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Specific Electric Polarizability of Copper Nanoparticles in the Optical Range of the Spectrum

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***Abstract*—Work is devoted to a research of dimensional changes in optical properties of nanosized copper particles with sizes less than 10 nm in statistically inhomogeneous systems. Experimental spectral and dimensional dependences of the complex specific electric polarizability of nanosized copper particles with experimental-analytical method are determined in the optical spectral range from 0.2 to 1.1 µm. The values of the complex specific electric polarizability were determined by analytical solution of Rosenberg's spectrophotometric equations with the use of experimental results of spectrophotometric measurements of transmission and reflection coefficients of copper islet films and the results of electron microscopic studies of their morphological microstructure, taking into account the statistical analysis of the particle size distribution. Nanosized copper particles with a statistically inhomogeneous structure in the system of islet films on quartz substrates were obtained by vacuum-magnetron sputtering. An analysis of function of copper nanoparticles distribution in size in a system with a statistically inhomogeneous structure was carried out using the Pearson's consensus criterion.**

To find out the features of optical absorption of nanosized copper particles, their experimental spectral and dimensional dependences of the complex specific electric polarizability are compared with the corresponding characteristics for model particles with properties characteristic for macroscopic volumes of copper. It was found that the optical properties of nanosized copper particles differ from optical properties of copper in a macroscopic volume. An increase in the absolute values of the components of the complex specific electric polarizability of spherical nanosized copper particles with decreasing their diameter within the range from 8 nm to 3.2 nm for wavelengths of 0.2 - 1.1 µm is established.

The spectral dependences of optical parameters of nanosized copper particles according to well-known theories of classical and quantum dimensional effects are calculated. In order to study the nature of dimensional dependences of optical parameters of copper nanoparticles, a comparative analysis of calculated and experimental spectral and dimensional dependences of their optical parameters was carried out. It is shown that the experimental dimensional changes in the complex specific electric polarizability of copper particles in the investigated range of sizes not be due to the classical or quantum dimensional effect in the dipole approximation.

Ref. 36, fig. 3.

Keywords* — *cooper nanoparticles; optics; electric polarizability; nanosized particles; experimental-analytical method.

I. Introduction

Nanosized metal particles and nanostructured metal-dielectric systems on their basis have a number of non-linear optical effects. It determines a widespread practical application of these structures in optoelectronics [1], information security and transmission systems [2], photoelectric and photothermal energy converters for energy-saving technologies [3, 4]. The example of nanostructured metal-dielectric system future usage is the optical waveguides for interconnections at the upper levels of integrated circuits [5]. In this case, the electro-optical receivers and emitters converting electric signals in the light are formed it the metal-dielectric layers of dielectric. These integrated optoelectronic devices can accelerate the information transmission by two orders and significantly decrease the energy consumption [6].

In practice, noble metals, gold and silver are the most widely used in nanostructured metal-dielectric systems, due to their electrophysical properties.

Copper has similar optical properties to noble metals [6, 7]. At the same time copper is technologically compatible with the processes used in the microelectronics. It allows to implement the optoelectronic devices on silicon technology. Therefore, the possibility of using copper instead of gold can reduce the cost of created devices. In a view of these features copper is a promising material for mass production of above devices. However, it should be noted that the essential disadvantage of copper is insufficient chemical resistance. As a result, it changes the optical parameters of copper [8]. This problem can be solved by using chemically stable dielectric components such as silicon dioxide and aluminum oxynitride in nanocomposite systems [9, 10]. In [11] it is shown that at the same time it is possible to increase and optimize the optical selectivity parameters of the metal-dielectric systems.

In order to solve the indicated applied and fundamental tasks the information on dimensional dependence of nanosized metal particles optical parameters (electric polarizability $\alpha = \alpha_1 - i\alpha_2$, dielectric permittivity $\varepsilon = \varepsilon_1 - i\varepsilon_2$, etc.) is important. It should be noted that reliable experimental data on α, ε metal nanoparticles dimensional dependences are limited in the literature [12, 13] or the microstructure in such studies is evaluated indirectly [10]. Therefore, as a rule, the metal nanoparticles optical parameters are identified with their values in macroscopic volume of the corresponding metals or theoretically calculated [11, 14]. This approach leads to significant errors in the predication of nanostructured systems optical parameters.

