The variance of the electronic structure in the near-surface regions of chemically homogeneous nanoparticles of oxide materials and its role in the conversion of chemisorption energy of water on the powder of zirconium dioxide

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Электронная структура приповерхностных областей наночастиц оксидного материала особого типа и возможность на этой основе получения специфических выпрямляющих свойств контакта изучаются теоретически, а затем проверяются экспериментально. Построены модели поверхностных состояний типа Тамма с учетом кулоновского дальнодействия. Обнаруженная дисперсия и ее зависимость от кривизны поверхности наночастиц позволяют модельно изучить условия формирования контактной разности потенциалов для случаев наночастиц одинакового радиуса (синергетический эффект), разных радиусов (легированный и нелегированный варианты), а также обнаружить возможность описания группы частиц порошка из данного материала в рамках модели Андерсона. Некоторые следствия предложенной концепции были исследованы в рамках эксперимента по характеру вольтамперных характеристик пары контактирующих частиц порошка с различными комбинациями радиусов, и они показывают наличие свойств, характерных для выпрямляющего контакта. Выдвигаются перспективы для дальнейших экспериментальных испытаний, вытекающих из предложенной теории.

Ключевые слова: сферические оксидные наночастицы, дисперсия электронных зон, локальные поверхностные уровни, контактная разность потенциалов, преобразование энергии хемосорбции

The electronic structure of the near-surface regions of oxide material nanoparticles of a special type and the possibility, on this basis, to obtain specifically rectifying properties of the contact are studied theoretically and then examined experimentally. Models of surface states of the Tamm type are constructed with taking into account the Coulomb long-range action. The discovered variance and its dependence on the curvature of the surface of nanoparticles make it possible to study modally the conditions for the formation of a contact potential difference in the cases of nanoparticles of the same radius (synergistic effect), different radii (doped and undoped variants), as well as to discover the possibility of describing a group of powder particles from a given material within the Anderson model. Some consequences of the proposed concept have been examined within the experiment on the character of the current-voltage characteristics of a pair of contacting powder particles with different combinations of radii and they show the

presence of properties characteristic for a rectifying contact. Prospects for further experimental tests arising from the accordance with the general theory are put forward.

Keywords: spherical oxide nanoparticals, variance of electronic zones, local surface levels, contact potential difference, conversion of chemisorption energy.

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I. Introduction

The beginning of the 21st century is also marked with a really fundamentally new contribution to science, technology which shifts the focus of researchers' attention from physical and chemical aspects to structural [1-5].

An example is a very curious approach of the following type: conversion of the energy of adsorption of water onto nanopowders of ionic crystals (such as zirconium oxide) with the creation of an electric voltage and, accordingly, current [6]. This interesting nanoeffect has been studied in many ways, including with engineering findings [7]. Nevertheless, attempts to analyze it theoretically (in particular, in search of optimal solutions) [8] encountered serious difficulties, the analysis of which led to the motivation for revising a number of fundamental questions on the electronic structure of these oxide nanopowders and physical-chemical processes [9, 10] on their surfaces.

The choice of the object of study (zirconium dioxide) is due to the high valence of its components and low permittivity, which guarantees a large Madelung energy gradient in the surface region. The latter, in turn, can be the reason for the narrowing of the band gap on the surface, i.e. the reason for the chemically uniform and homogeneous varizonicity (graded band-gap) of the ionic crystal, in contrast to the well-known graded-gap semiconductor, where varizonicity is caused by the concentration gradient of the additional component [10]. It is this possibility of realizing a new type of varizonicity in materials such as zirconium dioxide and a number of related effects that is the goal of this work.

II. Electronic structure of near-surface regions of crystals with ionic bonding

II.1. Variation of chemically homogeneous near-surface regions

The basic model for studying this issue can be the Seitz-Madelung model [11, 12], which used the concept of flat surfaces, but then it was generalized to the cases of convex, concave and fractal surfaces in several papers [13-15]. The most important element of these studies was the Coulomb long-range interaction between the components of the ionic crystal, and it was used for the flat surface in its analysis by Mark and Levin [16]. The generalized Seitz-Madelung scheme is shown [14] in Fig. 1, which demonstrates the inversion of the energy terms "plus" - and "minus" - the components of the crystal under congruent compression up to the size of the real interatomic distance R_0. The inversion of terms, which occurs as the components approach each other (with preservation of the structure), is caused by an increase in the Madelung energy, which is completely different for the regions inside a large bulk sample (U_b), on the surface (U_s), and in an intermediate state in the near-surface region ($U_{s/b}$).

