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REGULAR ARTICLE

Effect of Electron-Phonon Interaction on the Resistivity of Metal Films as Sensor Electronics Elements

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Modern technologies of electronics and sensor technic make it possible to obtain nanometer-thick film materials with unique properties that are not typical for the bulk state. It was experimentally established that the transition from bulk to film material leads to changes in its physical properties. The main reasons for this are related to: the different structure of materials; size effects that arise as a result of limiting the average length of the free path of electric current carriers by the outer surfaces of the film or the geometric dimensions of the crystallites; by changing the frequency and energy characteristics of the atoms of the crystal lattice under the influence of the temperature factor. Based on the temperature dependences of the resistivity of single-layer films of noble metals the features of high-temperature electron-phonon interaction were analyzed. We established that the angular coefficient of the linear section of the temperature dependences of the single-layer metal films resistivity increases with a decrease in their thickness. When the film thickness decreases, the average phonon energy increases, which leads to an increase in the efficiency of electron-phonon scattering and, as a consequence, an increase in resistivity.

Keywords: Single-layer metal films, Size effects, Debye temperature, Effect of electron-phonon interaction.

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1. INTRODUCTION

The modern development of microelectronics and sensor technology makes it possible to obtain nanometer-thick film materials with unique properties that are not typical for these materials in a massive state. It was experimentally established that the transition from massive to film material leads to changes in its physical properties [1-5].

The main reasons for this are related to the different structure of the films; with the influence of the thickness or size of the crystallites, which manifests itself in dimensional effects arising from the limitation of the average length of the free path of electric current carriers by the outer surfaces of the film or the geometric dimensions of the crystallites, as well as with a change in the frequency and energy characteristics of the atoms of the crystal lattice under the influence of temperature and mechanical factors.

The question of the peculiarities of the temperature dependence of the resistivity of film materials and temperature effects on the parameters of electrical transmission remain relevant, since they are of great importance in predicting the performance characteristics of sensitive elements of microelectronic sensors, which are widely used in integrated microelectronics [6-10], devices and medical equipment (see, for example, [11]).

In work [12] carried such an investigation based on first principles, combining electron-phonon and surface scatterings in the relaxation time approximation of Boltzmann's transport equation. We discuss the validity of different proxies of the resistivity at low dimensions (both for thin films and rectangular nanowires), including the so-called product, that do not require the computation of the electron-phonon relaxation time.

A systematic investigation of the differences in charge transport mechanism in ultra-thin nano-island like films of palladium with thickness varying between 5 nm and 3 nm have been conducted [13]. The thicker films were found to be metallic in a large temperature range with a dominant Bloch-Grüneisen mechanism of charge transport arising due to electron-acoustic phonon scattering. In work [13] these films were also found to exhibit an additional electron-magnon scattering. At temperatures below 20 K, the two films displayed a metal-insulator transition.

The aim of the work was to establish the influence of the Debye temperature change (Θ_D) on the effectiveness of charge carrier scattering in the thermoresistive properties of single-layer metal films as elements of sensor electronics.

2. EXPERIMENTAL DETAILS

A vacuum chamber VUP-5M type was used to form single-layer metal films of Pd, Pt, and Ag ($p \sim 10^{-3}$-10^{-4} Pa) and a high-vacuum installation based on a turbomolecular pump Pfeiffer-Balzers TPH-330

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(p ~ 10^{-5} Pa). Film materials were formed by condensation of metals using the thermoresistive method. Thickness (d) varied from 10 to 100 nm. The rate of deposition of metals was 1-1.5 nm/s. Cooling speed – 3 K/min. With the help of digital multimeters of the type UT70D and UT70B the electrical resistance of the films and the temperature of the substrate were monitored. Experimental data from multimeters RS232 and RS485 through the interface were transferred to the computer. The thickness of the films was monitored in situ by the quartz resonator method.

3. RESULTS OF EXPERIMENTS AND CALCULATIONS

Studies of the temperature dependence of the specific resistance for metal films show (see, for example, [14, 15]), that depends $\rho(T)$ features appear at characteristic temperatures, the value of which depends on the thickness of the films. The peculiarities of the temperature dependence of the resistance, which is due to scattering on the outer surfaces of the film, is determined by the degree of dispersion of the crystals.

The size dependences of the specific resistance were determined experimentally and are shown on Fig. 1.

