Metal coatings based on complex compounds of copper (II)
with organophosphorus complexones

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Abstract. An important problem of the metal coatings formation processes is the choice of
complexing agents for the preparation of process solutions. Nowadays a large number of
complex electrolytes for metal deposition have been developed and introduced into production.
However, the search for new, more efficient ligands allowing to obtain coatings with specified
functional properties is an urgent task and constantly attracts the attention of researchers. To
optimize and develop promising technological processes for producing metal coatings,
experimental studies of electrode reactions in complex electrolytes are necessary. From this
point of view, the study of electrochemical behavior of complex copper (II) ions with
hydroxyethylidene diphosphonic acid is of considerable theoretical and practical interest.
Oxyethylidene diphosphonic acid forms stable complexonates with copper (II) ions, the
compound is non-toxic and available on an industrial scale. To study the kinetics and
mechanism of copper deposition from solutions based on copper (II) complex compounds with
hydroxyethylidene diphosphonic acid we used modulation spectroscopy of electroreflection,
chronopotentiometry, and a rotary disk electrode. The paper shows that with increasing pH of
the solution, the overpotential of copper increases due to a change in the composition of the
discharging complex ion and adsorption phenomena on the electrode surface. In strongly
alkaline solutions, the discharge of complex ions flows from the adsorbed state.
Keywords: metal coatings, hydroxyethylidene diphosphonic acid, copper, electroreflection,
kinetic characteristics, adsorption.

1 Introduction

The transport industry, due to the continuous growth of the range of metal products, faces constant
expansion of application of metal coatings based on copper compounds. At the same time,
requirements are increasing for copper deposition technology and for the physicochemical properties
of the resulting depositions.

The promising direction for the development of new environmentally friendly technologies for
applying copper coatings is complex electrolytes based on organophosphorus compounds [1-4].
Complexes of copper (II) based on organophosphorus complexones have a wide variety of
applications [5-7]. The research showed [8, 9] that organophosphorus complexones can be used to
develop a highly efficient process of dielectrics metallization, a new technology for the chemical
deposition of copper without the use of toxic electrolytes.

The interaction of organophosphorus ligands with metal ions depends on a number of factors.
When complexon is introduced into the solution, conditions are created for the concentration between
the water molecules of the cation hydration shell and the ligand molecule. The necessary conditions
for the displacement of water from the aquacomplex are, first of all, a higher donor ability of the
ligand groups that bind to the metal, an appropriate pH value, and a rather convenient ligand structure.
Organophosphorus complexones are polydentate ligands, which molecule combines two types of complexing centers - acidic and basic [10-12]. This makes it possible for them to form cyclic structures with metal ions. One of the most interesting representatives with a spatially advantageous arrangement of complexing groups leading to the possibility of using all available donor ligand atoms in the complex is oxyethylidene diphosphonic acid (OEDP) [13]. Chelate compounds are more stable than complexes with monodentate ligands [14, 15].

Oxyethylidene diphosphonic acid has the following structure:

\[
\begin{array}{c}
\text{OH} \\
\text{O} = \text{P} - \text{C} - \text{P} = \text{O} \\
\text{OH} \\
\text{OH} \\
\text{OH} \\
\end{array}
\]

The equivalence of the two phosphonic groups, as well as the presence of a free hydroxyl group, were proved by IR spectroscopy, X-ray diffraction analysis, \(^1\)H and \(^{31}\)P NMR [17-20]. A special role of the hydroxyl group is manifested in the processes of ligand adsorption on a copper electrode, which was shown by electroreflectance spectroscopy [21-23].

In the literature there is information about the prospects of application organophosphorus ligands in the processes of chemical deposition of metals [24-27]. The nature of the ligand in chemical copper plating solutions plays an important role in ensuring the necessary stability with respect to the reaction of the metallic copper formation [28-30]. The stability of solutions is associated with the strength of the formed complex ions, their spatial structure, as well as with adsorption phenomena, surface-active properties of the ligand and complexes. Earlier, by the method of electron paramagnetic resonance, it was found that oxyethylidene diphosphonic acid forms stable complex compounds with copper (II) ions and is a promising ligand for producing high-quality metal coatings. To optimize the process conditions and develop an effective technology for applying copper coatings, further studies are needed to study the surface-active properties of the ligand, the state of the surface of the copper electrode, as well as the kinetics and mechanism of copper deposition from electrolytes based on organophosphorus complexones.

