ENERGY OF ADHESIVE BONDS IN A COPPER–SOLID SYSTEM

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Making use of the macroscopic methods of surface physics, the energy of adhesive bonds in nanosize layers near the interfaces between copper and various materials in a solid state (zinc, silicon, and quartz) has been considered. The energy of adhesive bonds and the adhesion work have been found to be of the order of magnitude as large as the interphase energy and the interphase tension, respectively. The behavior of temperature variations of the energy-related interphase and adhesive parameters of the Cu—Zn system has been studied.

1. Introduction

Owing to a perspective for copper condensates to be widely used in the modern microprocessor technology, the issue concerning energy-related properties of thin nanosize layers between copper and various inorganic materials is vital. In particular, it is of importance to possess the quantitative estimations of physical bonds that arise in a system of contacting materials. Such information explains variations of the electrical and mechanical parameters of the interphase layers, as well as a reduction of adhesion resistance.

It is known that the nature of structural mechanical stresses in the interphase layer at the metal—metal (or metal—insulator, or metal—semiconductor) interface has not been studied enough until now [1]. There are only partial model ideas concerning the mechanisms of emergence of those stresses, namely, the model of surface disordering, the model of grain boundary relaxation, the model of boundary growth, the impurity model [2–4]. Internal stresses are generally considered to be caused by the features of the coating formation process, the nonequilibrium character of the condensation, recrystallization, and the interaction between condensates and residual gases that penetrate into the interphase region.

It is also known [1] that the quantitative information about mechanical stresses in thin nanosize layers is obtained mainly using indirect methods of measurement after condensates having been formed. Therefore, the results of the corresponding measurements contain information concerning only integral macrostresses that appear after the diverse bodies having been brought into contact. Such "postprocessing" measurements do not provide the full information about the quantitative contribution of every component to the measured integral value of the stress [5]. A well-grounded thermodynamic analysis of the process of formation of structural stresses, of energy-related and adhesive bonds in a system of contacting bodies is also absent.

The purpose of this work was therefore to study the interphase and adhesive bonds in copper which contacts with various materials and to develop a relevant thermodynamic model for analyzing and comparing both energy characteristics and regularities of their changes.

2. Thermodynamic Description of Interphase Bonds in a System of Contacting Bodies

Our researches of the characteristics of interphase interaction are based upon the relations of nonequilibrium thermodynamics and solid surface physics [6, 7]. Using experimental data and tabulated

values of the physical parameters of inorganic materials [8–12], as well as the system of equations that describes mechanical and electric processes in surface layers [6, 7], let us estimate the interphase and adhesion energy parameters of a system of contacting materials in the equilibrium thermodynamic state.

3. A Method of Determination of Surface Energy Variations

In order to calculate the interphase energy, let us consider a macroscopic model of the surface layer in a solid (see Fig. 1), where a continuous medium (metal, in particular copper) fills the half-space $x > 0$ (V_1), whereas the half-space $x < 0$ (V_2) is occupied by another solid, namely, zinc, silicon, or quartz; x, y, and z being the Cartesian coordinates.

We write down the relations of the thermodynamic model for the surface layer of a metal (a copper film) that contacts with a substrate as follows [1]:

$$\sigma_h = \int_0^h \sigma_y dx, \quad \sigma_y = \sigma_z, \tag{1}$$

$$\sigma_y|_{x=h} + p = 0, \tag{2}$$

$$\gamma = \gamma_1 + \xi\gamma_2, \tag{3}$$

$$\frac{\partial\gamma}{\partial k} = \frac{\partial(\gamma_1 + \xi\gamma_2)}{\partial k} = 0; \tag{4}$$

$$\sigma_{ij} = E(\nu e/(1+\nu) - b\varphi/3)\delta_{ij}/(1-2\nu) +$$

$$+Ee_{ij}/(1+\nu), \tag{5}$$

$$\omega_v = \rho\omega = \varepsilon_0 k^2\varphi + bEe/(3(1+\nu)); \tag{6}$$

$$[\varphi = -\Phi_0]_{x=0}, \quad [\sigma_x = -(\varepsilon_0/2)(\partial\Psi/\partial x)^2]_{x=0}. \tag{7}$$