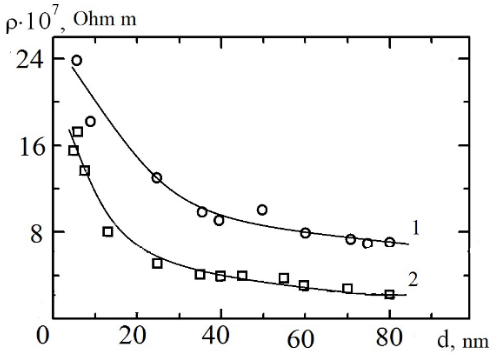


Fig. 1 – The size dependences of resistivity ρ for films Pt(1) and Pd (2)

The analysis of the experimental results obtained by us showed that the specific resistance of single-layer films of noble metals (Pd, Pt and Ag) is determined by the technological conditions of production and annealing. Asymptotic values ρ_∞, obtained by extrapolating the thickness to infinity ($d \to \infty$), equal: for films Pd – ρ_∞(Pd) = $2.5 \cdot 10^{-7}$ Ohm·m; for films Pt – ρ_∞ (Pt) = $6.1 \cdot 10^{-7}$ Ohm·m and for films Ag – ρ_∞ (Ag) = $16.2 \cdot 10^{-7}$ Ohm·m.

The resistance of conductors arises as a result of the scattering of conduction electrons and holes on electrons, phonons and defects in the crystal structure. For bulk samples of transition d-metals, the temperature dependence of the resistivity (Debye-Gruneisen theory) is expressed as ratio (1):

$$\rho_0(T) = \rho_{0з} + A \cdot T^2 + B\left(\frac{T}{\Theta_{0D}}\right)^3 \cdot j_3\left(\frac{\Theta_{0D}}{T}\right) + C\left(\frac{T}{\Theta_{0D}}\right)^5 \cdot j_5\left(\frac{\Theta_{0D}}{T}\right), \quad (1)$$

where $\rho_{0з}$ is residual resistance associated with scattering of electric current carriers on lattice defects, which does not depend on temperature; A, B, C is proportionality coefficients; Θ_{0D} is a Debye temperature for bulk material;

$$j_n(\Theta_{0D}/T) = \int_0^{\Theta_{0D}/T} \frac{x^n dx}{(e^x - 1)\cdot(1 - e^{-x})}$$ is a Debay integral.

The addition, proportional to T^2, is associated with electron-electron scattering and appears only when $T < 10$ K. Additions, which proportional accordingly T^3 and T^5, due to the scattering of an s-electron by a phonon into the d-zone or s-zone.

In the case of metallic film materials, the ratio (1) turns into the form:

$$\rho(T) = \rho_з + a \cdot T^2 + c^* \cdot \left(\frac{T}{\Theta_D}\right)^3 \cdot j_3\left(\frac{\Theta_D}{T}\right), \quad (1')$$

where a, b, c are coefficients of similar A, B, C; Θ_D are the Debye temperature in films; $c^* = b + c$ is the effective parameter of the electron-phonon interaction.

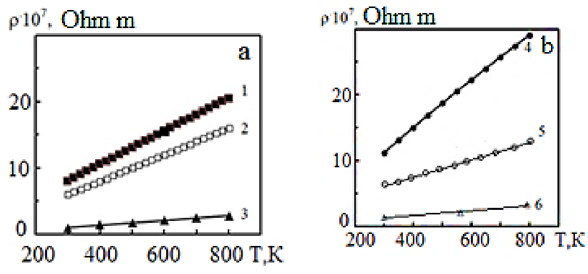
Parameter c^* is determined by the formula:

$$c^* = tg\alpha \frac{\Theta_D^3}{T^2} \cdot \frac{1}{J_3\left(\frac{\Theta_D}{T}\right)}, \quad (2)$$

where tgα is a the tangent of the angle of inclination of the linear section $\rho(T)$.

If you build a dependency $\rho(T)$ in the rectifying coordinates, then it can be determined a and c^* for different thicknesses. Since the temperature interval of our measurements is such that $0.625 \le \Theta_D/T \le 4.944$, then the proportionality coefficients near the corresponding terms turn out to be functions that weakly depend on the temperature at a fixed thickness. A ratio (2) can be used only for estimation, more accurate values are obtained in the determination c^* by the tangent of the angle of inclination of the corresponding straight line in the correcting coordinates from the ratio:

$$tg\alpha = c^* \frac{T^2}{\Theta_D^3} \cdot J_3\left(\frac{\Theta_D}{T}\right).$$



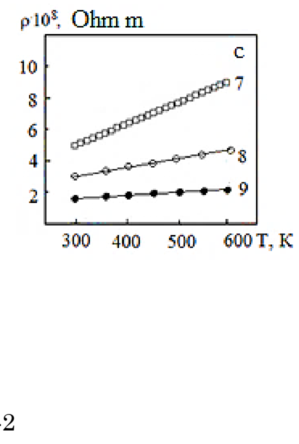


Fig. 2 – Experimental dependencies $\rho(T)$ for films Pd (a), Pt(b) and Ag(c). Thickness, nm: 20 (1); 35 (2); 10 (4); 50 (5); 25 (7); 85 (8) and for bulk samples (3, 6 and 9).

The ratio (1′) takes into account that in thin samples (foil, wires and films) the law $\rho_0 \sim T^5$ passes into law $\rho \sim T^3$ at low temperatures, and this makes it possible to combine the terms responsible for the Mott term *s-d* – scattering and *s-s* – scattering. In addition, it should be emphasized that the Debye temperature in film materials differs from Θ_{0D}.