A number of known theories describes dimension effects of electromagnetic properties in small metal particles [15, 16]. These theories bind the dipole resonance in metal particles to the surface plasmon resonance of conduction electrons. From a phenomenological point of view, the dipole resonance is conditioned by a fluctuation of ε values on the particle surface. According to the theories of electromagnetic parameters change, three types of dimension effects cause the reduction of particles size [17, 18, 19, 20]. The size of particle is compared in these theories to one of the following three microscopic metal parameters: the quantum effect is the length of de Broglie; the classical effect is the mean free path of conduction electrons; the screening effect is the lengths of Tomas Fermi screening. It is shown [15, 19] that in the classical dimensional effect the value of $|\varepsilon_2|$ particles increases with decreasing D_0, and $|\varepsilon_1|$ is not dependent on D_0. However, it should be noted that [12, 13] experimentally established that the silver nanoparticles ε_2 value decreases with decreasing D_0 in the spectral range 1 - 3 eV. Thus, the information on theoretical dimensional dependencies is highly controversial and requires an analysis and additional research.

According to [21] the mean free path of copper conduction electrons is 27 nm. Since copper α particles with a size in the range from 1 to 10 nm are studied in this work, it is important to carry out the analysis of α in terms of classical [19, 22] and quantum [18] theories of dimensional effect.

An experimental-analytical method of metal particle α value determining on the basis of spectrophotometric and electro-microscopic measurements on two-dimension systems with a statically homogeneous structure and the analytical solution application of the inverse problem of the spectrophotometric system of Rosenberg theory is presented and sustained in [23].

In addition, with the further development of the experimental-analytical approach, the method of α nanoparticles value determining in the systems with a statistically inhomogeneous structure is improved by taking into account the statistical analysis of the particle distribution by size. It is shown that the advanced experimental-analytical method application made it possible to increase the accuracy of obtaining the experimental values of α nanoparticles [24].

Analysis and research of methods of nanostructured layers formation, in particular copper, show that magnetron sputtering is effective and promising method [25, 26, 27, 28]. The work [27] presents the results of studies on technological parameters influence on the morphology of copper nanostructured films in magnetron sputtering. This method made it possible to use polymer materials as substrate. It extends the scope of nanostructured systems application.

The determination and reproducibility of electromagnetic parameters in real nanosized structures is a significant problem of nanostructured systems usage in the design and production of functional devices of different application [2, 29, 30].

The proposed methodology and developed analytical and calculating apparatus in [23, 24] made it possible to determine the nanoparticles electromagnetic parameters in real nanostructured systems and optimize the technological processes regimes of their formation.

Thus, the present work is devoted to the investigation of the experimental spectral characteristics of the complex specific electric polarizability of copper nanoparticles with size less than 10 nm in the range of wavelength 0.2 - 1.1 μm by using the experimental-analytical method. Copper nanoparticles are formed by magnetron sputtering in the form of monolayer (islet film) on a quartz substrate. The obtained spectral dependencies α_1, α_2 are compared to the corresponding characteristics of copper in macroscopic volume in order to find out the features of copper nanoparticles optical absorption. An analysis of nature of copper nanoparticles dimensional changes based on theories of quantum and classical dimensional effects is carried out in order to investigate the dimensional dependencies of their optical parameters.

II. *Methodology and Materials of the Experiment*

A. *Determination of the complex specific electric polarizability*

To investigate the optical properties of copper nanoparticles, we use complex specific polarizability of nanoparticle $\alpha = \alpha_1 - i\alpha_2$, where $\alpha = 4\pi\alpha'/V$, V is a volume, and $\alpha' = \alpha'_1 - i\alpha'_2$ is the complex polarizability of the nanoparticle.