Here, σ_h is the surface tension; $p = 100$ kPa is the atmospheric pressure; γ is the surface energy equal to the sum of electrostatic, γ_1, and mechanical, $\xi\gamma_2$, components;

$$\gamma_1 = \int_0^h w_1 dx, \quad \gamma_2 = \int_0^h w_2 dx;$$

$$w_1 = \frac{\varepsilon_0}{2}\left(\frac{\partial\Psi}{\partial x}\right)^2, \quad w_2 = \frac{\sigma_x(\sigma_x - 4\nu\sigma_y)}{2E} - \frac{(1-\nu)\sigma_y^2}{E};$$

h is the effective thickness of the surface layer; σ_{ij} and e_{ij} $(i, j = 1, 2, 3)$ are the components of the stress tensor,

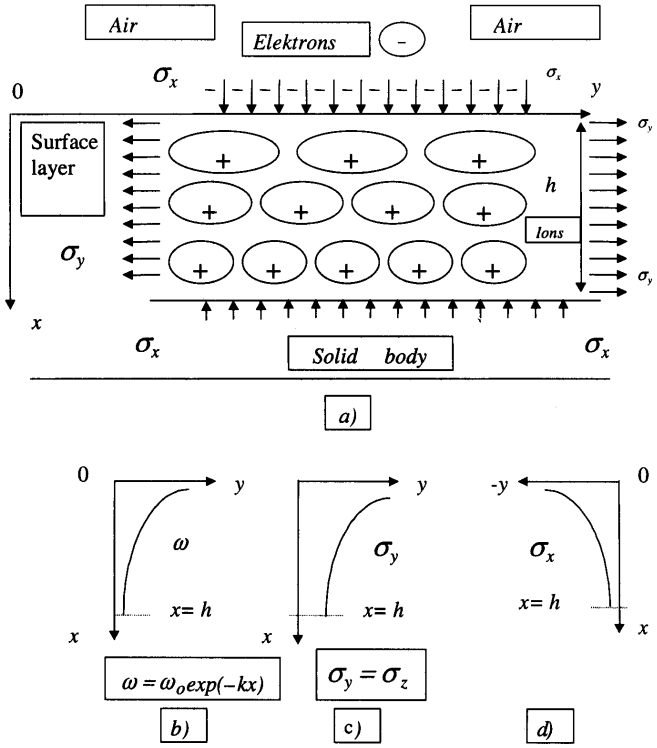

Fig. 1. Scheme of the surface layer and the corresponding distributions of electric charges and mechanical stresses

$\hat{\sigma}$, and the deformation tensor, $\hat{e}$, respectively, with $\sigma_{11} = \sigma_x$ and $\sigma_{22} = \sigma_y$; b, k, ξ, and $z_1 = \gamma_1/\gamma$ are the physical characteristics of the material; δ_{ij} is the Kronecker symbol; e is the first invariant of the deformation tensor; ρ is the medium density; ω_v and ω are, respectively, the spatial and mass densities of the electric charge; $\varphi = \Phi - \Phi_0$ is the deviation of the modified potential Φ of electric charges from its equilibrium value Φ_0 in the bulk of the body far from the body's surface; Ψ is the scalar potential of the electric field strength; E is Young's modulus, and ν is Poisson's ratio. It should be noted that the electrostatic component is represented separately in relation (3), similarly to what was done in a number of works dealing with surface physics [13].

Relations (1)—(4) make up a system of four equations for the determination of physical (ξ, b, and k) and geometrical (h) characteristics of the surface layer.

Using the balance equation [1]

$$\nabla\hat{\sigma} - \rho\omega\nabla\Psi = 0,$$

the equations of state (5) and (6), and the boundary conditions (7), the stresses in the surface layer can be

found by expanding them and the deformations into the series in the small dimensionless parameter $b_s = b\Phi_0$.

The relations, which describe the parameters of mechanical and electric fields in silicon (semiconductor) and quartz (insulator), are similar to relations (1)–(4). Since the density of free electric charges in silicon is insignificant and the polarization of atoms can be rather large, we use an approach, according to which the surface energy also includes, in addition to the mechanical component, a component that corresponds to bound electric charges. The theory of bound electric charges in bulk media was expounded, in particular, in monograph [14]. In work [15], this theory was applied when considering the surface layers of insulators.

