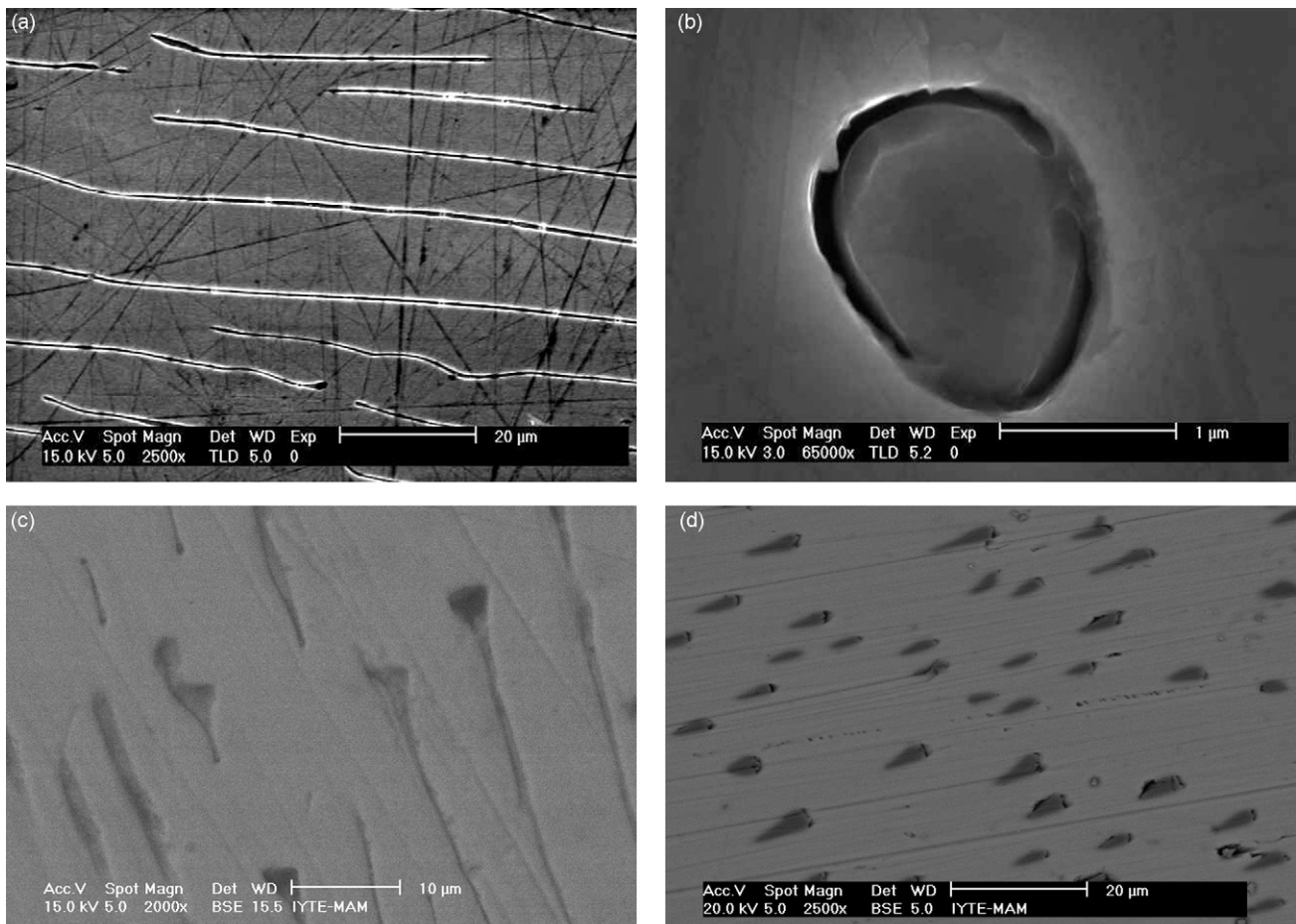


Fig. 2. SEM micrographs of GaSb–FeGa<sub>1.3</sub> and GaSb–FeGa<sub>1.3</sub>(Co) showing cross sections of the sample along (a and c) the longitudinal and (b and d) lateral direction of the metallic inclusions, respectively.

