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The Hall Effect, Electrical Resistivity and Spin–Orbit Interaction Parameters in Amorphous Alloys of the Fe–Cr–B System

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In this study, the temperature dependences of the electrical resistivity (ρ) and the Hall coefficient (R_H) of amorphous alloys of the $Fe_{85-x}Cr_xB_{15}$ ($x = 8$, 10, 12, 15) system based on 3*d* elements are experimentally investigated. The alloys are obtained from the liquid state by the melt-spinning (ultrarapid quenching) technique. Measurements are carried out in the temperature range 300–773 K using the Van der Pauw method. As established, the ferromagnetic–paramagnetic phase-transition temperature of the samples is fully correlated with the temperature dependences of both the Hall coefficient and the electrical resistivity, whereas the amorphous–crystalline phase-transition temperature varies depending on the iron content in the samples. The results of the mutual and temperature dependences of the electrical and galvanomagnetic properties of the samples are analysed. As a result of a comprehensive experimental study of the electrical and galvanomagnetic properties of amorphous Fe–Cr–B alloys, it becomes possible to estimate the

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effective spin–orbit interaction parameter for these samples.
Key words: amorphous alloy, Curie temperature, crystallization temperature, Hall coefficient, electrical resistivity, effective spin–orbit interaction parameter.

У цьому дослідженні експериментально вивчено температурні залежності питомого електричного опору (ρ) та Голлового коефіцієнта (R_H) аморфних стопів системи $Fe_{85-x}Cr_xB_{15}$ ($x = 8, 10, 12, 15$) на основі 3*d*-елементів. Стопи було одержано з рідкого стану методом спінінґування (надшвидкого гартування) розтопу. Міряння проводилися в діяпазоні температур 300–773 K методою Ван дер Пау. Було встановлено, що температура фазового переходу феромагнетик–парамагнетик зразків повністю корелює з температурними залежностями як Голлового коефіцієнта, так і питомого електричного опору, тоді як температура фазового переходу аморф–кристал змінюється залежно від вмісту Феруму у зразках. Було проаналізовано результати взаємних і температурних залежностей електричних і ґальваномагнетних властивостей зразків. В результаті комплексного експериментального дослідження електричних і ґальваномагнетних властивостей аморфних стопів Fe–Cr–B стало можливим оцінити ефективний параметер спін-орбітальної взаємодії для цих зразків.

Ключові слова: аморфний стоп, температура Кюрі, температура кристалізації, Голлів коефіцієнт, питомий електричний опір, ефективний параметер спін-орбітальної взаємодії.

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1. INTRODUCTION

At present, the research on the physical properties and internal structure of amorphous ferromagnetic alloys based on 3*d* transition metals remains an important scientific problem. The influence of temperature on the physical properties of metals and their alloys provides valuable information about their structural and volumetric changes, as well as about the melting process. This, in turn, has significant practical importance in mechanical engineering, in the heat treatment of metals, and in engineering calculations [1, 2].

Alloys based on transition metals and their mixtures with metalloid additions are promising subjects of modern materials science in terms of their applications. This is because amorphous alloys exhibit low coercive force, high magnetic absorption, and high electrical resistivity. In addition, when compared with crystalline materials, amorphous alloys demonstrate superior mechanical strength as well as improved resistance to corrosion [3, 4]. It should be emphasized that the aforementioned properties of iron-group-based alloys are mainly realized when these materials are in the amorphous or nanocrystalline state. These materials are promising for electronic applications as soft magnetic

materials, including cores for miniaturized transformers, field sensors, generators, and various energy conversion systems [5, 6].

In addition, amorphous alloys are used in magnetic recording and in electronic engineering as data storage devices [7, 8]. They also play an important role in industrial production [9, 10], in the aerospace sector [11], in medicine [12, 13], and in the military field, particularly, in defence equipment [14].