For silicon, in analogy with an insulator [15], the modified chemical potential Z_c of the bound electric charges was introduced. The potential Z_c in the expression $dU = Z_c d\omega_c + \ldots$ for the variation of the internal energy [15] is a parameter conjugated to the density ω_c of the bound electric charges. For silicon and quartz,

$$w_{1c} = \frac{\varepsilon_0}{2}\left(\frac{\partial Z_c}{\partial x}\right)^2$$

is the specific energy of the field of the bound electric charges,

$$\nabla\hat{\sigma}_c - \rho_c\omega_c\nabla Z_c = 0$$

is the balance equation, and $b_{bc} = b_c/Z_c$ is the small parameter.

The equation of state and the boundary conditions for silicon or quartz are written down in the form [15]

$$\sigma_{ijc} = E_c(\nu_c e_c/(1+\nu_c) - b_c\varphi_c/3)\delta_{ij}/(1-2\nu_c) +$$

$$+E_c e_{ijc}/(1+\nu_c), \tag{8}$$

$$\omega_{cv} = \rho_c\omega_c = \varepsilon_0 k_c^2\varphi_c + b_c E_c e_c/(3(1+\nu_c)), \tag{9}$$

$$\varphi_c = -Z_{c0}]_{x=0}, \left[\sigma_x = -(\varepsilon_0/2)(\partial Z_c/\partial x)^2\right]_{x=0}, \tag{10}$$

where $\varphi_c = Z_c - Z_{c0}$ is a deviation of the potential Z_c from its equilibrium value Z_{c0} attained far from the surface into the body bulk, $k_c = (\rho_c C_{ce}/\varepsilon_0)^{1/2}$ and b_c are the characteristics of the material, subscript c means that the relevant parameter or characteristic corresponds to silicon or quartz, and $i, j = 1, 2, 3$.

A substantiation of the method for estimating the surface energy of copper and its loading-induced variations is based on the relations of the method of atomic interactions [16], which takes into account the centrosymmetrical potential of central forces $u_{\alpha\beta}$ according to Born and Meyer [17]:

$$u_{\alpha\beta} = q^2/R_{\alpha\beta} - c_{\alpha\beta}/R^6_{\alpha\beta} -$$

$$-d_{\alpha\beta}/R^8_{\alpha\beta} + b_{\alpha\beta}\exp(-R_{\alpha\beta}/\rho_q). \tag{11}$$

Here, q is the electric charge of particles, $R_{\alpha\beta}$ is the distance between the α-th and β-th particles, $c_{\alpha\beta}$, $d_{\alpha\beta}$, and $b_{\alpha\beta}$ are constants, and ρ_q is the "stiffness" parameter.

In work [16], as well as in a number of other works on physical chemistry, the approximate relation

$$\sigma_{\alpha\beta} = \gamma\delta_{\alpha\beta} + \partial\gamma/\partial e_{\alpha\beta},$$

between the components of the surface forces $\sigma_{\alpha\beta}$ $(\alpha, \beta = 1, 2)$ and the surface energy γ for a two-dimensional medium is presented, while the expression for the surface tension looks like

$$\sigma_h = \sigma_{\alpha\alpha}/2 = (\sigma_{11} + \sigma_{22})/2.$$

In this work, we develop a three-dimensional approach to study surface effects. Therefore, the basic relations of the model (1)–(4) take into account the fact that the parameters σ_h and γ of the surface layer, although having identical dimensionalities, nevertheless possess somewhat different physical meanings: $[\sigma_h] = \mathrm{N/m}$ (the stresses summed up within the surface layer) and $[\gamma] = \mathrm{J/m^2}$ (the energy of the surface layer per unit of area).

4. Determination of the Interphase Energy and the Energy of Adhesive Bonds

We define the interphase energy W_m and the tension σ_m similarly to works [1, 6]:

$$W_m = \gamma_3 + \xi_m\gamma_4, \quad \gamma_4 = \int\limits_{-H}^{H} w_1 dx,$$

$$\gamma_5 = \int\limits_{-H}^{H} w_2 dx, \quad \sigma_m = \int\limits_{-H}^{H} \sigma_y dx. \tag{12}$$

Here, ξ_m and $z_e = \gamma_3/W_m$ are the physical characteristics of the interphase layer and $2H$ is its effective thickness.