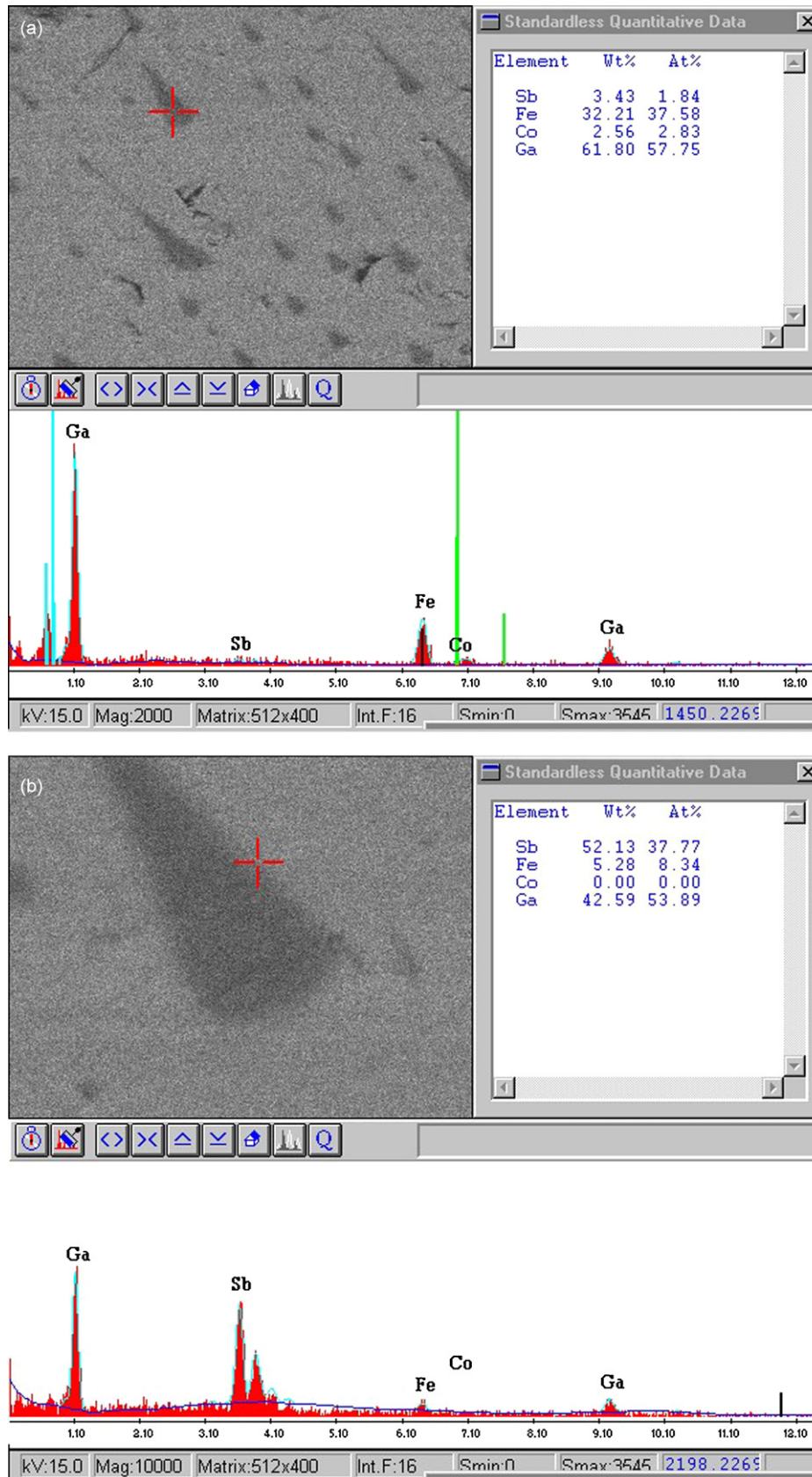


Fig. 3. X-ray spectra of GaSb–FeGa<sub>1.3</sub>(Co) obtained with SEM-EDX from the (a) inclusions and (b) matrix along the lateral direction of the specimens.