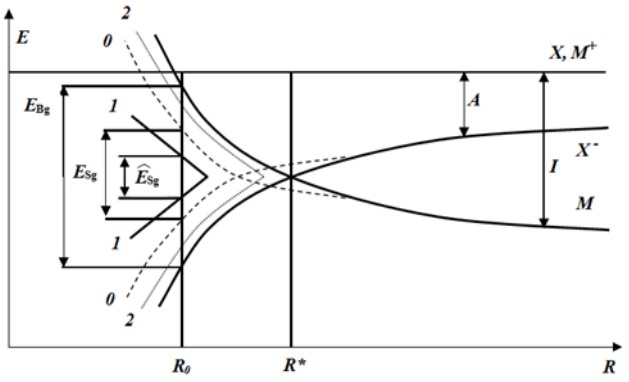


Figure 1. Generalized Seitz-Madelung diagram shows the inversion of the energy terms of metal and halogen at congruent compression of the lattice to the natural state. Terms "2" and "0" correspond to volume and surface (flat case) observation points; the term between them refers to the concave surface, and the term "1" - to the convex one (according to the generalized Seitz-Madelung scheme, the arrangement of terms in the near-surface region can be controlled by its curvature).

Since (according to Seitz [11]) the Madelung energy is related to the band gap (E_g), for all positions of the observation point, a different band gap is obtained ($E_g(x, y, z)$), where x, y, z axes are coordinates:

$$E_{gl}(x,y,z) = 2|U_i(x,y,z)|-I+a, \quad (1)$$

where $L=\{S, S/B, B\}$; I and a are the ionization and electron affinity potentials.

Since the surface itself is considered as a crystal

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defect (Tamm [17]), there is a drop in the Madelung potential, and this surface can be considered as an infinite crystal, to which the Madelung perturbation potential [12] is applied (with the opposite sign), starting at the point x=0 and slowly decreasing in the region x<0. This slow change in the perturbation is radically different from the "instantaneous" Tamm approximation [17], and therefore Tamm's ideas about the splitting off electronic states of allowed bands and their transformation into local states are problematic in this case. The concept of the displacement (on the surface) of both allowed zones to the middle of the forbidden zone is applicable, but as a whole. When to talk about the difference between the action of local and nonlocal perturbations on band structures, information can be found in Appendices 1 and 2 in Slater's book [18]. Thus, already in the normal state of the hypothetical lattice at ($R = R_0$) in the process of displacement of the observation point along the X axis deep into the crystal, we obtain for the dependence $E_{S/Bg}$ (x,y=const, z=const) the graded-gap behavior of the electronic spectrum. The depth of this variband (X=L) is determined by the condition E_{Bg}–$E_{(S/Bg)}$ (L,y,z)=2K_BT.

A particularly important case for us is the application of these procedures to a convex surface, in which the Madelung energy is calculated here, using the standard Madelung-Ewald Coulomb sums [19] require a certain modification (see [14, 15]). It is shown that the convex shape of the surface for each plane perpendicular to the y, z axes requires a decrease in the countable base of the indices, k, which reduces the contribution to the Madelung energy. As a result, all the Seitz-Madelung curves become closer to the middle of the band gap, which naturally turns out to be narrower on the crystal surface than for a flat boundary. It is clear that the opposite situation, the concave shape of the surface, leads to the opposite displacement of the curves of the Seitz-Madelung energy terms, i.e. they are located closer to the curves of a purely volumetric sample (Fig. 1) [12]. As a result, we get a hierarchical row of forbidden zones for all three cases: (volume, surface and intermediate states) (flat, convex and concave surfaces)

$$\widehat{E}_{S_g} < E_{S_g} < \breve{E}_{S_g} < \widehat{E}_{S/B_g} < E_{S/B_g} < \breve{E}_{S/B_g} < E_{B_g}, \quad (2)$$

where the upper symbols indicate the cases of convex and concave surfaces.

The hierarchical series (2) for materials with ionic bonding and low permittivity leads in some cases to unusual results. Indeed, if we consider the case of nanoparticles, then due to the confinement effect the band gap increases with decreasing nanoparticle radius according to the expression $E_{S_g} = E_{g\infty} + const / R^2$. Whereas according to the analysis considered in this article, while approaching the nanoparticle surface, the band gap decreases, i.e. dependence $\widehat{E}_{S_g}(R)$ decreasing value with decreasing R. In this case, the total band gap on the surface $\widehat{E}^t_{S_g}$ decreases with decreasing R. This leads to results when nanoparticles with a smaller correspond to a smaller band gap on the surface than for a nanoparticle with a larger radius (this is the case shown below).

II.2. Surface local states of ionic crystals

Thus, establishing the variance of the near-surface electronic structure requires a certain modification of Tamm's research procedure [13] to reveal new features of the surface state of an ionic crystal. Later, Tamm's works were followed by a large number of studies of surface electronic states: quantum chemistry (Shockley [20]), taking into account the presence of surface states in superconductors (A. Andreev [21]), a powerful method of the strength of the combination of the Green's function with the quantum chemistry of semiconductors (Lanno and Friedel [22]), the use of the notion of splitting off in ionic crystals (Mark and Levin[16]), as well as taking into account the non-flat surface of ionic crystals (B. Oksengendler, N. Turaeva [15]).