The condition of the interphase layer balance and the approximated boundary conditions (at $x = \pm H$) are [1]

$$\partial W_m/\partial x = \partial(\gamma_3 + \xi_m\gamma_4)/\partial x = 0,$$

$$\sigma_y^+ + p = 0 \quad (x = +H), \quad \sigma_y^- + p = 0 (x = -H). \tag{13}$$

Here, superscript "+" denotes copper parameters and "–" does the parameters of the other medium (zinc, silicon, or quartz).

The match conditions at the metal—insulator or metal—semiconductor interface (at $x = 0$) are [7, 15]

$$\varphi_+ = -\Phi_0, \quad \varphi_{c-} = \varphi_c = -Z_{c0},$$

$$\sigma_{x+} = \sigma_{x-}, \quad \sigma_{y+} = \sigma_{y-}. \tag{14}$$

The analogous conditions at the metal–metal interface (also at $x = 0$) are [6, 7]

$$\varphi_+ + \Phi_{0+} = \varphi_- + \Phi_{0-},$$

$$j_+ = j_-, \quad \sigma_{x+} = \sigma_{x-}, \sigma_{y+} = \sigma_{y-}. \tag{15}$$

Relations (12)—(15) compose the basis of the system of equations for the determination of the physical characteristics ξ_m, $b = (b_+, b_-)$, $k = (k_+, k_-)$ and the thickness $2H$ of the surface layer.

From the medium interface conditions (14), one can see that the problem of determination of the bound electric charge distribution belongs to the class of boundary problems, while the problem of determination of mechanical stresses does to the class of contact ones. Therefore, relations (12)–(14) constitute the basis of a contact-boundary problem. On the other hand, according to the medium interface conditions (15), both the problems of determination of the free electric charge distribution and mechanical stresses belong to the class of contact problems. Therefore, relations (12), (13), and (15) constitute the basis of the contact problem.

The work of adhesion $A_{\rm ad}$ in the system copper–contacting medium is determined making use of the known relation [18]

$$A_{\rm ad} = \sigma_{h+} + \sigma_{h-} - \sigma_m. \tag{16}$$

Similarly to expression (16), let us introduce the energy of adhesive bonds $W_{\rm ad}$:

$$W_{\rm ad} = \gamma_+ + \gamma_- - W_m. \tag{17}$$

It should be noted that the surface energy γ and the tension σ_h for liquids are equated in a lot of publications (see, e.g, [8, 16, 18]). But according to relations (1) and (3), it follows that γ and σ_h are not identical in general even for a liquid. Therefore, the energy characteristics of the surface and interphase layers, as well as those of the adhesive bonds $A_{\rm ad}$ and $W_{\rm ad}$, can be considered different for liquids too, and calculations confirm this conclusion.

5. Numerical Calculations. Discussion of Results

The numerical values of the relevant physical constants for media under consideration are as follows [8–12, 18]: for Cu:

$$E = 118 \text{ GPa}, \quad \nu = 0.372, \quad \omega = 8.45 \times 10^{28} 1/\text{m}^{-3},$$

$$\sigma_{h+} = 2.125 \text{ N/m}, \quad \gamma = 1.623 \text{ J/m}^2;$$

for Zn

$$E = 81 \text{ GPa}, \quad \nu = 0.25, \quad \omega = 13.1 \times 10^{28} \text{ m}^{-3},$$

$$\sigma_h = 0.9 \text{ N/m}, \quad \gamma = 1.01 \text{ J/m}^2;$$

for Si:

$$E = 109 \text{ GPa}, \ \nu = 0.317, \quad \omega = 5 \times 10^{28} \text{m}^{-3},$$

$$\sigma_h = 1.547 \text{ N/m}, \quad \gamma = 1.182 \text{ J/m}^2;$$

for quartz:

$$E = 70 \text{ GPa}, \ \nu = 0.25, \quad \omega = 7.92 \times 10^{28} \text{ m}^{-3},$$

$$\sigma_h = 1 \text{ N/m}, \ \gamma = 0.737 \text{ J/m}^2. \tag{18}$$

Here, the values of the surface energy γ were obtained using the method of atomic interactions [16] and relation (11).