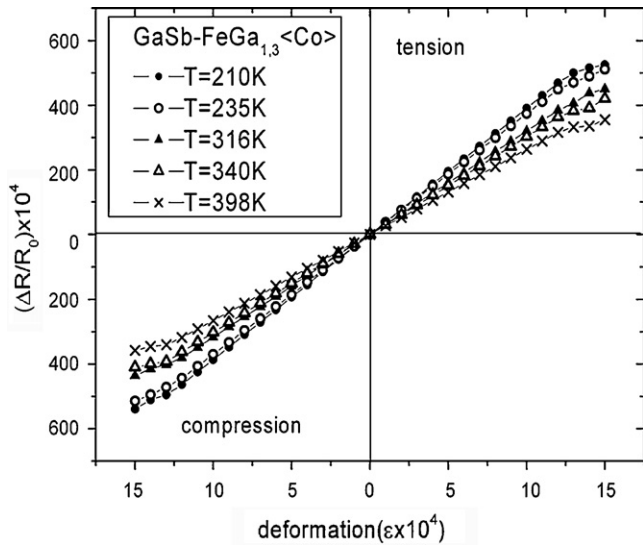


Fig. 4. The relative change of resistance versus strain at different temperatures for GaSb–FeGa<sub>1.3</sub>(Co).

3. Results and discussion

Fig. 2 shows a SEM micrograph of the GaSb–FeGa<sub>1.3</sub> (Fig. 2a and b) and GaSb–FeGa<sub>1.3</sub>(Co) (Fig. 2c and d) eutectics. The images show cross sections of the sample along the longitudinal and lateral directions of the needle-shaped metallic phase. As seen from the figures, the metallic inclusions in the GaSb–FeGa<sub>1.3</sub>(Co) have the form of nail-shaped needles.

From the SEM examinations, the metallic needles were found to be about 1.0–1.5 μm in diameter and 20–150 μm in length for the GaSb–FeGa<sub>1.3</sub>, and 1.5–2.0 μm in diameter and 20–50 μm in length for GaSb–FeGa<sub>1.3</sub>(Co) eutectics. In addition, the length of the inclusions in the GaSb–FeGa<sub>1.3</sub>(Co) was found to be about half of those in the GaSb–FeGa<sub>1.3</sub> eutectics. The X-ray spectra and the elemental compositions obtained from the needle and matrix phases are shown in Fig. 3. The SEM images are marked to show the location of the X-ray measurements. The EDX analysis revealed that the Co atoms are mainly accumulated within the metallic inclusions.

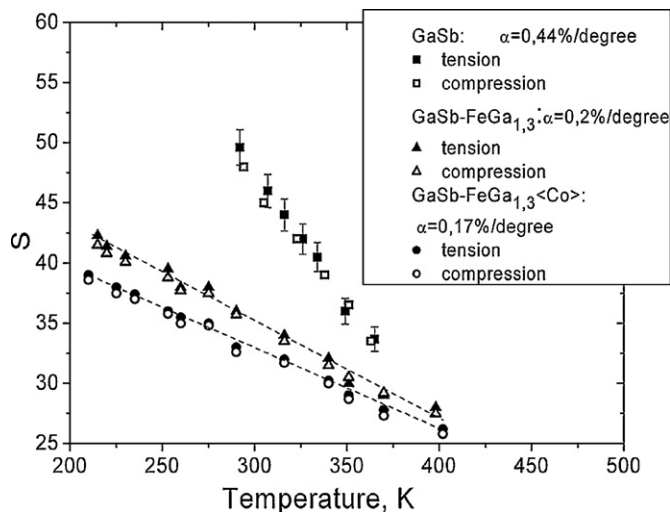


Fig. 5. The strain sensitivity coefficient of resistance versus temperature for the GaSb matrix, GaSb–FeGa<sub>1.3</sub>, and GaSb–FeGa<sub>1.3</sub>(Co). The data for GaSb–FeGa<sub>1.3</sub> and GaSb are taken from previous work [1].