The study of the Hall coefficient as a function of temperature in amorphous ferromagnets makes it possible to determine the sign and concentration of charge carriers, as well as to establish the relationship between the anomalous Hall coefficient R_S, the electrical resistivity ρ, and the saturation magnetization I_S [15, 16]. This provides important information about the nature of galvanomagnetic phenomena in amorphous ferromagnetic alloys depending on their composition and structure, as well as allows the identification of regularities in the variation of key parameters related to electrical transport and the transition to the crystalline state [17].

2. EXPERIMENTAL DETAILS

The aim of this study is the experimental investigation of the temperature dependences of the Hall coefficient R_H and the electrical resistivity ρ in amorphous ferromagnetic alloys based on iron-group metals, the determination of the Curie temperature and the crystallization temperature, and the identification of the relationships between these parameters. Furthermore, based on the results of the temperature dependences of ρ and R_H, the study aims to estimate the effective spin–orbit interaction parameter λ_{SO} in ferromagnetic amorphous alloys.

The electrical resistivity ρ and Hall coefficient R_H of the samples were experimentally measured using the Van der Pauw method device (High Temp Hall effect Measurement System (HMS7000 + AHT55T5) –RT $\cong$ 773 K) [18]. Experiments using this device were conducted in the temperature range of 300–773 K.

The measurements were carried out on samples of amorphous ribbons 20 mm wide, 20 μm thick, and several meters long, obtained by quenching from the melt on a rapidly rotating disk [19, 20]. From these samples, specimens measuring 10×10 mm^2 were cut.

The Van der Pauw method is a common method for measuring the resistivity and Hall coefficient of a sample. It requires that the sample be isotropic, homogeneous, flat, of uniform thickness, and free of defects.

The convenience of this method is that four point (or line) contacts A, B, C, D are taken on the side surface of a flat sample and, when measuring the Hall voltage, a current is passed through contacts A and C, and the Hall potential difference between contacts B and D is also

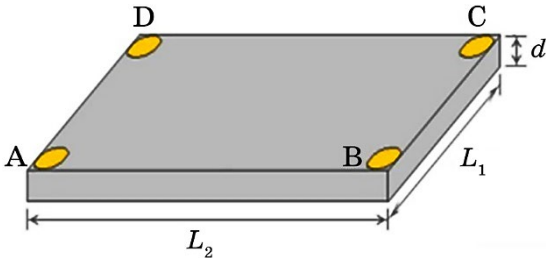


Fig. 1. General view of the sample.

measured. When calculating the resistance, a current is passed through contacts A and D. The voltage between contacts B and C is measured and the resistances are calculated [21, 22].

The specific electrical resistance is calculated knowing the resistances $R_{AB,CD}$ and $R_{BC,DA}$:

$$\rho = \frac{\pi d}{\ln 2} \frac{R_{AB,CD} + R_{BC,DA}}{2} f . \quad (1)$$

Here, d—sample thickness, $R_{AB,CD}$ and $R_{BC,DA}$ are the resistance values of the sample measured by the Van der Pauw method, f is the geometric correction factor, the value of which is calculated using the ratio $R_{AB,CD}/R_{BC,DA}$. The experiment requires that L_1 and L_2 be equal to each other ($L_1 = L_2$).

The theory of the Van der Pauw method is based on the theory of conformal reflection [23, 24]. The average Hall coefficient of the samples is calculated using the expression below:

$$R_H = \frac{R_{H(AC,BD)} + R_{H(BD,AC)}}{2} . \quad (2)$$

By comprehensively studying the electrical, magnetic, and galvanomagnetic properties, it is possible to evaluate the effective spin–orbit interaction parameter λ_{SO} [25, 26].

$$R_H = \frac{\rho_H}{B} = R_0 + \frac{2e^2}{\mu_0 \mu_B \hbar g} \rho^2 \lambda_{SO} \chi = R_0 + R_S \chi . \quad (3)$$

In this expression, the normal Hall coefficient, which is one of the components of the Hall effect, is significantly smaller than the anomalous Hall coefficient

$$R_S = \frac{2e^2}{\mu_0 \mu_B \hbar g} \rho^2 \lambda_{SO} \quad (4)$$

($R_0 << R_S$). Here, $e = 1.6 \cdot 10^{-19}$ C is the electron charge, $\mu_B = 0.927 \cdot 10^{-23}$

J/T is the Bohr magneton, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic constant, $\hbar = 1.054 \cdot 10^{-34}$ J·s is the Planck constant, Lande coefficient $g \approx 2$ for transition metals, ρ—electrical resistivity, λ_{SO}—effective parameter of the spin–orbit interaction.