The values of copper nanoparticle complex specific electric polarizability are determined by experimental-analytical method, taking into account the analysis of the particle distribution by size statistics [24]. The method is based on experimental studies of microstructure and spectrophotometric measurements of reflection transmission coefficients on two-dimensional systems and analytical solution of the inverse problem of the spectrophotometric system of Rosenberg equations, taking into account the function of nanoparticles distribution by size. In this case, a two-dimensional metal-dielectric system represents monolayers of metal nanoparticles on a transparent substrate. Experimental values of copper nanoparticles α_1, α_2 in a medium with dielectric permittivity ε_m are defined provided that $\varepsilon_m = (1 + \varepsilon_0)/2$, where ε_0 is the dielectric permittivity of the substrate [12].

The choice of a physically substantiated solution from the possible mathematical roots of α in the studied range of the spectrum is carried out in accordance with the principles presented in [24].

B. *Technology of forming samples. Microstructural and optical research*

To provide an experimental-analytical approach to the determination of copper nanoparticles optical parameters, a series of samples of copper islet films was made and the electro-microscopic and spectrophotometric studies were carried out. Samples of copper islet films with weight thickness of 0.5 - 2 nm were obtained by vacuum-magnetron sputtering on constant current with a flat target in which "deoxidized" copper is used. The process of nanosized copper layers formation was determined by varying of the following technological parameters: substrate temperature, working gas pressure, magnetron power. The range of working pressure after taking argon was 0.6 - 15 Pa. The thickness of the films and the rate of their deposition were controlled by the method of the quartz resonator. Samples were exposed to the air after cooling in vacuum to room temperature. The control of films weight thickness was carried out with the help of a quartz resonator method. Deposition of nanosized copper films was carried out on prepared (according to the standard method) substrate of quartz.

The results of electro-microscopic and spectrophotometric studies of copper islet films on a quartz substrate are described in [27].The morphological structure and phase composition of copper condensates are studied by the method of translucent electron microscopy and diffraction of electrons. The production of samples is carried out by a replica method according to standard methods. The technique of films preparation is selected to exclude changes in their structure.

Electro-microscopic studies have shown that nanosized copper films have an islet statistically inhomogeneous structure and the shape of particles is close to spherical. An analysis of function of copper nanoparticles distribution in size was carried out using the Pearson's consensus criterion χ^2 [31]. It is determined that nanosized cooper particles have a diameter of D_0 = 3.2 - 8.0 nm with a surface concentration of $N_0 = (4.5 \div 9.4) \cdot 10^{11}$ cm^{-2}.

Spectrophotometric measurements of copper islet films in the range of wavelength 0.2 - 1.1 μm at room temperature were performed using spectrophotometer SF-16. Measurements of the monochromatic transmission coefficients T were made on air at normal angles of light fall at sample. Measurements of the monochromatic coefficients of reflection R were made on aluminum mirror with a special prefix at angles of light fall at sample similar to the normal one. Measurement error for T was ±1%, and for R – not more than ±3%. An obtained spectral dependences of T, R of copper island films are presented in [27].

C. *Determination of optical parameters of nanoparticles based on theories of classical and quantum dimensional effects*

Theories of quantum [15, 18] and classical [22] dimensional effects associate the dipole resonance in metal particles with surface plasmon resonance of conduction electrons.

A theory of electromagnetic properties of small metal particles is developed in [15] based on idea that dimensional changes are conditioned by surface plasma excitations of conduction electrons due the influence of the particle surface.

The complex dielectric permittivity of small metal particles in this theory is determined by the relations:

$$\varepsilon_1(\omega, R_0) = \varepsilon_{1v}(\omega) + \varepsilon_{1s}(\omega, R_0) \quad (1)$$
$$\varepsilon_2(\omega, R_0) = \varepsilon_{2v}(\omega) + \varepsilon_{2s}(\omega, R_0) \quad (2)$$

where $\varepsilon_{1s}(\omega, R_0)$, $\varepsilon_{2s}(\omega, R_0)$ is the real and imaginary part of the complex dielectric permittivity of the particle, which takes into account the dimensional: $\varepsilon_{1v}(\omega)$ and $\varepsilon_{2v}(\omega)$ is the real and imaginary part of the complex dielectric permittivity of the material in a macroscopic volume; $\omega = 2\pi c/\lambda$ is cyclic frequency of electromagnetic radiation; c is speed of light; $R_0 = D_0/2$ is radius of the particle.