Solving the contact and contact-boundary problems (the system of equations (1)–(15)) with the use of the method of expansion into a series in a small parameter [19] (the small parameter is $b_s = b\Phi_0$ for metal, and $b_{sc} = b_c/Z_c$ for semiconductor or insulator), the following values of the energy and adhesive characteristics of the interphase layer material at room temperature ($T \approx 293$ K) were found:

a) for the system Cu—Zn:

$$W_m = 0.089 \ \text{J/m}^2, \ \sigma_m = 0.112 \ \text{N/m},$$

$$A_{\rm ad} = 3.023 \ \text{N/m},$$

$$z_a = A_{\rm ad}/\sigma_m = 27.0, \ W_{\rm ad} = 2.434 \text{ J/m}^2,$$

$$z_{\rm ad} = W_{\rm ad}/W_m = 27.3, \ \ z_e = \gamma_3/W_m = 0.0376; \tag{19}$$

b) for the system Cu—Si:

$$W_m = 0.258 \text{ J/m}^2, \ \sigma_m = 0.372 \text{ N/m}, \ A_{\rm ad} = 3.3 \text{ N/m},$$

$$z_a = A_{\rm ad}/\sigma_m = 8.87, \ W_{\rm ad} = 2.55 \text{ J/m}^2,$$

$$z_{\rm ad} = W_{\rm ad}/W_m = 9.9, \ z_e = \gamma_3/W_m = 0.111; \tag{20}$$

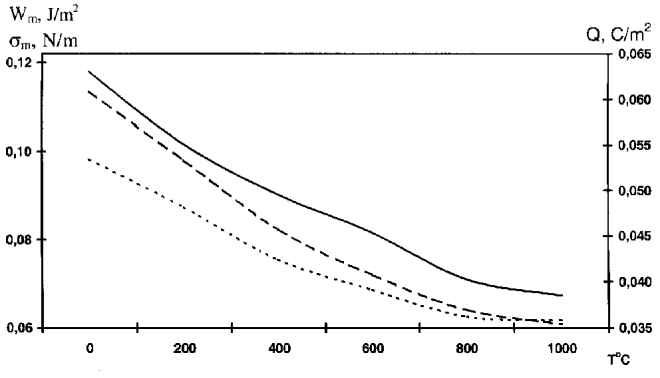

Fig. 2. Temperature dependences of the interphase energy $W_m(T)$ (dotted curve), the interphase tension $\sigma_m(T)$ (dashed curve), and the interphase electric charge $Q(T)$ (solid curve) in the Cu—Zn system within a temperature range of $0 - 1000°C$

c) for the system Cu—quartz:

$$W_m = 0.307 \text{ J/m}^2, \sigma_m = 0.44 \text{ N/m}, A_{\text{ad}} = 2.685 \text{ N/m},$$

$$z_a = A_{\text{ad}}/\sigma_m = 6.1, \; W_{\text{ad}} = 2.053 \text{ J/m}^2,$$

$$z_{\text{ad}} = W_{\text{ad}}/W_m = 6.68, \; z_e = \gamma_3/W_m = 0.133. \qquad (21)$$

The obtained numerical results (19)–(21) contain the information on peculiarities of the interphase and adhesive interactions between two metals [Cu and Zn, Eq. (19)], between a metal and a semiconductor (a copper condensate and silicon, Eq. (20)), and between a metal and an insulator [copper and quartz, Eq. (21)].

On the basis of Eqs. (19)—(21), it was established that the electric component of the interphase energy z_e in the Cu—Si and Cu—quartz systems differs substantially, namely, by a factor of 2.95 or 3.54, respectively, from that in the system of contacting metals Cu—Zn. At the same time, the energies of adhesive bonds W_{ad} in all those systems differ insignificantly by absolute value, but the ratio $z_{\text{ad}} = W_{\text{ad}}/W_m$ for the system of two metals is several times as large as the relevant values in the metal—semiconductor (by a factor of 2.76) and metal—insulator (by a factor of 4.09) systems. A new energy characteristic of the interphase layer, the energy of adhesive bonds W_{ad}, is greater than the interphase energy W_m in all the three cases, with the ratio z_{ad} between them being approximately equal to the ratio z_a between the adhesion work A_{ad} and the interphase tension σ_m.