Using formula (4), the value of λ_{SO} is found:

$$\lambda_{SO} = \frac{R_S \mu_0 \mu_B \hbar g}{2e^2 \rho^2}. \quad (5)$$

3. RESULTS AND DISCUSSION

Recent scientific studies of amorphous alloys show that within the temperature range of 100–1000 K, the electrical resistivity ρ is higher in the amorphous state compared to the crystalline state, while the temperature coefficient of resistivity is lower in the amorphous state than in the crystalline form [27]. Similarly, in our studied samples, the absolute value of the electrical resistance in the amorphous state from room temperature to the phase transition temperature shows that increasing content of chromium in samples leads to the increasing of value of resistivity of them. In all studied samples, the electrical resistivity ρ decreases sharply during the transition from the amorphous to the crystalline state and increases with a subsequent increase in temperature. In the crystalline state, $\rho(T)$ decreases with decreasing temperature. After the phase transition, the temperature coefficient of resistance in the crystalline state in all samples is greater than that in the amorphous state. When the temperature reaches the Curie temperature T_C, a significant sharp decrease in the value of the Hall coefficient $R_H(T)$ was observed, which is associated with the transition of the sample from the ferromagnetic state to the paramagnetic state [28].

The temperature dependences of the Hall coefficient and the electrical resistivity of the investigated alloys of the $Fe_{85-x}Cr_xB_{15}$ system ($x = 8–15$) are shown in Figs. 2 and 3. In this study, the measurements were performed within the temperature range of 300–770 K.

Figure 2 indicates that the Hall coefficient decreases from room temperature to 400 K in the $Fe_{77}Cr_8B_{15}$ sample. For other samples, such a sharp decrease in the Hall coefficient is also observed at lower temperatures compared to the first sample with an iron concentration of 77%. It can be noted that with a decrease in the concentration of iron in the sample, the temperature of such a sharp decrease also decreases, and for the sample with the lowest concentration of iron, the decrease occurs below room temperature. This behaviour of the Hall coefficient can be associated with a phase transition of the ferromagnetism–paramagnetism type, *i.e.*, with the Curie temperature, and for the samples we studied, it is of 430, 380, 330, 295 K, respectively, as given in Table 1.

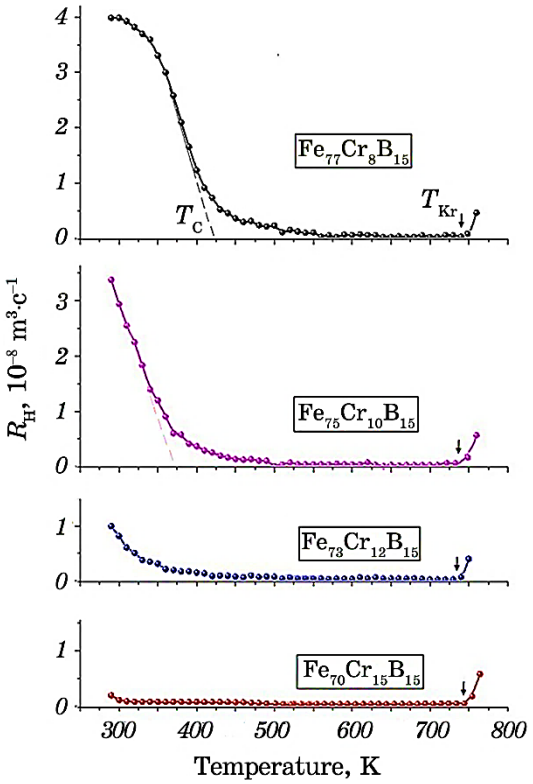


Fig. 2. Temperature dependence of the Hall coefficient of amorphous alloys of the Fe–Cr–B system.

