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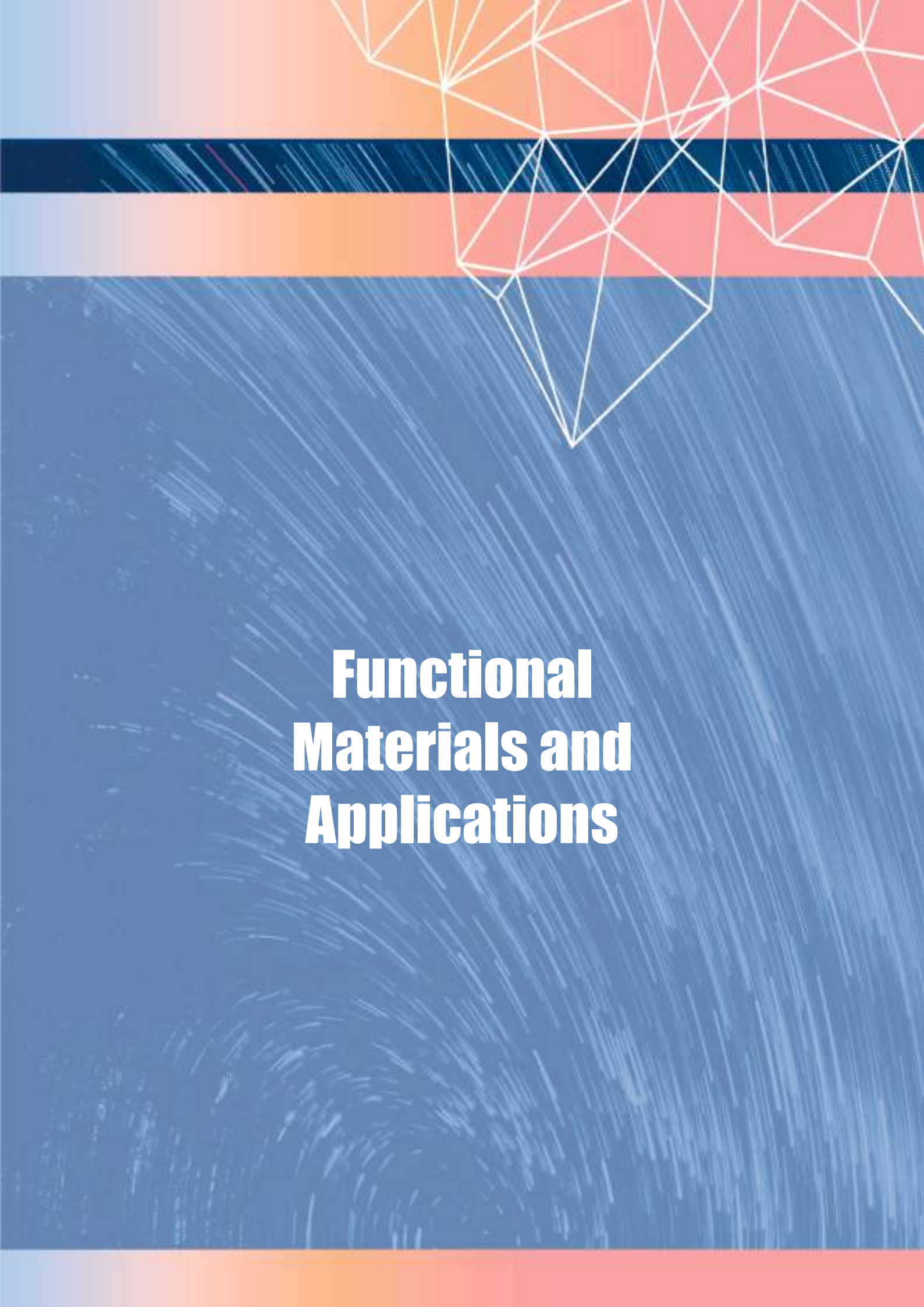
Functional
Materials and
Applications

made titanium dioxide films implement a zonal conductivity mechanism, these films being impurity semiconductors in which the adsorbed oxygen is a fine impurity.

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Electrical conductivity of nanocrystalline nonstoichiometric tin dioxide films near the metal-insulator transition

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Abstract

The temperature dependence of conductivity $\sigma(T)$ of nonstoichiometric tin dioxide films were studied in the temperature range 4-300 K. The films were fabricated by reactive DC magnetron sputtering with following 2-stage temperature annealing. Samples are characterized by high electron concentration (more than 10^{20} cm^{-3}) and a high degree of disorder. Several methods used to distinguish between metallic or insulating types of conductivity were employed to interpret experimental $\sigma(T)$ dependences. These methods give opposite conclusions. Model of polaron transport in metallic systems with strong lattice disorder stimulating dynamic process of electron-phonon coupling was proposed for our samples in order to settle the discrepancies.