If we compare the values of the relation $z_1 = \gamma_1/\gamma$, obtained on the basis of Eqs. (1)–(7), namely,

$$z_1 = 0.221 \text{ (Cu)}, \quad z_1 = 0.209 \text{ (Zn)},$$

$$z_1 = 0.241 \text{ (Si)}, \quad z_1 = 0.242 \text{ (quartz)}, \qquad (22)$$

with those of the ratio $z_e = \gamma_3/W_m$, calculated from Eqs. (19)—(21), a conclusion can be made that a contact of two media results in both an absolute and relative reduction of the power of the electrical double layer near the interface, the reduction manifesting itself through a difference between the relative components of energy characteristics z_e and z_1.

The dependences of the interphase energy W_m, the interphase tension σ_m, and the interphase electric charge Q in the Cu—Zn system on the temperature T were studied within the temperature range of 0—1000 °C. The results are presented in Fig. 2.

It should be noted that experimental dependences of the surface tension σ_h on the temperature T are linear for copper, zinc, quartz, and silicon within the range of 0—1000 °C [8]. They were taken as references when estimating the temperature variations of the energy quantity γ with the help of the atomic interaction method and using potential (11) as a basic one. The calculations showed that the values of γ for copper and zinc depend linear on the temperature within the range of investigation.

The temperature dependences of the interphase energy W_m, the interphase tension σ_m, and the interphase electric charge Q in the copper-quartz and copper—silicon systems are analogous to their counterparts in the copper-zinc one within the temperature range of 0—1000 °C and do not contain any additional qualitative physical information, being different only quantitatively. Therefore, they are not presented in this work.

From Fig. 2, one can see that the temperature dependences of the interphase physical quantities $W_m(T)$, $\sigma_m(T)$, and $Q(T)$ are nonlinear. Their relative variations in the range T=0—1000 °C can be estimated with the help of the relations

$$\Delta_w = 2(W_{m0} - W_{m1000}))/(W_{m0} + W_{m1000}) = 0.457,$$

$$\Delta_\sigma = 2(\sigma_{m0} - \sigma_{m1000}))/(\sigma_{m0} + \sigma_{m1000}) = 0.657,$$

$$\Delta_Q = 2(Q_0 - Q_{1000}))/(Q_0 + Q_{1000}) = 0.484. \qquad (23)$$

Here, subscripts 0 and 1000 correspond to the limit temperatures $T = 0$ and 1000 °C, respectively. On the basis of relations (23), a conclusion can be drawn that, among the quantities W_m, σ_m, and Q, the parameter σ_m undergoes the most substantial temperature variations.

The temperature dependences of other physical quantities, namely, W_{ad}, A_{ad}, z_e, and $z_{wa} = 0.2(A_{\text{ad}} -$

$W_{\rm ad})/(A_{\rm ad} + W_{\rm ad})$, for the Cu–Zn system within the temperature interval of 0—1000 °C are presented in Fig. 3. The relative variations of those quantities can be estimated analogously to relations (23):

$$\Delta_{W_{\rm ad}} = 0,495, \quad \Delta_{A_{\rm ad}} = 0,370,$$

$$\Delta_{z_e} = 0,875, \quad \Delta_{z_{wa}} = 0,458. \qquad (24)$$

Thus, a conclusion can be made that among the quantities $W_{\rm ad}$, $A_{\rm ad}$, z_e, and z_{wa}, the parameter z_e undergoes the most substantial temperature variation, which exceeds the corresponding variation of the parameter σ_m (see relations (23)).

The suggested method enables one to extend the calculations of interphase energy, interphase tension, and energy of adhesive bonds carried out for the interface between a metal film and a substrate made up of inorganic material, to other contacting systems which are used in microelectronics (e.g., Al—Ge, Al—quartz, etc.).

