JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. **17** No 2, 02031(4pp) (2025)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том **17** № 2, 02031(4cc) (2025)

REGULAR ARTICLE

Temperature Coefficient of Resistance of Nanoscale Materials for Flexible Electronic

I.P. Buryk, D.I. Tolstikov, L.V. Odnodvorets*

Sumy State University, 40007 Sumy, Ukraine

(Received 05 February 2025; revised manuscript received 18 April 2025; published online 28 April 2025)

The results of experimental studies of the temperature dependence of the resistance and the temperature coefficient of resistance (TCR) for nanoscale two-component film alloys based on Fe, Pd or Pt, Mo and Ni atoms are present. These materials have low sensitivity to deformation (strain coefficient 1.8-2.2 units) in the range of deformations up to 10 %, which makes them promising materials for sensor and flexible electronics. It was established that the properties of the films are affected by the processes of structural ordering under the influence of temperature, as well as surface and grain boundary electron scattering. It is shown that the TCR of film materials depends on the phase composition of the films and when the total thickness of the system changes from 10 to 80 nm in the temperature range of 300-850 K, it is $(2.0\text{-}9.5)\cdot 10^{-4}\,K^{-1}$ (phases FePd, FePt, $FePd_3$, $FePt_3$) and $(8.0\text{-}9.8)\cdot 10^{-4}\,K^{-1}$ (Ni_3Mo). The TCR measurement results confirm the high temperature stability of these systems.

Keywords: Nanoscale materials for affordable energy-efficient electronics, Phase formation processes, Temperature coefficient of resistance (TCR), High thermal stability, Low sensitivity to deformation.

DOI: 10.21272/jnep.17(2).02031 PACS numbers: 60.68.Bs, 72.10.Fk, 73.63.Bd

1. INTRODUCTION

At the modern stage of developmentof sensor and flexible electronics (see, for example, [1-4]), the main types of film materials for forming sensitive elements can be distinguished [5-7]: multilayer film systems and multilayers (alternating magnetic and non-magnetic layers); granular film materials; film alloys; combined multilayer systems of nanosized magnetic layers in the form of granular nanocomposites of magnetic nanogranules embedded in a non-magnetic matrix, non-magnetic interlayers and intermediate layers of a solid solution. In addition to the above, crystalline phases with certain features can be formed in metal/metal (Me/Me) systems: the chemical compound has a clearly defined ratio of element atoms, which corresponds to the stoichiometric composition; the chemical compound has a crystal lattice that may differ from the lattices of the initial components and have a constant melting point or certain unique properties.

The authors of [8] developed a general concept of ordering mechanisms in thermostable binary nanocrystalline alloys. The dependences of the long-range order parameter of alloys on pressure and temperature confirmed the presence of order-disorder phase transformations; the influence of temperature changes and near- and far-range magnetic orders on the scattering pattern of various types (electron, X-ray) waves in alloys based on metals with fcc and bcc lattices was revealed.

It has been established [8] that binary substitution alloys are characterized by a number of physical and mechanical properties that significantly depend on the concentration of atoms of individual components and heat treatment regimes. The volume of the unit cell of the L10 phase increases by an average of 2 % with an increase in the concentration of Pd atoms from 50 to 60 at. %.

Due to their high temperature stability, two-component film alloys based on ferromagnetic, noble and refractory metals are used to form passive elements of hybrid ICs by the method of multilayer metallization with the ability to predict the structure of individual layers and microregions by the value of contact resistance and operating characteristics of devices. Due to their high functionality, such materials have found wide use as sensitive elements of sensor technology (thermistors, strain gauges, etc.), and the prospects for their use are associated with the thermal stability of ordered structures and the stability of physical characteristics in a wide temperature range under the action of deformation and magnetic fields.

The development of modern flexible electronics involves the transition to new electronic devices and systems, such as small-sized and lightweight multifunctional sensors, electronic information storage and display devices, photovoltaic panels and reconfigurable antennas, flexible biological electronic implants, printed power batteries and accumulators. The distinctive features of flexible electronics devices [2, 9, 10] are thermal stability and low sensitivity to deformation.

* Correspondence e-mail: l.odnodvorets@aph.sumdu.edu.ua

Cite this article as: I.P. Buryk et al., *J. Nano- Electron. Phys.* 17 No 2, 02031 (2025) https://doi.org/10.21272/jnep.17(2).02031

The aim of the work was to determine the temperature coefficient of resistance of two-component film materials with low sensitivity to deformation based on Fe and Pd or Pt and Ni and Mo from the point of view of the possibility of their practical application as thermally stable elements of flexible electronics.