Fig. 4 shows the measured values of the relative change in resistance ( $\Delta R/R$ ) for the GaSb–FeGa<sub>1.3</sub>(Co) composites as a function of strain ( $\epsilon$ ) for various temperatures. It was revealed that the temperature dependence of the strain of the gauges is free of hysteresis.

As shown in the figures, there is a linear dependence of  $\Delta R/R$  on both tension and compression types of strain within the measured strain range due to the flexural bending of the substrate. One of the critical parameters for strain gauges is the limit at which this linearity of strain breaks down. This limit was found to be about  $\pm 1.2 \times 10^{-3}$  rel. unit for GaSb–FeGa<sub>1.3</sub>(Co). The linearity does not deviate with the variation in temperature. The strain sensitivity ( $S$ ) and temperature coefficient of strain sensitivity ( $\alpha$ ) were determined from the experiments using the following equations:

$$S = \frac{\Delta R/R}{\epsilon} \tag{2}$$

$$\alpha = \frac{\Delta S/S_0}{\Delta T} \times 100 \text{ [%/degree]} \tag{3}$$

where  $\Delta R = R_T - R_0$ ;  $\Delta S = S_T - S_0$  and  $\Delta T = T_T - T_0$ .  $R_T$ ,  $S_T$  and  $R_0$ ,  $S_0$  are the resistance and the coefficients of strain sensitivity at fixed temperature and at room temperature, respectively. The dependence of  $S$  on temperature for GaSb–FeGa<sub>1.3</sub>(Co) compared with data for GaSb and GaSb–FeGa<sub>1.3</sub> eutectics is presented in Fig. 5 for loading under tensional and compressive strains resulting from the bending of the substrate. The strain and temperature characteristics of the gauges show no hysteresis. Average values of  $S$  at room temperature and  $\alpha$  for GaSb–FeGa<sub>1.3</sub>(Co) were calculated to be  $34 \pm 5$  and 0.17%/degree, respectively. The temperature coefficient of the sensitivity of the GaSb–FeGa<sub>1.3</sub>(Co) gauge was found to be more than 15% lower than those with the GaSb–FeGa<sub>1.3</sub>.

The decrease in the values of  $\alpha$  may be associated with the presence of the additional deep impurity levels in the GaSb matrix. Based on the findings from the SEM-EDX, the Co atoms were found to be mainly accumulated in the metallic needles. This means that a fraction of the Co atoms would be expected to form deep levels in the matrix because the crystal symmetry due to an anisotropic strain deformation is broken and resulting in a vanishing of the degeneracy. The valance band edges of light and heavy holes are displaced in opposite directions and the redistribution of holes between sub-bands takes place. When a semiconductor material is doped with an impurity that generates deep levels, the change of the charge carrier concentration under deformation (strain) is significant. Because the changes in hole concentration and mobility as a function of temperature have opposite signs, the relative change of resistance under deformation is stable. This is one of the conditions that causes a reduction in the temperature coefficient of the sensitivity in these strain gauges.

The contact resistance and interaction between metal inclusions and the semiconductor matrix in these compositions plays a significant role in the tensoresistivity characteristics, and thus, these should be taken into consideration. As shown in our previous work [1], the presence of the oriented metallic phases generates an anisotropy in the strain characteristics. Any external effect, including additional doping, that results in a change of the density and dimensions of the metallic inclusions causes a change of interface resistance and in the degree of anisotropy. Therefore, the change in the density and dimensions of the inclusions of the GaSb–FeGa<sub>1.3</sub> eutectic composite doped with Co atoms directly results in an improvement in the temperature coefficient of sensitivity.

4. Summary

GaSb–FeGa<sub>1.3</sub> eutectics with and without Co doping were prepared using a vertical Bridgman technique. Microstructural

investigations on the cross section of the samples along longitudinal and lateral directions revealed needle-shaped metallic phases embedded within the semiconductor matrix. The metallic inclusions in the GaSb–FeGa(Co) were observed to form as nail-shaped needles. It was found that the length of the inclusions in the GaSb–FeGa<sub>1.3</sub>(Co) is about half of those in undoped GaSb–FeGa<sub>1</sub> eutectics. The EDX analysis has revealed that the Co impurity atoms accumulated mainly in the metallic inclusions.