2 Materials and methods

We studied the adsorption phenomena on the electrode surface using the method of electroreflection. The method of electroreflection is a promising spectroscopic method in electrochemical studies. The electrical reflection spectrum is the dependence of the electrical reflection signal on the quantum energy of the incident light. When an electromagnetic wave is reflected from the electrode surface, its amplitude-phase characteristics change depending on the electronic state of the metal-solution interface, which allows us to establish the conditions and potentials of oxide formation and analyze the adsorption phenomena on the electrode formation [28-30]. The electroreflection method uses the modulation principle and is based on measuring the relative change in the reflection coefficient with a change in the electrode potential, which allows to increase the sensitivity of measurements and their reproducibility.

To record the electroreflectance spectra and determine the C, E – dependences on a copper electrode, we used a setup, which functional diagram was described in [12]. The electroreflectance spectra were recorded at a modulation frequency of the potential of 77 Hz, the modulation amplitude was 100 mV. The preparation of the copper electrode consisted of polishing with diamond powder, degreasing the electrode and preliminary polarization. Spectra were recorded at a quasinormal angle of light incidence. An incandescent lamp KGM-24-150 was used as a light source.

The electroreflectance spectra were recorded in the range of quantum energies from 1.5 to 3.0 eV. For copper, this spectral range contains features that make it possible to detect the absence or presence of oxide-type compounds on the surface. As the criterion for their absence we can consider the presence of a peak in the quantum energy region of the 2.16 eV and the negative sign of the signal in the entire
spectral range. Additional restrictions were imposed when recording the electroreflectance spectra in solutions containing copper ions. In this case, the spectral range was limited to the region of light transmission in the solution, and this region basically coincided with the used range from 1.5 to 3.0 eV.

The possibility of recording spectra in solutions containing copper ions, i.e., during electrodeposition and growth of a metal deposit on the electrode, happened due, firstly, to the high overvoltage of complex copper ions discharge. Secondly, to the morphology of the electrode surface during the discharge of the complexes did not underwent significant changes, and the reflectivity of the electrode did not decrease, in contrast to, for example, acidic sulfate electrolytes, where the occurred deposition sharply affects the optical properties of the surface.

We recorded the electroreflectance spectra in electrolytes containing copper as follows: the electrode was polarized in a sodium sulfate solution at \( E = -0.9 \) V for 10 minutes, then immersed in the test solution and, after establishing the equilibrium potential, the electroreflectance spectrum was recorded. Then, the potential shifted by 100 mV to the cathode region, and we recorded the next spectrum after 5 minutes, when a stationary state was established and the current through the electrode did not change its value.

To determine the mechanism and kinetic characteristics of the electrode processes, we also recorded polarization curves depending on the rotation speed of the disk electrode. As we know, a rotary disk electrode has great advantages, in particular, the fairness of its surface. The theory of this method is well developed and described in the monograph [13]. The rotation speed of the electrode was determined using a frequency meter ChZ-35A.

Chronopotentiograms were recorded on an MBH base chronopotentiometer equipped with a V7-22A digital voltmeter. Before applying a current pulse, the electrode was held for a certain time at the initial stationary potential, and then transited from the potentiostatic to the galvanostatic mode without breaking the polarizing circuit, the dependence of the potential on time was recorded on a S8-13 oscilloscope. Transition time was determined by the Reinmus graphic method described in [14].

All test solutions were prepared from reagents of the “c.p.” and “p.a.” qualifications, purified additionally by repeated recrystallization from bidistylate. The quantitative research methods described above made it possible to provide the necessary measurement accuracy. All measurements were carried out in a thermostatically controlled cell; the accuracy of temperature maintenance was \( \pm 0.2^\circ\text{C} \) (thermostat U-10). The error in the measurement of potentials was \( \pm 1-2 \) mV. Weighing of the samples was carried out on an analytical balance VLR-502 with an accuracy of 0.0002 g. The pH of the solutions was measured on a universal ionomer EV-74 with an accuracy of 0.05 pH units.