2. METHODOLOGY AND TECHNIQUE

For obtain two-component film alloys based on Fe, Pd or Pt and Ni and Mo, a vacuum installation of the VUP-5M type ($p \sim 10^{-3}$-10^{-4} Pa) was used. Film materials were formed by varying the condensation rate, substrate (S) temperature, and annealing temperature. Evaporation was carried out by electron beam (Ni and Mo) and thermoresistive (Fe, Pd and Pt) methods.

The substrate temperature was varied in the range T_s = 300-500 K, the annealing temperature was T_{an} = 300-900 K. The annealing time at the maximum temperature was 15 minutes, and the cooling rate was 3 K/min. The metal deposition rate was regulated by changing the electric current (SM 7020-D device) and was 1-1.6 nm/s. The films were obtained by layer-by-layer or simultaneous condensation methods.

The simultaneous condensation of two metals was carried out with separate arrangements of evaporators, substrates, and thickness sensors. Varying the thickness of individual layers makes it possible to change the concentration of components, which in a multilayer film system is determined by the ratio:

$$c_i = \frac{D_i d_i \mu_i^{-1}}{\sum_{i=1}^{n} D_i d_i \mu_i^{-1}},$$

where D and μ – density and molar mass.

Obtaining the temperature dependence of the resistivity and calculating the TCR of film materials was carried out in automatic mode using a two-point scheme. Sithal and glass plates with applied low-resistance contact pads were used as substrates. A film with predetermined geometric dimensions was deposited through a special mask. The sample was placed in a quartz tube with a tungsten spiral. Resistance was measured through low-resistance pressure contacts with a multimeter HP 34410A at room temperature, for which a chromel-alumel thermocouple with an Escort EDM3150 multimeter (accuracy ± 1 K) was used to control the resistance.

The calculation of the average value of the TCR was carried out according to the cooling curve of the last thermostabilization cycle on the basis of the experimental dependences $R(T)$ or $\rho(T)$ according to the ratio:

$$\beta = \frac{1}{R}\frac{\Delta R}{\Delta T} \text{ or } \beta = \frac{1}{\rho}\frac{\Delta \rho}{\Delta T},$$

where ΔT – temperature interval.

The phase composition was studied by electron microscopy and transmission electron microscopy (PEM-125K instrument).

3. EXPERIMENTAL RESULTS

The thickness of individual layers of film materials was chosen in such a way that, in accordance with the state diagrams for massive samples, different phases should be stabilized in the film systems depending on the atomic concentration and temperature (see, for example, [11]).

During the annealing process, the following phases can form in films based on Fe and Pd or Pt: (Fig.1): solid solution (s.s.) of atoms Pd or Pt in bcc Fe (is phase (α-Fe); concentration c_{Pd} < 50 at. % and c_{Pt} < 15 at. %); Fe_3Pt (phase $L1_2$; $c_{Pt} \cong$ 14-30 at. %); FePd or FePt (phase $L1_0$; $c_{Pd} \cong$ 50-60 at. % and $c_{Pt} \cong$ 30-60 at. %). Electronographic studies indicate that the phase composition of the heat-stabilized samples corresponds to the predicted one.

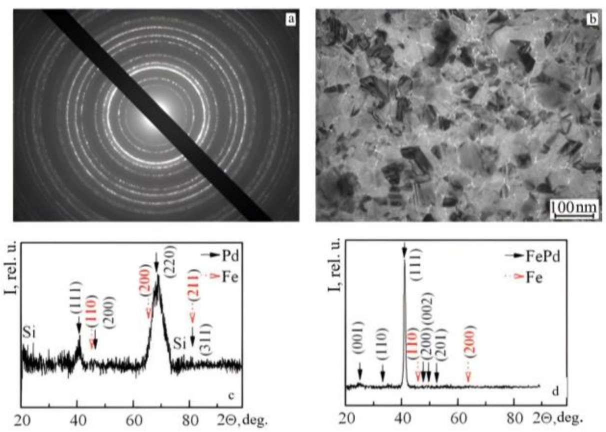

Fig. 1 – Diffraction pattern (a), microstructure (b) and X-ray diffraction patterns from the film alloy FePd/S

It was established that the character of the dependence $\rho(T)$ is determined by the ratio of the thicknesses of individual layers of the fragment (the total concentration of metal atoms) (Fig. 2): at the ratio of thicknesses d_{Pd}/d_{Fe} = 0.22-1.22 the following features of the resistivity temperature dependence: $\rho(T)$ is linear to temperature T =700 K for system Fe_3Pd/S (d = 30 nm) and to T = 600 K – for system Fe_3Pd/S (d = 15 nm). Film systems based on Fe and Pt with different total concentrations of Pt atoms were also studied: from 5 to 50 at. %. The following features of the temperature and concentration dependence of the TCR for the FePt phases were established. In all cases, the dependence $\beta \sim 1/T$ was present in the interval 300-700 K, although its value has different meanings in different concentration intervals.