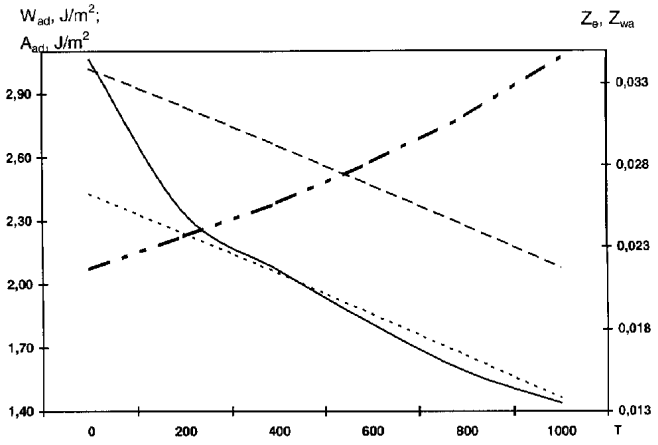

Fig. 3. Temperature dependences of the adhesive bond energy $W_{\rm ad}(T)$ (dotted curve), the adhesion work $A_{\rm ad}(T)$ (dashed curve), the ratio $z_e(T) = \gamma_3/W_m$ of the electrostatic component to the total interphase energy (solid curve), and the quantity $z_{wa} = 0.2(A_{\rm ad} - W_{\rm ad})/(A_{\rm ad} + W_{\rm ad})$ (dash — dotted curve) for the Cu—Zn system within a temperature range of 0 – 1000 °C

Conclusions

1. On the basis of the thermodynamic approach to studying the mechanoelectrical processes in nanosize layers near the interface metal—inorganic medium (metal, semiconductor, insulator), a relation between the contact and contact-boundary problems aimed at the determination of the distributions of free electric charges in the metal, the bounded electric charges in the insulator and semiconductor, and the corresponding mechanical stresses has been established.

2. It has been found that the electric components of the interphase energy in the Cu—Si and Cu—quartz systems differ substantially from that in the system of contacting metals Cu—Zn. In particular, the former are larger by a factor of 2.95 or 3.54, respectively, than the latter. This evidences for a dominating reduction of the power of the electrical double layer near the metal—metal interface, in comparison with the metal—semiconductor and metal—insulator ones.

3. It has been found that the energies of adhesive bonds $W_{\rm ad}$ in all the three systems Cu—Zn, Cu—Si, and Cu—quartz differ insignificantly by their absolute values, but the value of the ratio $z_{\rm ad} = W_{\rm ad}/W_m$ for the system of two metals is several times as large as the corresponding value for the system metal—nonmetal.

4. The absolute numbers have been determined for the interphase tension, the interphase energy, the adhesion work, and a new energy characteristic of the interphase layer, i.e. the energy of adhesive bonds $W_{\rm ad}$ which is larger than the interphase energy. The adhesion work $A_{\rm ad}$ occurred to be larger than the interphase tension σ_m by approximately the same factor.

5. A numerical experiment for the systems copper–zinc, copper–silicon, and copper–quartz showed that the thermodynamic approach, when estimating the interphase and adhesive energy characteristics of the surface layer, is less cumbersome as compared with the approach of atomic interactions. Moreover, it allows the electric component of the interphase energy W_3 to be taken into account.

6. The temperature variations of a number of the interphase and adhesive energy characteristics of the system of contacting metals Cu–Zn have been studied within the range $T = 0 - 1000$ °C. A linear behavior of the adhesive energy characteristics and a nonlinear one of the interphase energy characteristics have been revealed.

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ЕНЕРГІЯ АДГЕЗІЙНИХ ЗВ'ЯЗКІВ У СИСТЕМІ МІДЬ—ТВЕРДЕ ТІЛО

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Р е з ю м е

Із застосуванням макроскопічних методів фізики поверхні досліджено енергію адгезійних зв'язків у наношарах поблизу межі поділу між міддю та різними матеріалами (цинком, кремнієм і кварцом) у твердому стані. Встановлено, що енергія адгезійних зв'язків і робота адгезії відповідно на порядок більші порівняно з міжфазними енергією та натягом. Досліджено характер температурних змін енергетичних міжфазних та адгезійних параметрів системи Cu—Zn.