3 Results

To study the state of the copper electrode surface, in order to obtain information about the nature of the particles adsorbed on the electrode [15], this work uses the method of modulation spectroscopy of electroreflection, which allows us to establish the conditions and potentials of oxide formation and analyze adsorption phenomena directly during the experiment. Fig. 1 shows the electroreflectance spectra of a copper electrode in an OEDP solution and, for comparison, in a solution of \( \text{Na}_2\text{SO}_4 \) at pH = 9. In a sodium sulfate solution at \( E < -0.2 \) V (figure 1, a), the electroreflectance spectra have the form typical to the surface of metallic copper not coated with oxides [16].

At more positive potentials, a structure (figure 1a, cr. 5-6) caused by copper (I) oxide [17] appears in the electroreflectance spectra. In these OEDP solutions, under all studied conditions, the observed electroreflectance spectra (Fig. 1b) are typical for the unoxidized surface of copper. Therefore, the adsorption of OEDP prevents the formation of an oxide film and passivation of the electrode. The formation of surface complexes with partially reduced atoms is possible as a result of coordination of the ligand on the surface through the oxygen of the hydroxy group. Figure 2 shows the electroreflectance spectra for \( \text{Na}_2\text{SO}_4 \) and OEDP solutions at pH 12.8. As can be seen from the figure, the electroreflectance spectra in the OEDP and \( \text{Na}_2\text{SO}_4 \) solutions are of the same nature.
At $E \leq -0.4\, \text{V}$, the spectra have the form typical to an unoxidized surface of the copper electrode, and the formation of copper oxide (I) at $E > -0.4\, \text{V}$ leads to a change in the structure of the spectrum. The change in surface properties with increasing $\text{pH}$ of the solution can be explained by the emergence of competition during the simultaneous adsorption of the OEDP and $\text{OH}^-$ anions, which ultimately leads to the displacement of the OEDP anions. As a result, a passive film is formed on the surface of a copper electrode upon its contact with a OEDP solution at high $\text{pH}$ values, consisting of sparingly soluble copper compounds formed by the interaction of $\text{OH}^-$ ions with the electrode surface. In this case, probably, the main reaction is:

$$\text{Cu} + \text{OH}^- \rightleftharpoons \frac{1}{2} \text{Cu}_2\text{O} + \frac{1}{2} \text{H}_2\text{O} + e^- \quad (1)$$

The products of this reaction affect the stationary potential of copper in solution, as well as the speed of the cathodic process in the initial portion of the polarization curve. The formation of sparingly soluble compounds is also possible with cathodic polarization of electrodes.

Information on the processes of adsorption - desorption of compounds can also be obtained from the dependence of the electrofriction signal on the electrode potential. Figure 3 shows $\frac{\Delta R}{R}$, $E$-dependences recorded in the potentiodynamic mode (sweep speed 10 mV/s) in solutions of $\text{Na}_2\text{SO}_4$ and OEDP in the $\text{pH}$ range of 9 and 12.8.
In the presence of OEDP at pH 9, we observe a significant drop in the electroreflection signal in a wide range of potentials, and at a pH of 12.8, the dependence of the signal on the potential is close to that recorded in a surface-active electrolyte with the same pH value. A decrease in the electroreflection signal in a solution with pH 9 may indicate the adsorption of OEDP, since the electroreflection signal is proportional to the capacity of the double electric layer, which, in turn, decreases upon adsorption of organic compounds. The peak in the region of -0.5 V in the $\frac{\Delta R}{R}$ dependence is associated with the reduction of oxides on the surface and a sharp increase in the reflectivity of the electrode. In solutions of OEDP at pH 9, it is sharply weakened in comparison with the background electrolyte, which additionally indicates the stability of the surface properties of the electrode in the presence of OEDP. In cases of pH 12.8 in an OEDP solution, the decrease in the electroreflection signal is much smaller than at pH 9, which indicates a decrease in the interaction of OEDP with the electrode. As suggested above, an increase in the pH of the solution leads to the displacement of the adsorbed ligand molecules from the electrode surface as a result of its blocking by OH ions and the formation of oxide and hydroxide films.

The data obtained was confirmed by the results of chronopotentiometric measurements in $Na_2SO_4$ and OEDP solutions.

**Figure 3.** $\frac{\Delta R}{R}$, E-dependence for copper electrode ($h\omega = 2.17\ EV$) in the solution: 1, 2 – OEDP (0.1 mol/l); 1′, 2′ – $Na_2SO_4$ (0.1 mol/l); 1, 1′ – pH 9; 2, 2′ – pH 12.8.