Keywords: metal-insulator transition, tin dioxide, metallic conductivity, localization, polaron.

Introduction

Tin dioxide (SnO_2) has attracted intense theoretical and experimental attention due to its wide applications in a variety of applications. A remarkable feature of SnO_2 is the possibility of coexistence of high *n*-type conductivity and optical transparency even in amorphous state. The main source of free charge carriers in undoped samples are ionized oxygen vacancies which act as shallow donors. As a result the metallic state in nonstoichiometric SnO_2 can be achieved by increasing of the concentration of oxygen vacancies without additional doping with low energy donors. As far as the concentration of oxygen vacancies can be quite easily adjusted by variation of technological synthesis parameters the SnO_2 can be considered as siutable objects to investigate metal-insulator transition (MIT).

MIT is one of the most striking physical phenomenon and has been intensively studied over the last several decades. Nevertheless existing theories of MIT (Anderson and Mott mechanisms) fail to explain some experimental results. For example, Mooij correlations phenomenon stated that the slope of the resistivity curves $\rho(T)$ for many materials near MIT is inversely proportional to extrapolated

zero-temperature value ρ_0 [1]. As far as this relation is observed even at high temperatures the effects of weak localization cannot be involved to resolve this long-time standing puzzle.

Experimental

Nonstoichiometric $SnO_{2-\delta}$ films were fabricated by reactive DC magnetron sputtering in argon-oxygen plasma of tin onto glass substrates with subsequent thermal oxidation of the formed layers in air. The oxygen content during the deposition process was of about 1 vol. %. The 2-stage heat treatment process with the isothermal annealing at 200 °C (near the melting temperature of Sn) followed by high temperature annealing at 375 °C was used in order to fabricate conductive and transparent tin oxide films [2]. The thickness of the films was about 100 nm. The XRD analisys and optical transmission spectroscopy was used for samples characterization [2]. By using the Debye-Scherrer equation values of about 5–7 nm for average grain size were estimated. The bandgap E_g for the films was determined to be 3.2 eV using conventional Tauc expression. The main reason of the reduced bandgap in our polycrystalline films as compared with monocrystalline tin dioxide (with Eg ~ 3.6 eV) are the density of states tails in the forbidden gap due to structural inhomogeneity of the samples. The temperature and magnetic field dependences of the resistance were measured using closed-cycle Helium refrigerator CFHF Cryogenics Ltd. in the temperature range of 4-300 K. Contacts were made by Ag paint. According to Hall measurements data the samples considered in this paper have the electron concentration higher than 10^{20} cm^{-3} and mobility of about 3 $cm^2/V{\cdot}s$.

Results and discussion

Fig.1 represents the temperature dependence of the relative value of conductivity ($\sigma(T)/\sigma(300\ K)$) of $SnO_{2-\delta}$ film. The main feature of this dependency is a negative temperature coefficient of resistivity (TCR) $d\rho/dT < 0$ for whole investigated temperature interval (4-300 K). This behavior is not typical for metallic systems with positive TCR values ($d\rho/dT > 0$). Crossover from the positive TCR to the negative one can be observed for disordered metals or semiconductors at low temperatures in the case the weak localization or/and electron electron interaction effects becomes essential. However, the maximum $\sigma(T)/\sigma(300\ K)$ value is about 0.55 for our samples is not usual for activation conductivity mechanism typical for semiconductors. Therefore we can assume that our sample is near MIT (on the metallic or insulating side of the transition). Moreover, in the high temperature range (50-300K) the experimental results can be approximated by linear dependence $\sigma(T)$ whereas at low temperature a more significant increase in conductivity with the temperature is observed.