For the phase s.s.(α-Fe), the maximum value of TCR is observed: from $2.5 \cdot 10^{-3}$ K^{-1} (300 K) to $1.4 \cdot 10^{-3}$ K^{-1} (700 K), which is consistent with the value β for single-layer films.

For phase Fe_3Pd ($L1_2$) the TCR value changes from $2 \cdot 10^{-3}$ K^{-1} (300 K) to $9.0 \cdot 10^{-4}$ K^{-1} (700 K). Minimum value of TKO (i.e. the greatest thermal stability) takes place in phase FePd ($L1_0$) – $(2.0\text{-}8.0) \cdot 10^{-4}$ K^{-1}, which can be explained by the processes of structural ordering after annealing. The concentration dependence of TCR for systems based on Fe and Pd or Pt is shown in Fig. 3.

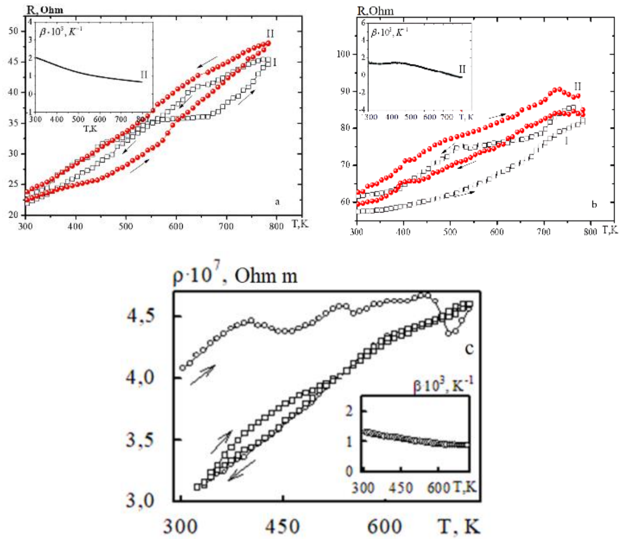

Fig. 2 – Temperature dependence of resistance (a, b) and resistivity (c) and TCR for film systems: a – phase Fe_3Pt, film thickness 80 nm; b – phase FePt, film thickness 50 nm; c – phase Ni_3Mo, film thickness 70 nm

For film materials of the ferromagnetic/noble metal type, the value of the parameter TCR largely depends on the chemical composition and type of crystal lattices of the thermostabilized film material (see, for example, [12]), since, most likely, a ballistic charge transfer mechanism is implemented in them.

During annealing of fims based on Ni and at 750 K, α-Mo crystallization occurs and the phase composition corresponds to fcc Ni and bcc Mo with lattice parameters $a = 0.352$ and 0.315 nm, respectively. After annealing, due to the processes of defect healing and recrystallization, the average size of Ni crystallites increases by up to 2 times compared to non-anneling samples. For the Mo layer, the average crystallite size $L \cong 10 \times 10$ nm. The TCR value for the Ni_3Mo film alloy is (8.0-11.0) $\cdot 10^{-4}$ K^{-1}.

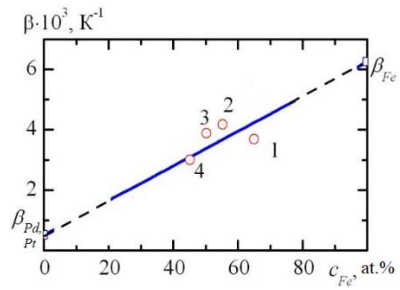

Fig. 3 – Concentration dependence of TCR for film systems:1 – phase FePd (d = 10 nm); 2 – FePd (d = 15 nm); 3 – phase FePt (d = 15 nm); 4 – phase FePd (d = 20 nm). Magnitudes $\beta_{Pd,\,Pt}$ and β_{Fe} correspond to thickness films 20 nm

4. CONCLUSION

1. The phase composition and thermoresistive properties of film alloys based on Fe, Pd or Pt, Mo and Ni atoms with low sensitivity to deformation (strain sensitivity coefficient 1.8-2.2 units) in the range of deformations up to 10 % were studied.