Below we will discuss the case of varibandity in ionic crystals (Fig. 2).

If we consider the procedures of stitching [15] of an incident plane wave of an electron from the side of vacuum to the surface with the corresponding wave functions of the surface from inside the crystal, then we can distinguish three fundamentally different cases (Fig. 2):

1) stitching occurs in the energy range of the forbidden zone;

2) stitching occurs in the region of the energy of realization of the graded-gap structure;

3) stitching occurs in the energy region above the level of transition of the graded-gap structure to the normal volumetric one.

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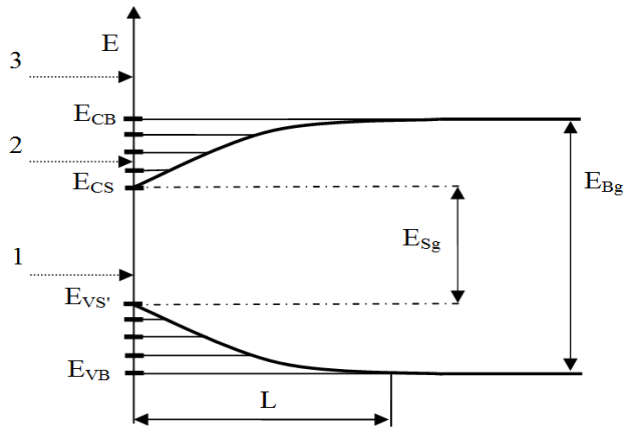


Figure 2. The graded-gap energy structure of the near-surface zone of an ionic crystal with the graded-gap parameters (energy difference and depth) and a diagram of the origin of surface local states (1, 2, 3 means the incidence of electron waves on the surface for different energy ranges and their derivatives when the wave functions of free space and crystal match; within zone "1" and states different from Tamm's states appear.

It is quite obvious that cases 1 and 3 are actually close to the situations analyzed by Tamm, with the slight difference that in the region of varibandity of the band gap the inclination of the upper boundary of the band should be taken into account, and the latter can be easily done by the method considered by Mott and Sneddon [23]. Case 2 is fundamentally new, because in a part of the crystal from the surface the electron finds itself in a wedge-shaped potential well and has discrete electronic states in it, described by the Airy function [24].

The standard matching of two functions (Airy and a plane wave), as well as the derivatives of these functions on the surface itself, leads to new results for the energy of local states in region B. Roughly speaking, all states in the wedge-shaped region acquire certain broadenings depending on the level number and special details of such indicated broadening can be easily calculated [23, 25]. Thus, the broadening pattern, as well as the arrangement of the levels, reflecting the individuality of wedge-shaped potential wells for nanoparticles of different radii, in the case of their combination, is a system of a certain three-dimensional lattice of potential wells, each of which belongs to a particular nanoparticle. This may turn out to be essential for the through conduction.

III. Contact potential difference between nanopowders (nanoparticles)

The fact that ionic nanoparticles have a graded-gap near-surface structure and a special kind of electronic surface states makes certain adjustments to the physics of creating a contact potential difference between two nanopowders [26, 27]. Let us single out non-trivial and interesting cases.

III.1. The case of non-alloyed and defect-free nanoparticles of the same radius

In such a combination, we must discuss the scheme shown in Fig. 3.

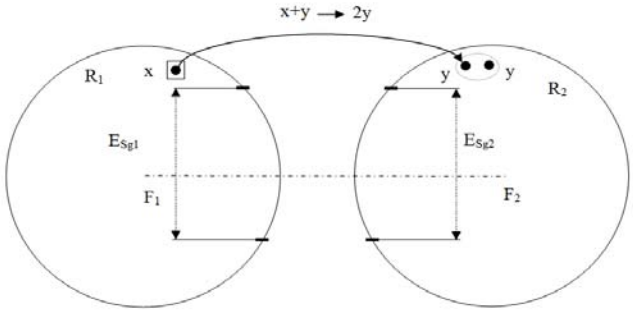


Figure 3. Scheme of the contact between two nanoparticles (of equal radius), and possible description of charge transfer and pinning of a pair of electrons in the framework of an irreversible autocatalytic reaction ($x+y\rightarrow 2y$) in a highly polarizable nonlinear medium.

Both nanoparticles have the same Fermi level F1=F2 and the absence of a contact potential difference in this system is obvious ($V_c=F_1-F_2=0$). However, in conditions of significant non-equilibrium of a system with strong polarization properties, somewhat non-standard arguments can be presented.