**Figure 4.** The dependence of the electrode potential on time for solutions (mol/l): 1 – 0.05 $Na_2SO_4$; 2 – 0.05 OEDP; $i = 2.38\ mA/cm^2$; pH 12.8.
In the E-t oscillograms (figure 4), in cases of pH 12.8, we observe a potential delay, which, according to the value of the potential, corresponds to the region of reduction of copper (I) oxide.

Thus, a significant amount of cathodic polarization at high pH values may be caused by passivation of the electrode and adsorption phenomena occurring on the surface. The unstable activity of the electrode resulting from the formation of sparingly soluble compounds [18, 19] makes it difficult to experimentally determine the kinetic parameters of the process in strongly alkaline solutions. In this regard, the electrode processes in the Cu(II) – HEDP – H₂O system were studied in more detail in the pH range 9-10. As we have previously established [8], at these pH values, mainly one type of complex is formed in the solution, [Cu(HL)₂]^{6-}.

Figure 5 shows a series of polarization curves taken in the potentiodynamic mode, depending on the speed of rotation of the electrode. Processing of the experimental data in the coordinates \( i - \sqrt{\omega/2\pi} \) showed that the observed limiting current is caused by the slowed-down electrochemical diffusion stage. In accordance with the theory of the rotary disk electrode method, for the first-order electrode reaction proceeding in the region of mixed kinetics, the following equation is valid [11]:

\[
\frac{1}{i} = \frac{1}{nFkc} + \frac{1.61v^{1/6}}{nFD^{2/3}c} \cdot \frac{1}{\sqrt{\omega^{1/2}}}
\]

Figure 5. The dependence of current density on the speed of rotation of the electrode at potentials (V):
1 – 0.7; 2 – 0.75; 3 – 0.8; 4 – 0.85; 5 – 0.9; \( C_{Cu(II)} = 0.1 \text{ mol/l}; C_{HEDP} = 0.5 \text{ mol/l}; \text{pH} = 9 \).

Figure 6 shows \( 1/i, 1/\sqrt{\omega/2\pi} \) dependences, the linear nature of which indicates the occurrence of an electrochemical reaction of the first order.

Figure 6. Dependence \( 1/i \) on \( 1/\sqrt{\omega/2\pi} \) at potentials (V):
1 – 0.7; 2 – 0.75; 3 – 0.8; 4 – 0.85; \( C_{Cu(II)} = 0.1 \text{ mol/l}; C_{HEDP} = 0.5 \text{ mol/l}; \text{pH} = 9 \).
Extrapolation of the obtained dependences to $\omega \to \infty$ allows us to determine the true kinetic currents. The values of the true kinetic currents were used to construct the Tafel dependences, from which we determined the exchange current density and coefficient $b_k$. The obtained kinetic parameters are given in table 1.

As can be seen from the table, with an increase in the concentration of copper ions, the exchange current density increases and the discharge process is facilitated. The obtained values of the coefficient $b_k$ indicate that the discharge of copper ions occurs, apparently, according to a staged mechanism with a delayed addition of the first electron.

### Table 1. Kinetic characteristics of the discharge of copper (II) complexes with HEDP.

| $C_{Cu(II)}$, mol/l | $i_0 \cdot 10^6$, $A \cdot cm^{-2}$ | $\kappa_5 \cdot 10^7$, $cm \cdot sec^{-1}$ | $\eta_k$, mV |
|----------------------|---------------------------------|---------------------------------|--------------|
| 0,02                 | 0,48                            | 1,2                             | 171          |
| 0,05                 | 1,2                             | 1,2                             | 171          |
| 0,1                  | 2,1                             | 1,1                             | 167          |

To establish the electrochemically active form of the complex ion, we determined the reaction orders for the ligand and complex metal ions, and recorded polarization curves depending on the concentration of the complex ion. An increase in the concentration of complex ions in the range of 0.01 - 0.1 mol/l leads to an acceleration of the cathodic reaction and an increase in the limiting current. The order of the cathodic reaction for complex ions has a value close to 1:

$$P_k = \frac{\partial \log i}{\partial \log [Cu(HL)_2]} = 0,87,$$

which corresponds to the conclusion drawn on the basis of the linear nature of the $i / i - 1 / \sqrt{\omega / 2\pi}$ dependence obtained using a rotary disk electrode.