For the studied alloys, a trend toward increasing R_H is observed in the temperature range of 720 K for the $Fe_{77}Cr_8B_{15}$ alloy and 750 K for the $Fe_{70}Cr_{15}B_{15}$ alloy. This experimental finding confirms that increasing Cr concentration and decreasing Fe concentration increase crystallization temperatures.

Based on the analysis of the obtained results, it can be concluded, that the iron concentration in the samples decreases and the metalloid concentration increases, the magnitude of the Hall coefficient and Curie temperature decreases, while the crystallization temperature increases.

The temperature dependence of the specific electrical resistance of amorphous alloys of the Fe–C–B system is shown in Fig. 3. It can be seen from this figure that for all samples the resistivity depends weakly on temperature. In almost all amorphous metal alloys based on iron-group elements, the specific electrical resistance ρ changes almost linearly from room temperature to the crystallization temperature, and the temperature coefficient of resistance TCR—$\partial\rho/\partial T$ takes the fol-

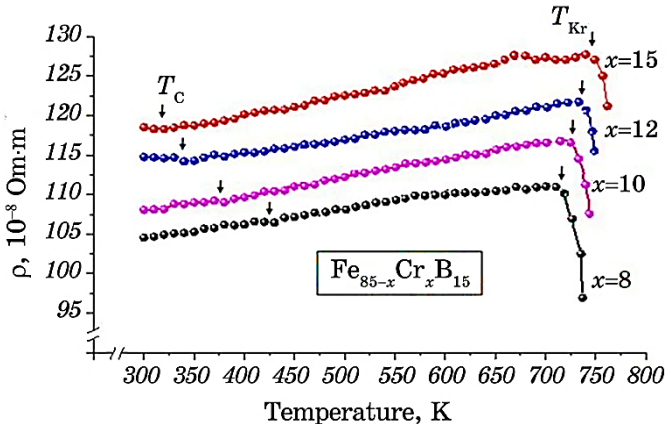


Fig. 3. Temperature dependence of the specific electrical resistance of the amorphous alloy of the Fe–Cr–B system.

lowing values: for the amorphous alloy $Fe_{70}Cr_{15}B_{15}$, $\partial\rho/\partial T = 2.62\cdot10^{-2}$ (μOm·cm)/K; for the alloy $Fe_{73}Cr_{12}B_{15}$, $\partial\rho/\partial T = 2.45\cdot10^{-2}$ (μOm·cm)/K; for the sample $Fe_{75}Cr_{10}B_{15}$, $\partial\rho/\partial T = 2.23\cdot10^{-2}$ (μOm·cm)/K; and for the sample $Fe_{77}Cr_8B_{15}$, $\partial\rho/\partial T = 1.89\cdot10^{-2}$ (μOm·cm)/K. The initial values of specific electrical resistance at room temperature for the samples $Fe_{70}Cr_{15}B_{15}$, $Fe_{73}Cr_{12}B_{15}$, $Fe_{75}Cr_{10}B_{15}$ and $Fe_{77}Cr_8B_{15}$ are as follow: $118.5\cdot10^{-8}$ Om·m, $114.8\cdot10^{-8}$ Om·m, $107\cdot10^{-8}$ Om·m and $104\cdot10^{-8}$ Om·m, respectively, that is, the absolute value of specific electrical resistance increases with the increase of chromium concentration.

Analysing the graphs of temperature dependence of specific electrical resistance $\rho(T)$ for the studied samples, we can come to the following conclusions.

The absolute value of resistivity increases with decreasing iron con-

TABLE 1. Hall coefficient and specific electrical resistance, Curie temperature and crystallization temperature for the studied amorphous alloys.