The strain and temperature characteristics of the GaSb–FeGa<sub>1.3</sub>(Co) based gauges showed no hysteresis. Average values of  $S$  at room temperature and  $\alpha$  for GaSb–FeGa<sub>1.3</sub>(Co) were calculated to be  $34 \pm 5$  and 0.17%/degree, respectively. The temperature coefficient of the sensitivity of the GaSb–FeGa<sub>1.3</sub>(Co) gauge was found to be about 15% lower than those with the GaSb–FeGa<sub>1.3</sub>.

## References

- [1] M.I. Aliyev, A.A. Khalilova, D.H. Arasly, R.N. Rahimov, M. Tanoglu, L. Ozyuzer, *Appl. Phys.: A* 79 (2004) 2075–2079.
- [2] M.I. Aliyev, A.A. Khalilova, D.H. Arasly, R.N. Rahimov, M. Tanoglu, L. Ozyuzer, *J. Phys. D: Appl. Phys.* 36 (2003) 2627–2633.
- [3] W.R. Wilcox, L.L. Regel, *Acta Astronautica* 38 (1996) 511–516.
- [4] E.M. Omelyanovskiy, V.I. Fistul, *Impurity of Transition Metal in Semiconductors* (in Russian), Metallurgy, Moscow, 1983, p. 282.

## Biographies

**Rashad Nizameddin Rahimov** graduated from Azerbaijan State University, Baku (1973) in semiconductor physics and received his PhD in semiconductor and dielectric physics in 1983. At present, he is a leading researcher at the Institute of Physics of Azerbaijan National Academy of Sciences. His main interests are electron and phonon processes in solid solutions and eutectic composites based on the III–V semiconductor compounds and their practical applications.

**Almaz Ahmediyya Khalilova** graduated from Azerbaijan State University, Baku in 1962. Since 1961, she has been researcher at the Institute of Physics of Azerbaijan National Academy of Sciences. She received the PhD degree in 1967 in semiconductor and dielectric physics. At present, she is a leading researcher at the Institute of Physics of Azerbaijan National Academy of Sciences. Her main interests include materials science and new tensosensors based on the eutectic composites of III–V semiconductor compounds.

**Durdana Hamid Arasly** graduated from Azerbaijan State University, Baku in 1961. Since 1961, she has been a researcher at the Institute of Physics of Azerbaijan National Academy of Sciences. She received the PhD degree in 1967 and the Full D in semiconductor and dielectric physics in 1987. At present, she is a principal researcher at the Institute of Physics of Azerbaijan National Academy of Sciences. Her main interests are electron and phonon processes in solid solutions and eutectic composites based on the III–V semiconductor compounds and their practical applications.

**Maksud Isfendiyar Aliyev** graduated from Azerbaijan State University, Baku in 1950. Since 1961, he has been a researcher at the Institute of Physics of Azerbaijan National Academy of Sciences. He received the PhD degree in 1957 and the Full D in semiconductor and dielectric physics in 1966. At present, he is a principal researcher at the Institute of Physics of Azerbaijan National Academy of Sciences. His main interests are transport phenomena in solid solutions and eutectic composites and their practical applications.

**Metin Tanoglu** has a BS from Istanbul Technical University, Turkey in 1992 and an MSc (1996) and a PhD (2000) from University of Delaware, USA in materials science and engineering. Since 2004, he has been acting as an associate prof. of Mechanical Engineering Department, Izmir Institute of Technology. His main research interests are the processing and characterization of composite materials; nanocomposites; layered clays and carbon nanotubes; and mechanical, physical, and microstructural characterization of materials.

**Lutfi Ozyuzer** graduated from physics engineering (BS), Hacettepe University, Turkey in 1991. He received MS degree in physics at Illinois Institute of Technology, USA in 1995, and a PhD degree at the same institute in 1999. He worked as a research associate and postdoctoral researcher at Materials Science Division of Argonne National Laboratory, USA from 1995 to 2000. Since 2004, he has been working as an associate professor of physics at Izmir Institute of Technology, Turkey. His main research areas are tunneling spectroscopy of superconductors, Josephson junctions, and terahertz generation from superconductors.