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## Thermo-EMF of nanosized $\text{In}_2\text{O}_3/\text{SnO}$

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***The results of studies of differential thermo-EMF and Seebeck coefficient of nanosized  $\text{In}_2\text{O}_3/\text{SnO}$  (ITO) films obtained by magnetron sputtering of a compact target are presented. The dependence of the thermoelectric coefficient of films on temperature is shown, and its correlation with the temperature dependence of electrical conductivity is explained. An automated device for measuring the thermo-EMF of films and distributing it over the surface of the plate in the temperature range from 300 to 450 K has been designed. The results obtained allow us to predict the possibility of further use of ITO films in electronics.***

***Keywords:*** ITO films, thermo-EMF, Seebeck coefficient, Fermi level, charge carrier concentration.

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### Introduction

Transparent conducting  $\text{In}_2\text{O}_3/\text{SnO}$  (ITO) films are widely used as a primary material for optoelectronic devices, biosensors, electrochemical analysis sensors, and temperature sensors. Since thin ITO films in all the above-mentioned applications are used in various combinations with metallic and semiconducting materials over a wide temperature range, the problem of accounting for the thermo-EMF arising at their contact arises. The thermo-EMF is a critical characteristic of metals and semiconductors. Knowing its value allows one to calculate their electrophysical characteristics, such as the Seebeck coefficient, the position of the Fermi level, the charge carrier concentration, and the density of states in the conduction band [1, 2].

Therefore, the aim of this work is to measure the intrinsic thermo-EMF coefficient of ITO films, which will make it possible to predict the potential for further application of these films in electronics.

The Seebeck coefficient  $S_{AB}$  for two contacting materials is determined by the formula:

$$S_{AB} = \frac{dU}{dT} = \alpha_A - \alpha_B, \quad (1)$$

where  $\alpha_A$  and  $\alpha_B$  are the thermo-EMF coefficients of materials A and B, respectively.

As a rule, thermo-EMF coefficients are taken relative to lead or platinum, since it is considered that these materials do not generate a potential difference under a temperature gradient, and their coefficients are known quantities for many metals. Thus, by measuring the Seebeck coefficient of the contact of an ITO film with a metal whose thermo-EMF coefficient is known, one can calculate the intrinsic thermo-EMF coefficient of the film.

In ITO films, electrical conductivity is realized both through delocalized states near the Fermi level, caused by the degeneracy of the semiconductor, and through hopping via localized states, which are oxygen vacancies.

In the low-temperature range (10–100 °C), ITO films represent a degenerate semiconductor with a high degree of amorphization. In this case, the most suitable formula for determining the thermo-EMF is that proposed by Mott:

$$\alpha = \frac{\pi^2 \cdot k^2 \cdot T}{3} \cdot \left( \frac{d(\ln \sigma)}{dE} \right)_{E=E_f} \quad (2)$$

where  $\alpha$  is the thermo-EMF coefficient,  $k = 1.38 \times 10^{-23} \frac{\text{J}}{\text{K}}$  is the Boltzmann constant,  $T$  is the temperature,  $E_f$  is the position of the Fermi level relative to the bottom of the conduction band, and  $\sigma$  is the electrical conductivity.

From formula (2), the position of the Fermi level relative to the bottom of the conduction band can be determined:

$$E_c - E_f = \frac{\pi^2}{3} \cdot \frac{k^2 \cdot T}{q} \cdot \frac{1}{\alpha}. \quad (3)$$

Then, using the Burstein–Moss formula, the electron concentration in the conduction band can be calculated:

$$n = \frac{8 \cdot \pi \cdot (3 \cdot m_e^*)^{\frac{3}{2}}}{3 \cdot h^3} \cdot (E_f - E_c)^{\frac{3}{2}}, \quad (4)$$

where  $m_e^*$  is the effective electron mass, and  $h = 6.63 \times 10^{-34} \text{ J} \cdot \text{s}$  is the Planck constant.

However, at higher temperatures, electrical conductivity in ITO films begins to occur via a hopping mechanism. In this case, the energy levels of oxygen vacancies are degenerate, i.e., they have approximately the same energy, which facilitates the formation of a band through which electrical conductivity takes place. Then the temperature dependence of the thermo-EMF can be represented by the following expression:

$$\alpha = \omega_1 \cdot \left( -\frac{\pi^2}{3} \cdot \frac{k^2 \cdot T}{q} \cdot \frac{1}{E_F} \right) + \omega_2 \cdot \left( -\frac{k}{q} \cdot \left( \frac{\pi - 2}{\pi} \cdot \frac{\Delta E_a}{k \cdot T} + \frac{2 \cdot \pi}{3} \cdot k \cdot T \right) \cdot \frac{1}{E_F} \right), \quad (5)$$

where  $\omega_1$  is the contribution of the degeneracy of the energy levels of oxygen vacancies to the

thermo-EMF value,  $\omega_2$  is the contribution of the hopping conductivity mechanism to the thermo-EMF value, and  $\Delta E_a$  is the electrical conductivity activation energy, which can be found from its temperature dependence:

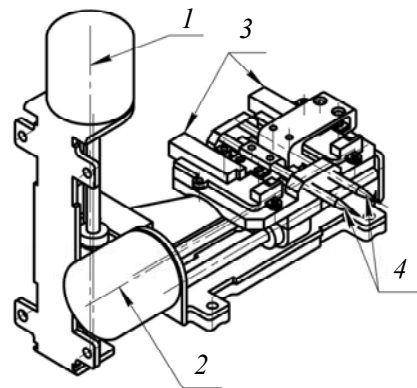
$$\sigma = \sigma_0 \cdot \exp \left( -\frac{E_a}{2kT} \right). \quad (6)$$

The most common method is measuring the Seebeck coefficient of thin ITO films by creating a thin-film thermocouple with a reference material, for example, ITO-tungsten [4–8].

### Experimental Setup

In this work, a tungsten wire with a diameter of 1 mm is used as the measurement electrodes. The movement of the measurement electrodes is performed using four stepper motors with a lead screw. To increase positioning accuracy, the control drivers use a microstepping function with a 1/16 division; the positioning accuracy in this case equals  $\pm 5 \mu\text{m}$ .

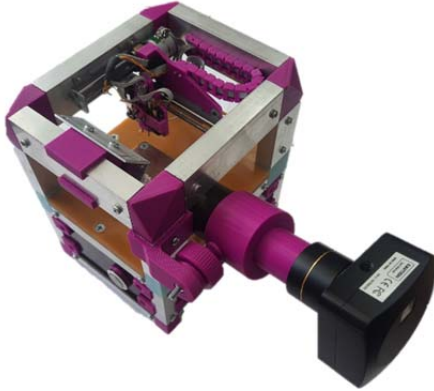
Thermo-EMF voltage measurements of nanoscale conducting films are carried out at four points, which allows the measurement accuracy to be increased and the thermo-EMF distribution profile over the sample surface to be presented. Also, the developed test bench provides the capability to study the dependence of the thermo-EMF voltage on temperature. A 3D model of the measuring part of the setup is presented in Figure 1.



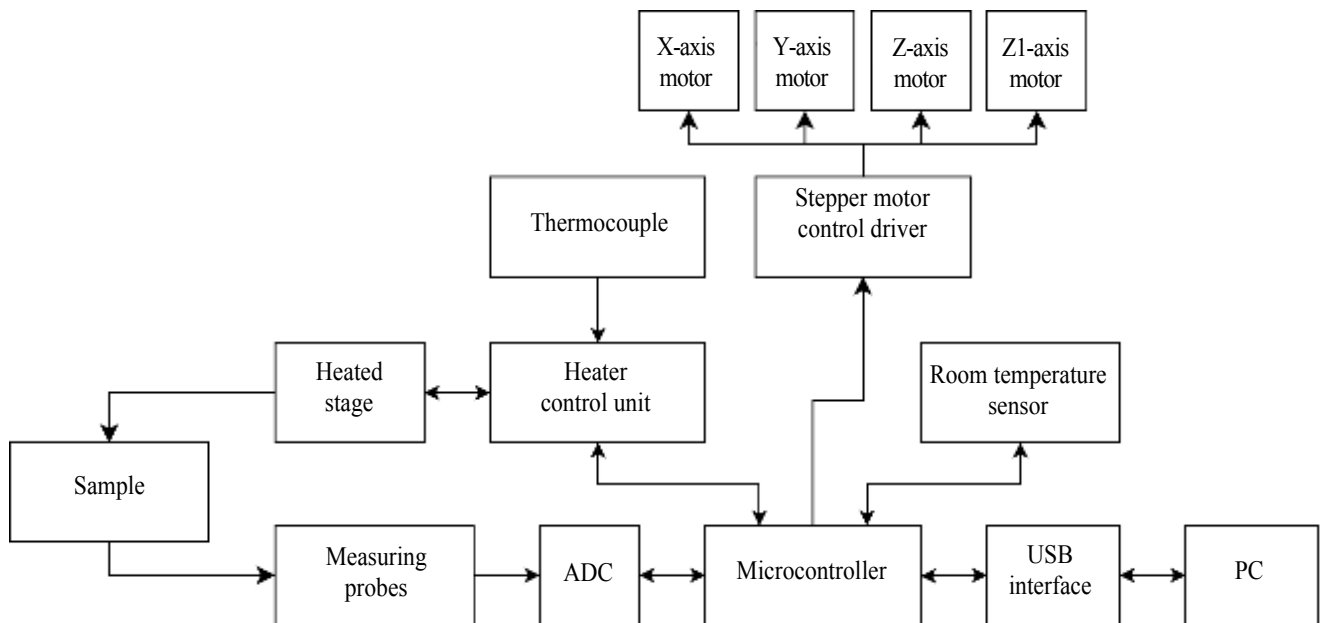
**Fig. 1. 3D model of the measuring part of the setup:**  
1 – Y-axis motor, 2 – X-axis motor, 3 – Z-axis motors,  
4 – copper electrodes