Expressions of dimensional changes $\varepsilon_{2s}(\omega, R_0)$ are used in the case of a quantum dimensional effect conditioned by the quantization of electron states in the conduction band [18]:

$$\varepsilon_{2s}(\omega, R_0) = \frac{32e^2 f(\nu)}{\pi\hbar\omega R_0} \quad (3)$$

where $f(\nu) = \nu^{-3}\int_{\nu_0}^{1}\sqrt{x^3(x+\nu)}dx$; $\nu = \frac{\hbar\omega}{E_F}$, $\nu_0 = 1 - \nu$ for $\nu < 1$ and $\nu_0 = 0$, when $\nu > 1$; E_F – Fermi energy; $\hbar$ – Planck constant.

In [18] dependences $\varepsilon_{1s}(\omega, R_0)$ are not represented.

The dimensional changes in the electromagnetic parameters of particles are related to the restriction of the particle size of the free path of conduction electrons.

Assuming that Drude theory [16] of metals about the diffuse nature of the scattering of conduction electrons on the surface is applicable, and provided that ω significantly exceeds the frequency of collisions of electrons in a macroscopic metal, in [22] are obtained the relations:

$$\varepsilon_{1s}(\omega, R_0) = 0 \quad (4)$$
$$\varepsilon_{2s}(\omega, R_0) = \frac{\omega_p^2}{\omega^3}\cdot\frac{v_F}{R_0} \quad (5)$$

where $\omega_p = \sqrt{\frac{4\pi n_0 e^2}{m_0}}$ is the frequency of three-dimensional plasmon resonances in macroscopic metal; e is the electron charge; and n_0, m_0 are numbers, the effective mass of free electrons.

In accordance with the classical electromagnetic theory, the complex polarizability of a particle $\varepsilon = \varepsilon_1 - i\varepsilon_2$ is related to its complex dielectric permittivity by the expression [12]:

$$\alpha' = \frac{V}{4\pi}\frac{\varepsilon-\varepsilon_a}{\varepsilon_a+f(\varepsilon-\varepsilon_a)} \qquad (6)$$

where ε_a is the dielectric permittivity of the external environment, f is the particle shape factor. $f = 1/3$ for a spherical particle [16].

The dielectric permittivity and the optical constants n, k are related by means of the relation [32]:

$$\begin{cases} \varepsilon_1 = n^2 - k^2, \\ \varepsilon_2 = 2nk. \end{cases} \qquad (7)$$

Expression (6) is valid under the condition (dipole approximation) that the particle size ($D_0 = 2R_0$) is much smaller than the length of the electromagnetic wave in this medium ($D_0 << \lambda$). This condition justifies the use of the values ε_1 and ε_2 dependent on D_0 in small particle sizes ($D_0 < 20$ nm) in expression (6).

III. Results and discussion

The obtained by experimental-analytical method spectral dependencies of the specific complex electric polarizability of copper nanoparticles at the various values of the particle diameter D_0 are shown in Fig. 1.

A comparative analysis of the obtained experimental values of α_1, α_2 of copper nanoparticles with corresponding characteristics of model spherical particles α_{1Cu}, α_{2Cu} with properties characteristic of copper in macroscopic volume are of interest. Optical constants n and k of copper in macroscopic volume obtained in [33] are used to calculate α_{1Cu}, α_{2Cu}. To achieve the correspondence between the calculated and experimental values of α, the calculations are carried out according to the equation (6) - (7) provided that $\varepsilon_m = (1+\varepsilon_0)/2$, for values $\varepsilon_0 = 1$ and $\varepsilon_0 = 2.38$ (fused quartz). The spectral dependences α_{1Cu}, α_{2Cu} are shown in Fig. 2.