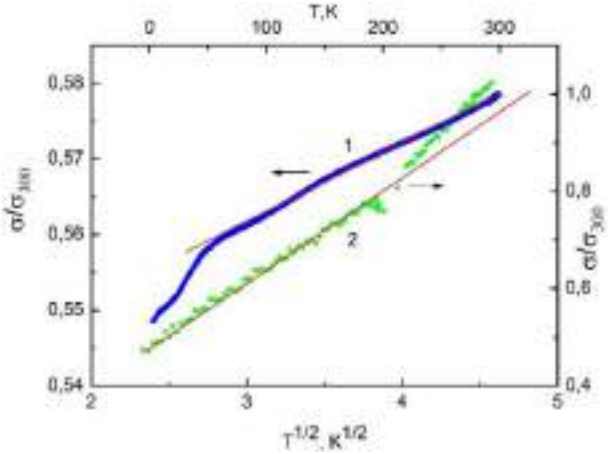

Figure 1. $\sigma(T)/\sigma(300\ K)$ vs T (curve 1) and $\sigma(T)/\sigma(300\ K)$ vs $T^{1/2}$ in the temperature range 5 K< T < 20 K (curve 2) for a $SnO_{2-\delta}$ film

One of the common method to verify the mechanism responsible for the charge transport in the system is to estimate the linearity of the temperature dependence of the conductivity by replotting the experimental data according to the known models. However, there is possibility that several different charge transport models can simultaneously fit the temperature dependence of the conductivity within some temperature interval that affects the true and accurate analysis of the experimental data [3]. Therefore in most cases more robust Zabrodskii analysis [4] is employed to verify whether the sample is characterized by the metallic or insulating (activating or hopping) conductivity type. According this method the parameter $W(T)=d(\ln R)/d(\ln T)$ is calculated from the experimental data. A negative slope of $\ln[W(T)]$ vs $\ln T$ indicates that the sample is insulating, whereas a positive slope corresponds to the metallic behavior of the sample.

As shown in Fig. 2, the W value exhibits only very slow increase with $\ln T$, and the slope of the approximation red line is 0.15. The blue line in Fig. 2 represent $\ln[W(T)]$ vs $\ln T$ calculated from the linear approximation of W data. The slope of this dependence is positive which indicates to metallic behavior of sample conductivity. The contradictive results obtained from different methods of analysis of the $\sigma(T)$ dependences of disordered systems is one of the reason for diametrically opposite conclusions about conductivity mechanisms that can be found in literature concerning investigations of conductivity of samples in the vicinity of the MIT. The other problems of interpreting experimental results of conductivity mechanisms near MIT is presented in review [3].

Analyzing the spreading W data in temperature range 5-20 K in Fig. 2 gives mean value of W equal to 0.47. It means that the $\sigma(T)$ satisfies the law $\sigma(T) = \sigma_0+aT^q$, where σ_0 is the conductivity at zero temperature, a is a coefficient and index q is nearly equal to 0.5. This is exactly the law theoretically predicted by Altshuler et al. [5] while considering the interference between electronic waves in the case of static disorder in metallic state. The linearity of $\sigma(T)/\sigma(300\ \mathrm{K})$ vs $T^{0.5}$ for low temperatures in Fig. 1 provides additional proof of this dependence. The second requirement for a sample to be in metallic state is positive value of σ_0 [4], which is also satisfied.

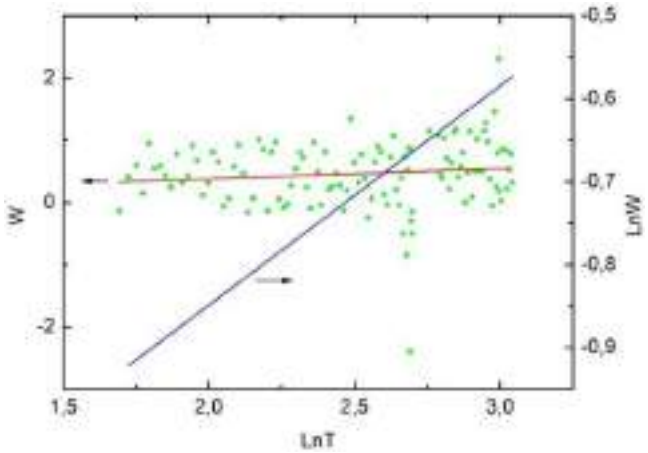

Figure 2. W and LnW vs T. Points are experimental W data, red line is linear approximation of W vs T data. Blue line represent LnW *vs* LnT

Nevertheless, we considered the other theoretical requirements for sample to be degenerate semiconductor with metallic conductivity. As was stated in [6] the investigated in this work samples with carrier concentration $n > 10^{20}$ cm^{-3} completely satisfy the Mott criterion [7] for minimal carrier concentration n_c for sample to be metallic: $n_c^{1/3}a_B = 0.26$, where for SnO_2 $n_c = 2.24\cdot10^{18}$ cm^{-3} and a_B is the effective Bohr radius. On the other side the the Ioffe-Regel criterion [7] for Fermi wave

vector $k_F = (3\pi^2 n)^{1/3}$ and electron mean free path l states that $k_F l \gg 1$ which is rather not satisfied. For a typical mobility of the samples investigated $\mu < 3$ cm^2/V·s l is of the order of interatomic distance and therefore contradicts the Ioffe-Regel criterion for being metallic.