Parameter value depending on composition				
Amorphous alloys	Curie temperature T_C, K	Crystallization temperature T_K, K	Values of specific electrical resistance at room temperature $\rho_0\cdot10^{-8}$ [Om·m]	Hall coefficient values at room temperature $R_H\cdot10^{-8}$ [m³/C]
$Fe_{70}Cr_{15}B_{15}$	295	750	118.5	0.16
$Fe_{73}Cr_{12}B_{15}$	330	740	114.8	1
$Fe_{75}Cr_{10}B_{15}$	380	730	107	3.4
$Fe_{77}Cr_8B_{15}$	430	720	104	4

tent and increasing metalloid concentrations in samples, while the temperature coefficient of resistivity decreases.

Increasing metalloid concentrations, firstly, reduces the effective number of charge carriers and, secondly, increases the scattering potential, resulting in an increase in electrical resistivity ρ. At the same time, according to the Moodgi criterion, $\partial\rho/\partial T$ decreases with increasing electrical resistivity ρ [29, 30].

According to the literature [31, 32] that with increasing metalloid concentration, the electrical resistivity ρ increases, $\partial\rho/\partial T$ decreases, and there are cases in which the electrical resistivity does not vary with temperature, and such materials can serve as resistive components. It can be explained by the increase in the concentration of metalloid in the composition of the samples and the increase in the crystallization temperature of the samples, the increase in the stability of the amorphous state and the strengthening of the covalent bond between the alloy elements.

Based on the temperature dependences of the Hall coefficient and electrical resistivity, the Curie and crystallization temperatures for the investigated alloys were determined, as presented in Table 1.

The tables show that, with increasing chromium concentration, the Curie temperature T_C in the samples decreases and the crystallization onset temperature T_K increases. The observed behaviour is attributed to the antiferromagnetic properties of Cr [33].

Experimental findings demonstrate that lowering the iron concentration and increasing the metalloid content in the samples result in decreased Hall coefficient and Curie temperature, accompanied by an increase in crystallization temperature. The main analytical results are summarized in graphical form.

Figure 4 illustrates the dependence of the crystallization tempera-

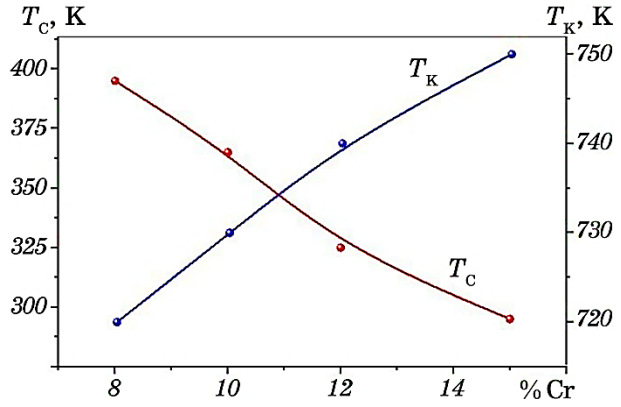


Fig. 4. Dependence of T_C and T_K for the amorphous alloys of Fe–Cr–B system on the concentration of Cr.

TABLE 2. λ_{SO} for the Fe–Cr–B-system amorphous alloys.

	$Fe_{77}Cr_8B_{15}$	$Fe_{75}Cr_{10}B_{15}$	$Fe_{73}Cr_{12}B_{15}$	$Fe_{70}Cr_{15}B_{15}$
T [K]	$\lambda_{SO}\cdot10^{-14}$ [J]	$\lambda_{SO}\cdot10^{-14}$ [J]	$\lambda_{SO}\cdot10^{-14}$ [J]	$\lambda_{SO}\cdot10^{-14}$ [J]
300	17.7	12.3	2.9	0.54
320	16.6	9	1.8	0.4
340	15.2	5.7	1.2	0.33
360	13	3.63	0.72	0.2
380	8.6	2	0.3	
400	5.1	1.1		
420	2.9	0.5		
440	1.6			

ture T_K and the Curie temperature T_C of amorphous Fe–Cr–B alloys on chromium concentration.

It has been calculated the effective spin–orbit interaction parameter λ_{SO} in ferromagnetic amorphous alloys of the Fe–Cr–B system using formula (5). The results of calculations are presented in Table 2.