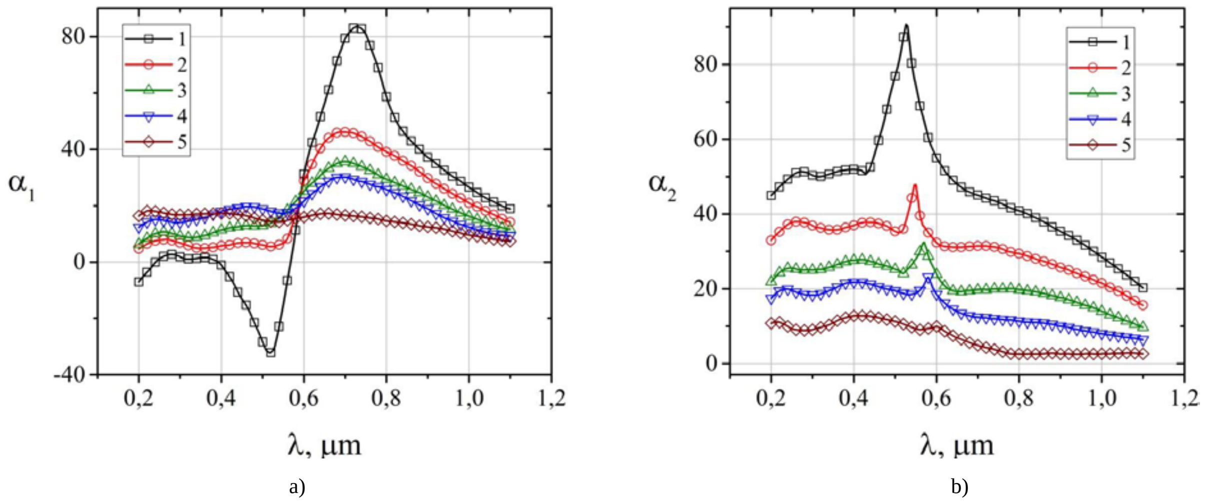

Fig. 1 Spectral dependences of the real (a) and imaginary (b) parts of the complex specific electric polarizability of the cooper nanosized particles at different values of the size D_0: 1 – D_0 = 3.2 nm; 2 – D_0 = 4.0 nm; 3 – D_0 = 4.8 nm; 4 – D_0 = 5.6 nm; 5 – D_0 = 8.0 nm

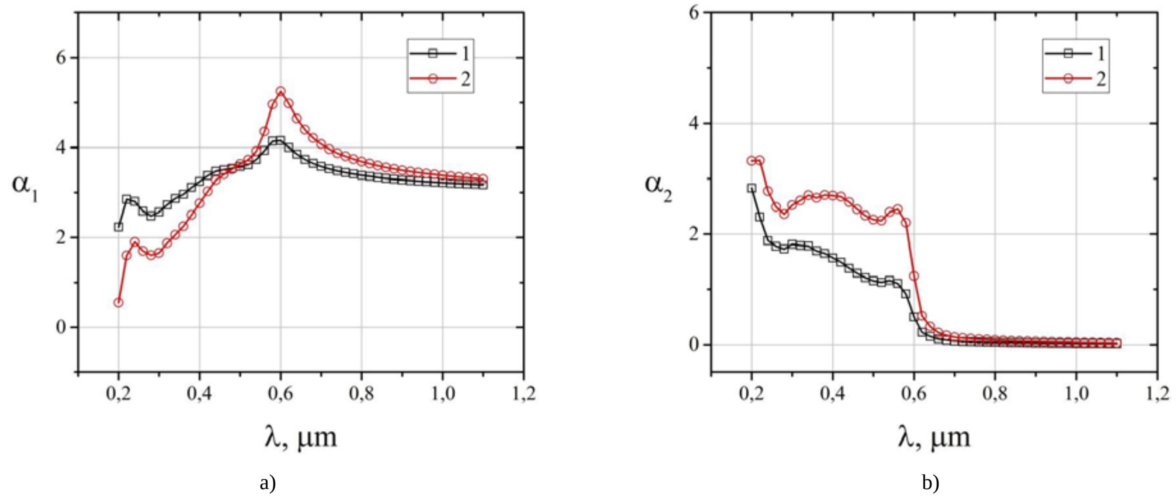

Fig. 2 Spectral dependences of the real (a) and imaginary (b) parts of the complex specific electric polarizability of the copper nanosized particles for the model sphere with values of the electromagnetic parameters characteristic of copper in the macroscopic volume [33] at different values of ε_m: 1 – ε_m = 1 ; 2 – ε_m = 1.69