Fig. 2 shows that for films Pd, Pt and Ag value tgα increases with decreasing film thickness *d* due to the strengthening of the electron-phonon interaction, since the average energy of the phonon in general increases.

For single-layer films of noble metals Pd, Pt and Ag (Fig. 2) an increase in the angle of inclination of the temperature dependences is observed $\rho(T)$ when reducing the thickness of the film material: from $1.9\cdot10^{-10}$ to $2\cdot10^{-9}$ Ohm·m/K (for Pd films with the thickness to 35 nm); from $6\cdot10^{-10}$ to $3{,}7\cdot10^{-9}$ (for Pt films with the thickness to 50 nm) and from $0.3\cdot10^{-10}$ to $1.3\cdot10^{-10}$ Ohm·m/K (for Ag films with thickness to 85 nm). All this indicates an increase in the role of electron-phonon interaction in thermoresistive properties in the interval of intermediate operating temperatures. It should also be borne in mind that relation (1) describes the temperature dependence of the resistivity of non-ferromagnetic samples in the most general case, therefore it does not take into account peculiarities at the points of magnetic transitions and at the Debye temperature.

Electron-phonon scattering plays a major role in the resistivity of thin films, and the shift of the phonon spectrum in films, compared to bulk samples, is one of the reasons for the decrease in the value of the Debye temperature in the film. Depending on the thickness of the film, the Debye temperature has a value Θ_D(Pd) = 540-565 K; Θ_D(Pt) = 510-530 K and Θ_D(Ag) = 490-505 K.

All of the above is confirmed by the results of calculations based on the experimental dependences of the resistivity on the temperature of the electron-phonon interaction parameters for single-layer Pd and Pt metal films (Table 1). It was found that when the thickness decreases from 50 to 20 nm parameter in Pd and Pt films *c** in the temperature range 300-800 K grows in 1.2-1.6 times.

Table 1 – Calculations results of electron-phonon interaction parameters for Pd and Pt films

T, K	$c_1^*\cdot10^{-9}$, Ohm·m	$c_2^*\cdot10^{-9}$, Ohm·m	T, K	$c_1^*\cdot10^{-9}$, Ohm·m	$c_2^*\cdot10^{-9}$, Ohm·m
Pd			**Pt**		
	d = 35 nm	d = 20 nm		d = 50 nm	d = 20 nm
300	0.365	0.435	300	0.358	0.430
400	0.353	0.418	400	0.346	0.417
500	0.347	0.400	500	0.334	0.405
600	0.331	0.382	600	0.321	0.395
700	0.324	0.372	700	0.313	0.376
800	0.315	0.364	800	0.302	0.361
	$\overline{c_1^*} = 0.339\cdot10^{-9}$ Ohm·m	$\overline{c_2^*} = 0.395\cdot10^{-9}$ Ohm·m		$\overline{c_1^*} = 0.329\cdot10^{-9}$ Ohm·m	$\overline{c_2^*} = 0.397\cdot10^{-9}$ Ohm·m

4. CONCLUSION

Based on the temperature dependence of the resistivity of single-layer metal films, the features of the high-temperature electron-phonon interaction and its influence on the Debye temperature were analyzed. We found that the angular coefficient of the linear section of the temperature dependences of the resistivity of single-layer metal films Pd, Pt and Ag increases with a decrease in their thickness. This indicates an increase in the role of surface electron scattering effects in thermoresistive properties at temperatures higher than the Debye temperature.

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Ефект електрон-фононної взаємодії в питомому опорі металевих плівок як елементів сенсорної електроніки

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Сучасні технології електроніки і сенсорної техніки дозволяють отримувати плівкові матеріали нанометрової товщини із унікальними властивостями, які не є типовими для масивного стану. Експериментально встановлено, що перехід від масивного до плівкового матеріалу призводить до змін його фізичних властивостей. Основні причини цього пов'язані: з різною структурою матеріалів; розмірними ефектами, які виникають у результаті обмеження середньої довжини вільного пробігу носіїв електричного струму зовнішніми поверхнями плівки або геометричними розмірами кристалітів; зміною частотних і енергетичних характеристик атомів кристалічної решітки під дією температурного фактору. На основі температурних залежностей питомого опору одношарових металевих плівок благородних металів (Pd, Pt і Ag) проаналізовані особливості високотемпературної електрон-фононної взаємодії. Нами установлено, що кутовий коефіцієнт лінійної ділянки температурних залежностей питомого опору одношарових плівок зростає при зменшенні їх товщини. При зменшенні товщини плівки середня енергія фонона збільшується, що призводить до підвищення ефективності електрон-фононного розсіювання і, як наслідок цього, – зростання питомого опору.

Ключові слова: Одношарові металеві плівки, Розмірні ефекти, Температура Дебая, Ефект електрон-фононної взаємодії.