2. It was shown that the value of the TCR of film materials depends on the phase composition of the films (formation of phases of different composition) and when the total thickness of the system changes from 10 to 80 nm in the temperature range of 300-850 K is (2.0-9.5) $\cdot 10^{-4}$ K^{-1} (FePd, FePt, $FePd_3$, $FePt_3$ phases) and (8.0-9.8) $\cdot 10^{-4}$ K^{-1} (Ni_3Mo), which confirmed the high temperature stability of the above systems.

This work was supported by the IEEE Magnetics Society ("Magnetism for Ukraine" program) via the STCU Project No. 9918.

REFERENCES

1. G. Ciuti, L. Ricotti, A. Menciassi, P. Dario, *Sensors* **15**, 6441 (2015).
2. E. Liu, Z. Cai, Y. Ye, M. Zhou, H. Liao, Y. Yi, *Sensors* **23**, 817 (2023).
3. M. Amit, L. Chukoskie, A.J. Skalsky, H. Garudadri, T.N. Ng, *Adv. Funct. Mater.* **30**, 1905241 (2020).
4. D. Maddipatla, B.B. Narakathu, M. Atashbar, *Biosensors* **10**, 199 (2020).
5. Yu.O. Shkurdoda, L.V. Dekhtyaruk, A.G. Basov, A.P. Kharchenko, A.M. Chornous, Yu.M. Shabelnyk, *Eur. Phys. J. B* **91** No 12, 300 (2018).
6. L.V. Odnodvorets, I.Yu. Protsenko, Yu.M. Shabelnyk, N.I. Shumakova, *J. Nano- Electron. Phys.* **12** No 2, 02014 (2020).
7. O.V. Synashenko, O.P. Tkach, I.P. Buryk, L.V. Odnodvorets, S.I. Protsenko, N.I. Shumakova, *Probl. At. Sci. Technol.* **6**, 169 (2009).
8. V.A. Tatarenko, O.V. Sobol', D.S. Leonov, Yu.A. Kunyts'kyy, S.M. Bokoch, *Usp. Fiz. Met.* **12** No 1, 1 (2011) [In Ukrainian].
9. I.Yu. Protsenko, K.V. Tyschenko, L.V. Odnodvorets, M.O. Shumakova, *J. Mech. Eng. Technol.* **1** No 1, 34 (2013).
10. L.V. Odnodvorets, I.Yu. Protsenko, A.K. Rylova, D.I. Tolstikov, *J. Nanomat.* **2022**, 2862439 (2022).
11. M. Ohtake, A. Itabashi, F. Kirino, M. Futamoto, *IEEE Trans. Magn.* **49**, No 7, 3295 (2013).
12. M.V. Vasyukhno, V.S. Klochok, N.I. Shumakova, A.K. Rylova, I.Yu. Protsenko, *2021 IEEE 11th International Conference "Nanomaterials: Applications and Properties", MTFC31* (2021).

Температурний коефіцієнт опору нанорозмірних матеріалів для елементів гнучкої електроніки

І.П. Бурик, Д.І. Толстіков, Л.В. Однодворець

Сумський державний університет, 40007 Суми, Україна

У роботі наведені результати експериментальних досліджень температурної залежності опору і температурного коефіцієнту опору нанорозмірних двокомпонентних плівкових сплавів на основі атомів Fe, Pd або Pt, Mo і Ni. Ці матеріали мають низьку чутливість до деформації (коефіцієнт тензочутливості 1,8-2,2 одиниці) в інтервалі деформацій до 10 %, що робить їх перспективними матеріалами для сенсорної та гнучкої електроніки. Установлено, що на властивості плівок впливають процеси структурного упорядкування під дією температури, а також поверхневе і зерномежове розсіювання електронів. Показано, що величина ТКО плівкових матеріалів залежить від фазового складу плівок та при зміні загальної товщини системи від 10 до 80 нм в інтервалі температур 300-850 К становить $(2.0\text{-}9.5)\cdot10^{-4}$ К$^{-1}$ (фази FePd, FePt, $FePd_3$, $FePt_3$) та $(8.0\text{-}9.8)\cdot10^{-4}$ К$^{-1}$ (Ni_3Mo). Результати вимірювання ТКО підтверджують високу температурну стабільність вищевказаних систем.

Ключові слова: Нанорозмірні матеріали для доступної енергоефективної електроніки, Процеси фазоутворення, Температурний коефіцієнт опору (ТКО), Висока термічна стабільність, Низька чутливість до деформації.