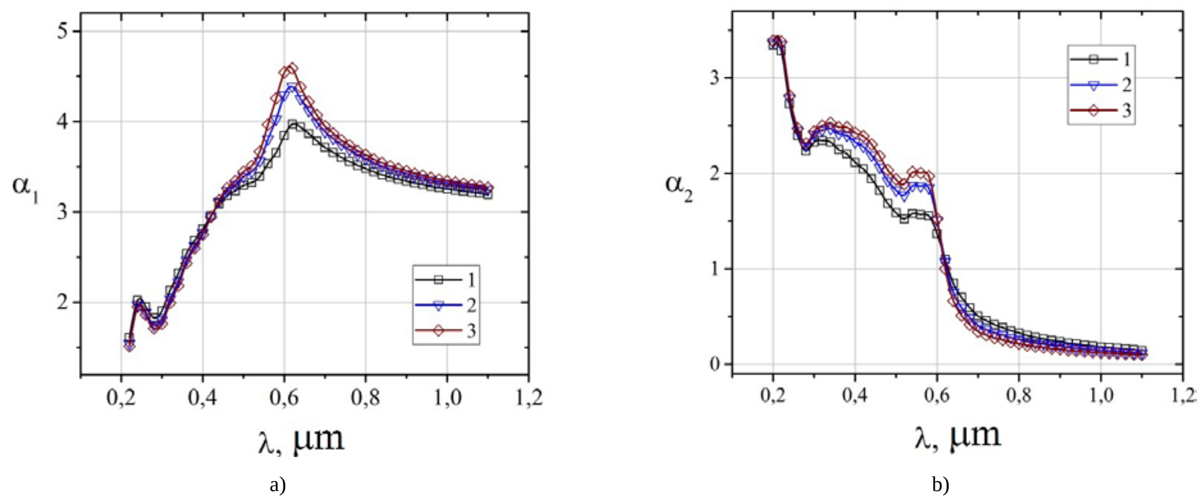

Fig. 3 Spectral dependences of the real (a) and imaginary (b) parts of the complex specific electric polarizability of the copper nanosized particles calculated according to the classical dimensional effect theory at ε_m = 1.69 and values of the diameter of particles D0: 1 – D_0 = 3.2 nm; 2 – D_0 = 5.6 nm; 3 – D_0 = 8.0 nm

The results of numerical calculations of α_1, α_2 nanoparticles of copper determined by the theory of classical dimensional effect are shown in Fig. 3.

The calculation of α of copper nanoparticles is made using the theory of quantum and classical dimensional effects. The uncertainty in the nature of the dimensional changes $\varepsilon_{1s}(\omega, R_0)$ in the theory of quantum dimensional effect causes the calculation of α_1, α_2 in this theory similarly as in the case of classical dimensional effect under condition (4). Due to the fact that the size of the studied particles is quite large, D_0 = 3.2 - 8 nm for the influence of the quantum effect, therefore, it does not appear on the dimensional dependences of α. Calculated values of α on the theory of quantum dimensional effect do not differ significantly from the corresponding values of α of the classical dimensional effect.

From Fig. 1, Fig. 2 it follows that spectral dependences α_1, α_2 of copper nanoparticles qualitatively and quantitatively significantly differ from the corresponding dependences of model spherical particles with properties of copper in macroscopic volume. Withal the specific polarizability in absolute magnitude increases significantly with decreasing D_0. The size increase of copper nanoparticles from 3.2 nm to 8 nm leads to decreasing divergence and approximation of the values α_1, α_2 nearly to the values of α_{1Cu}, α_{2Cu}.

There is a series of bands in the spectral dependences α_2 in the range 0.2 - 1.1 μm. Namely, in the wavelength region 0.38 - 0.46 μm and less than 0.3 μm.