The electrodes measure the thermo-EMF of nanoscale conducting films at four points, which allows the measurement accuracy to be increased and the thermo-EMF distribution profile over the film surface to be presented.

Figure 2 shows the external view of the setup.



**Fig. 2. External view of the setup for measuring the thermo-EMF of nanoscale conducting films**

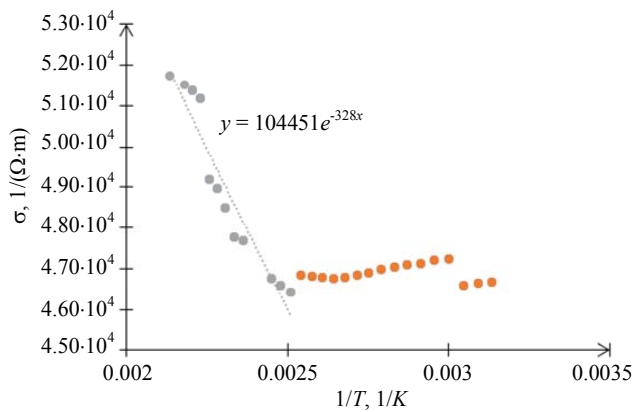


**Fig. 3. Block diagram of the setup for measuring the thermo-EMF of nanoscale conducting films**

### Find the results

The samples studied in this work were obtained by magnetron sputtering from a compact indium-tin target (90 % In, 10 % Sn) in an argon gas environment with the addition of oxygen. The oxygen pressure amounted to 10–30 % of the total pressure in the chamber [9, 10]. Silicon and

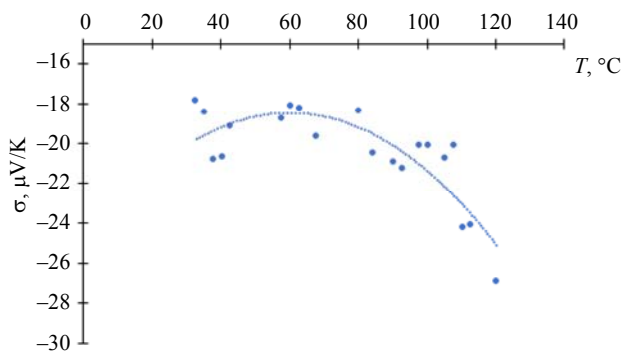
borosilicate glass were used as substrates. Sputtering lasted for 20 minutes onto a substrate preheated to 350 °C, followed by vacuum annealing at 400 °C for 30 minutes. The resistivity of the obtained films was measured by the 4-probe method, and the temperature dependence of electrical conductivity was recorded, which is presented in Figure 4.



**Fig. 4. Temperature dependence of the electrical conductivity of the ITO film**

Two regions are clearly discernible on the dependence curve. In the region up to 110 °C, a metallic type of electrical conductivity is noticeable, which indicates that at these temperatures the ITO film is a degenerate semiconductor and electrical conductivity occurs via delocalized states near the Fermi level. The higher-temperature region corresponds to hopping conductivity via oxygen vacancies, which are F-centers. Each such center facilitates the capture of one or two electrons depending on the vacancy charge. In this region, the temperature dependence of electrical conductivity has an activation character with an electrical conductivity activation energy on the order of 0.05 eV, which is characteristic of the hopping mechanism of electron transfer.

Next, using the experimental setup, the temperature dependence of the thermo-EMF was recorded and the temperature dependence of the Seebeck coefficient of the tungsten-ITO contact was plotted, which is presented in Figure 5.



**Fig. 5. Temperature dependence of the Seebeck coefficient of the tungsten-ITO contact**

By approximating the experimental values, it can be noted that in the temperature range of

30–110 °C the Seebeck coefficient values are small and practically independent of temperature, which is characteristic of metals, since the main contribution to the generation of thermo-EMF in metals is made by electrons, whose concentration is constant and whose energy is close to the Fermi level located in the conduction band. At these temperatures, changes in the distribution of electrons over energy levels are insignificant, and consequently, the potential difference between two metals in contact under a temperature gradient is insignificant and constant.