As shown in Table 2, the effective spin–orbit interaction parameter in the ferromagnetic state depends only weakly on temperature and decreases with rising temperature. These results imply that, in the ferromagnetic state, the effective spin–orbit interaction parameter λ_{SO} is mainly associated with the reduction of spin scattering of charge carriers [34, 35].

4. CONCLUSION

Based on the obtained results, the following conclusions may be drawn.

Analysis of the temperature dependences of $\rho(T)$ and $R(T)$ reveals that increasing the metalloid concentration in the investigated amorphous alloys leads to an increase in the Hall coefficient and the crystallization temperature, while the Curie temperature decreases.

In the studied samples, increasing metalloid concentrations increases the absolute value of their electrical resistivity and crystallization temperature. The temperature of crystallization decreases.

A comprehensive experimental investigation of the electrical and galvanomagnetic properties of amorphous Fe–Cr–B alloys enables the estimation of the effective spin–orbit interaction parameter for these samples.

AUTHORS' CONTRIBUTIONS

O. Kuvandikov and I. Subkhankulov supervised the project, developed

the main conceptual ideas, checked the analytical approaches and provided critical feedback. N. S. Hamraev and R. M. Razhabov developed the project, reviewed the literature and collected data on electronic and mechanical properties, supervised the results of this work and provided feedback. Sh. A. Khomitov obtained the results of the experimental experiment, reviewed the literature and collected data on electronic and mechanical properties, and wrote the manuscript taking into account the contributions of all authors. O. Z. Turgunov obtained the results of the experimental experiment, reviewed the literature and compared the obtained experimental results with the literature. All authors approved the final version of the manuscript.

REFERENCES

1. K. Russew and L. Stojanova, *Production, Properties and Applications of Glassy Metals* (Berlin–Heidelberg: Springer: 2016).
2 V. K. Nosenko, *Visn. Nac. Acad. Nauk Ukr.*, **4**: 68 (2015) (in Ukrainian).
3. O. K. Kuvandikov, I. Subxankulov, D. H. Imamnazarov, and Sh. A. Khomitov, *Metallofiz. Noveishie Tekhnol.*, **44**, No. 7: 823 (2022).
4. O. M. Hertsyk, T. H. Hula, O. A. Yezerska, and M. O. Kovbuz, *Mater. Sci.*, **59**, No. 4: 546 (2024).
5. R. Hasegawa, *Applications of Amorphous Magnetic Alloys, Properties and Applications of Nanocrystalline Alloys from Amorphous Precursors (NATO Science Series, Vol. 184)* (Eds. B. Idzikowski, P. Švec, and M. Miglierini) (Dordrecht: Springer: 2005), pp. 189–198.
6. F. C. Li, T. Liu, J. Y. Zhang, S. Shuang, Q. Wang, A. D. Wang, J. G. Wang, and Y. Yang, *Mater. Today Adv.*, **4**: 100027 (2019).
7. R. Hasegawa, *J. Non-Cryst. Solids*, **287**, Nos. 1–3: 405 (2001).
8. O. Kuvandikov, N. S. Hamraev, R. M. Razhabov, I. Subkhankulov, S. A. Khomitov, and D. H. Imamnazarov, *Bull. Russ. Acad. Sci. Phys.*, **88**, No. 12: 2055 (2024).
9. A. Inoue and A. Takeuchi, *Acta Mater.*, **59**, No. 6: 273 (2010).
10. E. Axinte, *Mater. Des.*, **35**: 518 (2012).
11. F. R. Ismagilov, L. Papini, V. E. Vavilov, and D. V. Gusakov, *IEEE Trans. Ind. Electron.*, **67**, No. 3: 1750 (2020).
12. M. M. Khan, K. M. Deen, and W. Haider, *J. Non-Cryst. Solids*, **523**: 119544 (2019).
13. A. Jabed, M. M. Khan, J. Camiller, M. Greenlee-Wacker, W. Haider, and I. Shabib, *Surf. Coat. Technol.*, **372**: 278 (2019).
14. Jinn P. Chu, J. S. C. Jang, J. C. Huang, H. S. Chou, and Y. Yang, *Thin Solid Films*, **520**, No. 16: 5097 (2012).
15. M. Yu. Barabash, L. Yu. Kunyts'ka, L. G. Khomenko, and Yu. A. Kunyts'ky, *J. Nano- Electron. Phys.*, **2**, No. 1: 42 (2010).
16. A. P. Shpak, Yu. A. Kunits'kii, M. I. Zakharenko, and A. S. Voloshchenko, *Magnetyzm Amorfnykh ta Nanokrystalichnykh System* [Magnetism of Amorphous and Nanocrystalline Systems] (Kyiv: Akademperiodika: 2003) (in Ukrainian).