The study of the cathodic polarization in the potentiodynamic mode during the reduction of copper (II) complexes depending on the concentration showed that in the potential range of -0.6 - 0.8 V, with increasing concentration of HEDP, the cathodic polarization increases to a certain concentration of the ligand in the solution. A further increase in the concentration of HEDP does not lead to significant changes in the cathodic polarization. The observed effect can be explained by the fact that up to a concentration of 0.04 mol/l HEDP in the solution, a complete complexation of Cu (II) ions is not yet observed. When a complete complexation is reached, the cathodic polarization is practically independent of the ligand concentration, i.e., the order of the cathodic reaction in the ligand is 0:

$$P_k = \frac{\partial \log i}{\partial \log [HEDP]}E = \text{const} = 0.$$

At potentials above -1.1 V, i.e., in the region of hydrogen release, the process is accelerated with increasing ligand concentration. At the studied pH value, HEDP exists in solution mainly in a dissociated form of $H_2L$. Under these conditions, hydrogen can be released by the catalytic mechanism during the discharge of the protonated form of the acid:

$$H_2L^{3+} + e \rightleftharpoons HL^{2+} + H.$$

This effect during the electroreduction of copper ions was established in [20]. The analysis of the dependence in the coordinates $i / \sqrt{\omega} - i$ confirmed that the cathodic process is not complicated by the slow preceding chemical reaction.

Additional information on the mechanism and kinetics of reduction of complex ions in the Cu (II)-HEDP-H$_2$O system was obtained by the method of chronopotentiograms at various cathodic polarizing current densities depending on the concentration of the complex ion and the pH of the solution.

In the region of pH 9, one transition time is observed on the E-t oscillograms. The values of $i \cdot \tau^{1/2}$ at various current densities are presented in table 2.
Table 2. Values of $i \cdot \tau^{1/2}$ at various current densities; $C_{Cu(II)} = 4 \cdot 10^{-3} \text{mol} / \text{l}$; $C_{HEDP} = 2 \cdot 10^{-2} \text{mol} / \text{l}$; $pH = 9$.

| $i$, mA/cm² | $\tau$, sec | $i \cdot \tau^{1/2}$, mA·sec$^{1/2} \cdot$cm$^{-2}$ |
|-------------|-------------|---------------------------------------------|
| 1.0         | 0.682       | 0.826                                       |
| 1.5         | 0.321       | 0.850                                       |
| 2.0         | 0.175       | 0.837                                       |
| 2.5         | 0.113       | 0.840                                       |
| 3.0         | 0.081       | 0.855                                       |
| 3.5         | 0.059       | 0.848                                       |
| 4.0         | 0.045       | 0.847                                       |
| 4.5         | 0.035       | 0.838                                       |
| 5.0         | 0.029       | 0.849                                       |

As can be seen from the table, the value $i \cdot \tau^{1/2}$ is practically independent of the density of the polarizing current, which confirms the earlier conclusion about the direct discharge of complex ions. The diffusion coefficient calculated by the equation:

$$i \cdot \tau^{1/2} = 0.5(nD)^{1/2} \cdot n \cdot F \cdot c,$$

is $1.6 \cdot 10^{-6}$ cm$^2$/sec.

To find the kinetic parameters of the process, we also processed chronopotentiograms in the coordinates $E - \ln \left[1 - \left(\frac{i}{I}\right)^{1/2}\right]$ in accordance with the equation:

$$\Delta E = -\frac{RT}{anF} \ln \frac{i}{i_0} + \frac{RT}{anF} \ln \left[1 - \left(\frac{i}{I}\right)^{1/2}\right].$$

Extrapolated the lines at $t = 0$, we determined the values of the transition overpotential, which were used to build the Tafel dependence. The slope of the straight line $\Delta E - \ln \left[1 - \left(\frac{i}{I}\right)^{1/2}\right]$ is 55 mV, which indicates the presence of electrochemical polarization during the reduction of copper complexes. From the ratio $\frac{RT}{anF} = 0.055$, $an = 0.47$ was determined, and extrapolation of the $\Delta E - \ln i$ dependence to zero polarization made it possible to calculate the exchange current $i_0 = 7.14 \cdot 10^{-6}$ A/cm².