It should be noted that in the region of wavelengths 0.6 μm, with decreasing size of the copper particle from 8 nm to 3.2 nm, the maximum of the band is shifted toward shorter wavelengths. The position of peaks in the spectral region 0.38 - 0.46 μm and less than 0.3 μm within the accuracy of the method does not depend on the size of the particles.

The comparative analysis of Fig. 1 and Fig. 3 shows significant quantitative and qualitative differences between the experimental and theoretical spectral dependencies of α_1, α_2 for copper nanoparticles with sizes less than 10 nm.

In this case, the absolute values of α_1, α_2 calculated according to the theories of quantum and classical dimensional effects decrease with decreasing nanoparticle size. In contrast, the experimental absolute values of α_1, α_2 increase with decreasing nanoparticle volume. A similar trend exists for dimensional dependencies α_2 in the spectral range $\lambda < 0.6$ μm. These results indicate that the experimental dimensional dependences of the dynamic polarizability of copper nanoparticles not be conditioned on classical or quantum dimensional effect in the dipole approximation.

Conclusions

In the continuation of the investigations of the optical properties of nanoparticles in statistical inhomogeneous systems that we started in [24, 27] with the help of an experimental analytical method, the optical characteristics of nanosized copper particles in a two-dimensional system islet copper film on a quartz substrate are determined. It is shown that taking into account the analysis of the particle size distribution in the experimental-analytical method makes it possible to apply this approach to nanostructured systems with a statistically inhomogeneous structure and reliably estimate their optical parameters. The experimental-analytical method makes it possible to determine the optical parameters of nanoscale particles depending on their morphological microstructure in the system. In turn, it is possible to establish a relationship between the optical properties of nanostructured systems and the technological parameters of their synthesis [27]. Thus, this methodology makes it possible to optimize the optical characteristics of nanostructured systems and synthesize structures with given properties.

The experimental spectral and dimensional dependences of the complex specific electric polarizability of nanosized copper particles with a size of less than 10 nm in the spectral range from 0.2 to 1.1 μm were studied. It is found that the optical properties of nanoscale copper particles differ from the optical properties of copper in a macroscopic volume. Assuming that the band structure of the copper in macroscopic volumes is also characteristic of nanoparticles, one can assume that the bands in the dependences α_1, α_2 at wavelengths less than 0.48 μm are also due to interband transitions. The question about the nature of the band α_1, α_2 in the region of 0.6 μm, the position and intensity of which when the particle size decreases significantly differs from α copper in macroscopic volumes, requires further study.

A significant increase in the values of α_2 and absolute values of α_1 of particles is established with a decrease in their diameter in from 8 nm to 3.2 nm for light wavelengths of 0.2 - 1.1 μm. This trend in the size dependences of α_1, α_2 for nanoscale copper particles agrees and confirms the regularities observed by us in the corresponding dependences for nickel particles [13, 24, 34], chromium [35], and also the "giant" growth of the values of α described in the works [12, 36].

To study the nature of the dimensional dependences of the optical characteristics of nanoscale spherical copper particles, numerical calculations of their complex dielectric permittivity and complex specific dynamic polarizability were carried out according to the theories of classical and quantum size effects. A comparative analysis of the calculated theoretical and experimental spectral and dimensional dependences of optical parameters of copper particles has been carried out. The results indicate that the experimental dimensional dependences of α copper nanoparticles cannot be due to the classical or quantum dimensional effect in the dipole approximation.

The results of the investigations are of interest from the point of view of a fundamental study of the optical properties of nanosized particles and nanostructured systems based on them. Also for the creation on their basis of functional devices for various applications with specified optical characteristics.