The electron concentration in the ITO film at room temperature, calculated using Formula (4), amounted to  $2.6 \times 10^{20} \text{ cm}^{-3}$ . The Fermi level is then located above the bottom of the conduction band by 0.42 eV.

At temperatures above 110 °C, the Seebeck coefficient begins to increase in absolute value and becomes temperature-dependent, which is characteristic of non-degenerate semiconductors. In such semiconductors, the concentration of free charge carriers depends on temperature.

A correlation can be noted between the temperature dependences of the Seebeck coefficient and the electrical conductivity, which at temperatures up to 110 °C has a metallic character, and at higher temperatures a semiconducting character, caused by the presence of oxygen vacancies [4].

To calculate the electron concentration in the hopping conductivity region, it should be taken into account that oxygen vacancies in ITO films are formed both during their sputtering and during vacuum annealing. The films studied in this work were subjected to vacuum annealing for 30 minutes at 400 °C. Knowing these technological parameters, the concentration of oxygen vacancies in the film can be calculated using the following formula:

$$N_v = N_0 \cdot \exp\left(-\frac{E_{Eb}}{kT}\right), \quad (7)$$

where  $N_0$  is the concentration of oxygen atoms at the stoichiometric composition of the film material, and  $E_{Eb}$  is the binding energy of an oxygen atom with an  $\text{In}_2\text{O}_3$  molecule, equal to the energy of oxygen vacancy formation.

It should be understood that electrical conductivity may not occur via all oxygen

vacancies, since not all oxygen vacancies are located in a suitable energy band to participate in charge transfer. For this reason, oxygen vacancies located far from the Fermi level cannot effectively participate in charge transfer.

As a rule, electrons with energies on the order of  $kT$  near the Fermi level participate in hopping conductivity. The concentration of such electrons is equal to:

$$n = kT \cdot N(E_F), \quad (8)$$

where  $N(E_F)$  is the density of states at the Fermi level, which is calculated using the following formula:

$$N(E_F) = \frac{3}{4 \cdot \pi \cdot R^3 \cdot E_a}, \quad (9)$$

where  $R$  is the electron hopping length.

The calculated concentration of oxygen vacancies in the film amounted to  $9.93 \times 10^{21} \text{ cm}^{-3}$ , and the concentration of electrons participating in hopping conductivity amounted to  $1.8 \times 10^{21} \text{ cm}^{-3}$ . Despite the high concentration of these electrons, the increase in electrical conductivity after vacuum annealing of the films does not exceed

20 %, which is associated with their low mobility under the hopping mechanism – in this case, not exceeding  $0.3 \text{ cm}^2/(\text{V} \cdot \text{s})$  [3, 10].

## Conclusion

In this work, the thermoelectric and electrical properties of nanoscale ITO films obtained by magnetron sputtering were investigated, and it was established that their thermo-EMF at temperatures from 20 to 110 °C increases monotonically (in absolute value) and has a magnitude from  $-15$  to  $-25 \text{ } \mu\text{V/K}$ . A correlation was established between the temperature dependence of electrical conductivity and the temperature dependence of the thermo-EMF. It has been demonstrated that the developed prototype of the measuring setup shows promise for its use in scientific research.

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## REFERENCES

1. Zeng S., Baillargeat D., Ho H. P., and Yong K. T., Chemical Society Reviews **43**, 3426–3452 (2014).
2. Erickson D., Mandal S., and Yang A., J. Microfluid Nanofluid **4**, 33 (2008).
3. Mott N. Electronic processes in non-crystalline substances. Moscow: Mir, 1974.
4. Parfenov O. E. and Shklyaruk F. A., Physics and technology of semiconductors **41** (9), 1041–1045 (2007).
5. Sytchkova A., Zola D., Bailey L. R., Mackenzie B., Proudfoot G., Tian M., and Ulyashin A., Materials Science and Engineering **178** (9), 586–592 (2012).
6. Zhongkai Zhang, Zhaojun Liu, Jiaming Lei, Luntao Chen, Le Li, Na Zhao, Xudong Fang, Yong Ruan, Bian Tian, and Libo Zhao, iScience **26**, 1–19 (2023).
7. Rafiq Mulla and Charles W. Dunnill, Carbon Trends **4**, 1–9 (2021).
8. Xiaohui Zhao, Hongmin Wang, Zixiang Zhao, and Wanli Zhang, Nanoscale Research Letters **4** (2017).
9. Zhidik Y., Ivanova A., Smirnov S., Zhidik K., Ynusov I., and Trojn P., Coatings **12** (120), 1868 (2022).
10. Smirnov S. V., Minin O. N., Chistoedova A. A., and Petryuk A. E., Nanotechnologies: development, application – XXI century **11** (1), 14–18 (2019).

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