17. Q. J. Chen, *A Method for Crystallizing Fe-Based Amorphous Alloy, Fe-Based Amorphous Alloys with High Glass Forming Ability* (Singapore: Springer: 2025), p. 517.
18. L. J. van der Pauw, *A Method of Measuring Specific Resistivity and Hall Effect of Discs of Arbitrary Shape, Semiconductor Devices: Pioneering Papers* (Ed. S. M. Sze) (Singapore: World Scientific: 1991), pp. 174–182.
19. I. V. Zolotukhin, *Sorovsk. Obraz. Zh. Fiz.*, **4**: 73 (1997) (in Russian).
20. P. N. V'yugov and A. E. Dmitrenko, *Vopr. At. Nauki Tekh., Ser.: Vak., Chist. Mater., Sverkhprovodn.*, **6**: 185 (2004) (in Russian).
21. L. J. van der Pauw, *Philips Res. Repts*, **13**, No. 1: 1 (1958).
22. Y. Geng, *J. Phys.: Conf. Ser.*, **2321**: 012027 (2022).
23. J. D. Weiss, R. J. Kaplar, and K. E. Kambour, *Solid-State Electron.*, **52**, No. 1: 91 (2008).
24. U. Ausserlechner, *Solid-State Electron.*, **133**: 53 (2017).
25. M. Trudeau, R. W. Cochrane, D. V. Baxter, J. O. Strom-Olsen, and W. B. Muir, *Positive Phys. Rev.*, **37**, No. 9: 4499 (1988).
26. O. Kuvandikov, I. Subkhankulov, R. M. Razhabov, and S. A. Khomitov, *Bull. Russ. Acad. Sci. Phys.*, **88**, No. 11: 1836 (2024).
27. O. Kuvandikov, I. Subkhankulov, R. M. Razhabov, N. Hamraev, S. Khomitov, and D. Imamnazarov, *AIP Conf. Proc.*, **3377**, No. 1: 050006 (2025).
28. O. K. Kuvandikov, I. Subxankulov, B. U. Amonov, and D. H. Imamnazarov, *Metallofiz. Noveishie Tekhnol.*, **43**, No. 12: 1601 (2021).
29. J. H. Mooij, *Phys. Status Solidi A*, **17**, No. 2: 521 (1973).
30. N. F. Mott and E. A. Davis, *Electronic Processes in Non-Crystalline Materials* (Oxford: Clarendon Press: 1979).
31. O. Kuvandikov, I. Subkhankulov, N. S. Hamraev, R. M. Razhabov, Sh. A. Khomitov, and O. Z. Turgunov, *The Third International Forum 'PHYSICS–2024'* (Samarkand: 2024), p. 109.
32. D. M. Minić and A. Maričić, *Mater. Sci. Eng. B*, **172**, No. 2: 127 (2010).
33. O. K. Kuvandikov, Z. M. Shodiev, Kh. B. Khasanov, B. A. Khairullaev, and J. Sh. Akhtamov, *Metallofiz. Noveishie Tekhnol.*, **47**, No. 6: 595 (2025).
34. P. Ogrodnik, K. Grochot, Ł. Karwacki, J. Kanak, M. Prokop, J. Chęciński, W. Skowroński, S. Ziętek, and T. Stobiecki, *ACS Appl. Mater. Interfaces*, **13**, No. 39: 47019 (2021).
35. C. M. Hurd, *The Hall Effect in Metals and Alloys* (New York: Plenum Press: 1972).