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Питома електрична поляризованість наночастинок міді в оптичному діапазоні спектру

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Реферат—Робота присвячена дослідженню розмірних змін оптичних властивостей нанорозмірних частинок міді з розмірами менше 10 нм в статистично неоднорідних системах. В оптичній області спектра в діапазоні довжин хвиль від 0,2 до 1,1 мкм визначено експериментальні спектральні та розмірні залежності комплексної питомої електричної поляризованості нанорозмірних частинок міді за допомогою експериментально-аналітичного методу. Зна-

чення комплексної питомої електричної поляризованості одержані на основі аналітичного розв'язку спектрофотометричних рівнянь теорії Розенберга з використанням експериментальних результатів спектрофотометричних вимірів коефіцієнтів пропускання і відбивання острівкових плівок міді та результатів електронно-мікроскопічних досліджень їх морфологічної мікроструктури з урахуванням статистичного аналізу розподілу частинок за розмірами. Нанорозмірні частинки міді в системі острівкові плівки на кварцових підкладках отримували методом вакуумного магнетронного розпилення. Аналіз функції розподілу наночастинок міді за розмірами в системі з статистично неоднорідною структурою проведено на основі критерію узгодження Пірсона.

Для з'ясування особливостей оптичного поглинання нанорозмірних частинок міді, їх експериментальні спектральні та розмірні залежності комплексної питомої електричної поляризованості співставляються з відповідними характеристиками для модельних частинок з властивостями характерними для макроскопічних об'ємів міді. Виявлено, що оптичні властивості нанорозмірних частинок міді відрізняються від оптичних властивостей міді в макроскопічному об'ємі. Встановлено, що абсолютні значення компонентів комплексної питомої електричної поляризованості сферичних нанорозмірних частинок міді збільшуються при зменшенні їх діаметру в межах інтервалу від 8 нм до 3,2 нм. При цьому положення максимуму смуги в області 0,6 мкм зміщується в сторону більш коротких хвиль при зменшенні об'єму наночастинки міді. Тенденція розмірних змін комплексної питомої електричної поляризованості для наночастинок міді узгоджується і підтверджує закономірності виявлені в відповідних залежностях для частинок нікелю, хрому, срібла.

Розраховані спектральні залежності оптичних параметрів нанорозмірних частинок міді по відомим теоріям класичного і квантового розмірних ефектів. З метою досліджень природи розмірних залежностей оптичних параметрів наночастинок міді проведено порівняльний аналіз розрахованих та експериментальних спектральних і розмірних залежностей їх оптичних параметрів. Показано, що експериментальні розмірні зміни комплексної питомої електричної поляризованості частинок міді в досліджуваному інтервалі розмірів не обумовлені класичним або квантовим розмірним ефектом в дипольному наближенні.

Результати досліджень розмірних та спектральних залежностей оптичних параметрів наночастинок міді можуть найти використання для розробки металодіелектричних структур та функціональних пристроїв різного прикладного призначення з заданими оптичними характеристиками. Вони також представляють інтерес з точки зору фундаментальних проблем оптики нанорозмірних систем.

Бібл. 36, рис. 3.

Ключові слова — наночастинки міді; оптика; електрична поляризованість; експериментально-аналітичний метод.

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Удельная электрическая поляризуемость наночастиц меди в оптическом диапазоне спектра

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***Реферат*—В оптической области спектра в диапазоне длин волн от 0,2 до 1,1 мкм определены экспериментальные спектральные зависимости комплексной удельной электрической поляризуемости наноразмерных частиц меди диаметром менее 10 нм с помощью экспериментально-аналитического метода.**

Обнаружено, что оптические свойства наночастиц меди отличаются от оптических свойств меди в макроскопическом объеме. Установлено увеличение абсолютных значений компонентов комплексной удельной электрической поляризуемости сферических частиц меди при уменьшении их диаметра от 8 нм до 3,2 нм. Рассчитаны спектральные зависимости оптических параметров наноразмерных частиц меди по теориям классического и квантового размерных эффектов и для модельных частиц со свойствами характерными для макроскопических объемов меди. Проведен сравнительный анализ расчетных и экспериментальных спектральных и размерных зависимостей оптических параметров частиц. Показано, что экспериментальные размерные изменения оптических параметров частиц меди в исследуемом интервале размеров не обусловлены классическим или квантовым размерным эффектом в дипольном приближении.

Библ. 36, рис. 3.

Ключевые слова — наночастицы меди; оптика; электрическая поляризуемость; экспериментально-аналитический метод.