Thus, considering some contradictictory results concerning temperature dependence of the conductivity of nonstoichiometric tin dioxide films one can conclude that classical localization theories of Mott and Anderson cannot be fully applicable for these samples. At the same time there is no doubt that the strong disorder has a significant impact on the electronic transport behavior and leads to a negative TCR with the preserving metallic type of conductivity.

New localization theories are proposed to explain conductivity near MIT in other classes of materials. It is known that in organic metals mean free path l may be less than one-tenth of the molecular separation [8]. To explain this phenomena a novel scenario for an electron transport which combines the bandlike and hopping transports by introducing decoherence time into the electron dynamics [9]. It was proposed that electron-phonon interaction in organic metals leads to formation of mobile polarons making them poorly conducting with the preserving metallic type of conductivity at the same time. Thus, the mechanism can be considered as quantum diffusion of polarons. This means that for a "bad" metal the quantum localization processes caused by a dynamic random environment rather than static should be taken into consideration. The dynamic nature of this type of disorder implies that localization processes are transient suppressing the conductivity but favoring bad metal behavior.

It was suggested in [10] that the localization scenario developed for organic metals is able to explain the similar kind of processes in metals and degenerate semiconductors with strong disorder. The theory is based on the electron coupling to slow fluctuating degrees of freedom. Whereby the electronic processes in metals involves band states that are much less sensitive to disorder. Nevertheless, it was found that process of polaron formation is significantly different in clean and disordered system. In the former case a strong electron-phonon coupling is needed to form polarons while in the later case only a weak or moderate electron-phonon coupling is needed in the vicinity of the MIT. This theory can also provide explanation of the above mentioned Mooij correlations puzzle [11]. It should be pointed out that this process is described as permanent decrease of $\sigma(T)$ slope with positive TCR until at MIT it becomes zero. We suggest that after crossover to the negative TCR the system remain on the metallic side of the MIT preserving linear temperature dependence of resistivity at high temperature range as can be seen from Fig. 1.

This mechanism can also be responsible for the negative TCR reported for nanostructured gold films within 24–300 K temperature range [12]. These films possess a large number of lattice defects and is composed of randomly oriented nanocrystals divided by grain boundaries.

Conclusion

The classical localization theories of Anderson and Mott cannot be applied without modification for interpretation of the temperature dependence of resistivity for strongly disordered conducting materials in the vicinity of the metal-insulator transition. Therefore, the main conclusions of these theories (for example, conserning continuous or discontinuous type of transition, existence of minimal metallic conductivity and possibility for coexistence of localized and delocalized states at the same energy level) have to be revised. New ideas proposed for describing the conductivity mechanism for organic metal should be drawn as well as mechanisms of electron coupling to dynamic fluctuations in strongly disordered systems. We demonstrated that experimental results of the nonstoiciometric tin dioxide films SnO_2 can be utilized for this theory development as they can preserve high conductivity at high disorder degree (which can be easily adjusted by changing parameters of the synthesis procedure).

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Influence of Fe-Ni Films Microstructure on Magnetoresistive Effect

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Abstract

Currently, many researchers are showing interest in materials that be used as a magnetic transducer. One of these materials is Fe-Ni. This material is widely used to create magnetic field sensors, as well as magnetic recording devices, etc.

The purpose of this article was to study the influence of the microstructure of Fe-Ni films on the magnetoresistive effect at different directions of the magnetic field.

The results show that with a perpendicular orientation of the magnetic induction vector relative to the flowing current, an increase in electrical resistance is observed. The increase in resistance occurs due to the influence of the magnetic field on the trajectory of charged particles, which leads to a decrease in their free path, which, in turn, increases the electrical resistance of the film.

Keywords: Ni–Fe film, structure, magnetoresistive effect.

Introduction

Currently, many researchers are interested in materials that can be used as a magnetic transducer. One of these materials is the Fe-Ni alloy, which has been studied for quite a long time [1]. Fe-Ni films are widely used as functional magnetic materials in magnetic field sensors [2, 3], in magnetic recording devices [4, 5], as a material for various spintronics elements, and also used in the creation of electromagnetic shields. Such an extensive use of soft magnetic films of Ni-Fe alloy is due to both good mechanical and magnetic properties. One of these properties is the magnetoresistive effect.