Thus, the set of experimental data obtained by the methods of a rotary disk electrode and chronopotentiometry allows us to present the mechanism of recovery of complex ions in the Cu (II) - HEDP - H$_2$O system in the pH 9 region as follows:

$$[Cu(HL)_2]^6^+ + e \rightarrow [Cu(HL)_2]^7^-$$  \hspace{1cm} (8)

$$[Cu(HL)_2]^7^- + e \rightarrow Cu^0 + 2HL^3^-$$  \hspace{1cm} (9)

The discharge process is described by a kinetic equation of the form:

$$i_e = K \cdot [Cu(HL)_2]^6^+ \cdot \exp \left(-\frac{\alpha F E}{RT}\right).$$

Processing of chronopotentiograms recorded in solution with a metal - ligand ratio of 1:2 under conditions of pH 12.8, in the coordinates $i \cdot \tau^{1/2} - i$, indicates that the value $i \tau^{1/2}$ depends on the density current; with increasing $i$ this product increases, but not in a straight line. The character of the dependence $i \tau^{1/2} - i$ suggests that at the initial moment of electrolysis, the adsorbed complex ions are restored, and as the near-electrode zone is depleted, diffusing particles begin to discharge. The length of the Faraday delay on the waveform is proportional to the amount of substance that has reacted, therefore [14]:

$$i \cdot \tau = n \cdot F \cdot \Gamma + \frac{(n \cdot F \cdot c)^2 \cdot \pi \cdot D}{4 \cdot l},$$

where $\Gamma$ – surface concentration of adsorbed particles.
An analysis of the dependence in the coordinates \( i \tau - 1/i \) showed that \( i \tau \) increases linearly with \( 1/i \). This in agreement [143] indicates the predominant reduction of adsorbed complexes.

To obtain data on the state of the surface of a copper electrode in strongly alkaline solutions, we recorded the electroreflectance spectra in solutions with copper ions. It turns out that at potentials of \(-0.2 \text{ to } -0.4 \text{ V}\), the electrode surface in this solution is covered with a film of copper oxide, and the electrical reflection spectrum is similar to that recorded at the same potential in a solution without copper ions.

The separation of metallic copper becomes possible after reaching a certain value of the reduction potential of copper oxide \( E_{\text{Cu/Cu}_2\text{O}} \). With more cathodic polarization, the shape of the spectrum changes, and the sign of the electroreflection signal in the entire range of quantum energies turns out to be negative, which is also observed for the electroreflectance spectrum of copper in a surface-inactive electrolyte. However, the electroreflectance spectrum in this case is not analogous to the electroreflectance spectrum of copper itself, since, for example, there is no peak at an energy of 2.2 eV corresponding to the onset of interband transitions in the metal. It is possible that poorly soluble compounds formed during the electrolysis are included in the volume of the electrolytic deposition, which leads to a change in the reflectivity of the electrode.

According to the distribution of the complexes depending on the pH of the solution [9] in a strongly alkaline medium (pH 12.5), the binuclear complex \( \text{Cu(II)} - \text{HEDP} - \text{H}_2\text{O} \) accumulates in the \( \text{Cu (II)} - \text{HEDP} - \text{H}_2\text{O} \) system. It follows from the experimental data that, at high pH values, the cathodic polarization upon discharge of the complex ions \([\text{Cu}_2\text{L}_2]^{6-}\) prevailing in the solution can be caused by chemical restrictions. Their reason is the passivation of the electrode surface formed both in the absence of current and in the process of electrolysis of sparingly soluble compounds.

### 4 Discussions

A systematic study of complex copper (II) ions electrochemical behavior with oxyethylidene diphosphonic acid in a wide pH range of the medium was carried out. We have obtained a new data on adsorption phenomena on the surface of a copper electrode in a HEDP solution by modulation reflectance spectroscopy. Using chronopotentiometry and a rotary disk electrode in the \( \text{Cu (II)} - \text{HEDP} - \text{H}_2\text{O} \) system, the research has shown that with an increase in the pH of the solution, the overpotential of copper evolution increases. This is due to a change in the composition of the discharging complex ion and adsorption phenomena on the electrode surface. In strongly alkaline solutions, the discharge of complex ions flows from the adsorbed state, as evidenced by the analysis of the dependence \( i \tau^{-1/2} = i \).

The obtained experimental data on the complexation and electrochemical behavior of copper (II) complex compounds with oxyethylidene diphosphonic acid can be used in further scientific and practical studies to optimize and develop new technological processes for producing metal coatings based on complex compounds with oxyethylidene diphosphonic acid.

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