Let us denote the electron in the left nanoparticle by x, and in the right nanoparticle by y. As a result of fluctuation, the electron x passes to the right, pairing with y, and this is energetically favorable in a strongly polarizing medium. This is really real and energetically favorable, since the polarization energy is proportional to the square of the charge (the stabilization of the system is characterized by the energy $|\Delta E_p| \sim 2^2-2=2$), and it is by this value that the right state is energetically more favorable than the initial symmetric state. Such energetics can be described as an irreversible autocatalytic chemical reaction $x+y\rightarrow 2y$.

Let us analyze the stability of a system with such reactions. The affinity of such a reaction is determined by the expression $A\sim\ln((xy)/y^2)$; and the speed of this irreversible reaction is $v\sim xy$. Then the product of the increments of affinity and the rate of reactions during fluctuations will be $\delta A\delta v$, hence the index of

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instability of the reaction is $T\delta\sigma=\delta A\delta v<0$ [28]. Thus, the conclusion is as follows: under the conditions for the implementation of electron pairing during the transition of left electrons to the right (autocatalysis), non-equilibrium (the advantage of pairing) and an increase in the polarizability of the medium with each transition, we obtain a classical synergistic effect [28] – spontaneous separation of negative and positive charges, which stops when the balance of flows is carried out: from left to the right under the influence of autocatalytic non-equilibrium chemistry, and from right to the left of electrical origin. Estimates show that the value of V_c is the more, the greater the benefit in polarization due to bound charges. The latter is precisely characteristic for graded-gap nanoparticles with a graded-gap structure of the near-surface regions.

III.2 The case of doped nanoparticles of various radii ($R_1 \neq R_2$)

Consider two ionic nanoparticles doped with the same deep level donor. From the standard equation of electro-neutrality [26], we obtain an expression for the Fermi level of such particles: $F=-E_d/2+k_bT\ln\Phi$, where Φ is a combination of nanoparticle parameters that are insignificant for us. Obviously, in the case of identical donors, the contact potential difference is zero ($V_c=F_1-F_2=-(E_{d1}-E_{d2})/2=0$)).

This is a clear standard result for any macro semiconductor object. If we now turn to nanoparticles, then we are faced with a new and very interesting situation. Let us use for the analysis the most serious theory of deep levels in semiconductors by L. Keldysh [29] (Fig. 4).

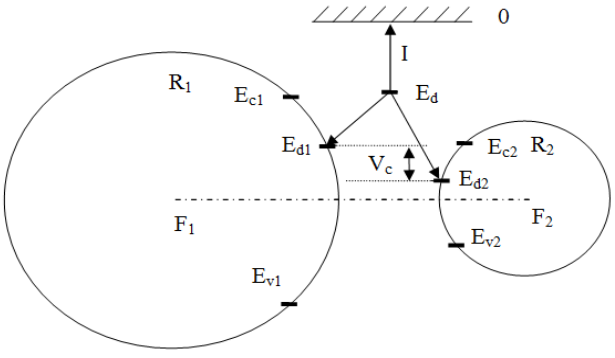


Figure 4. Formation of a contact potential difference in the system of two contacting nanoparticles (of different radii) when they are doped with the same donor element: the mechanism is due to the different contribution to the total wave function of a deep level.

In this approach to the theory of deep levels, Keldysh used a deep analogy with such an object as a hydrogen atom, taking into account vacuum fluctuations. The role of the vacuum in the semiconductor was played by the states of the valence and conduction bands, and the role of the hydrogen atom was played by the ligating impurity itself. The Dirac equation was used, which actually must be used to detect vacuum fluctuations, which means that the wave function of the deep level was considered as a superposition of the wave function of the "hydrogen atom" itself and the wave functions of both nearest allowed bands (valence and conductivity). L. Keldysh [29] obtained the depth of the deep donor impurity as a nonlinear function of the band gap (E_g):

$$E_d = \frac{1}{2} E_g \left[1 - 2me^4 / E_g \xi^2 \hbar^2\right]^{1/2}, \qquad (3)$$

where m and e are the mass and charge of the electron, ξ is the dielectric constant.

Now it is quite obvious that for various nanoparticles in which $R_1 \neq R_2$, and therefore $E_{g1} \neq E_{g2}$, we get: $E_{d1} \neq E_{d2}$. Thus, under the conditions of applicability of formula (3), we obtain $V_c=-1/2(E_{d1}-E_{d2})\neq 0$.

IV. The mechanisms of transformation of the energy of physical-chemical chemisorption of water into electricity and Anderson's model

The above considerations about the graded gap of ionic nanoparticles and a number of consequences from this allow us to put forward a hypothesis about the nature of the mechanisms – the resulting stage of the entire problem. At present, a number of theoretical ideas have been put forward on the ways of converting adsorption energy into electrical energy [30, 31, 7, 9]. It was understood, that systems with low dimensions (nano) are of particular interest [32] and we can understand why this is so. The fact is that in such objects, a special relationship between the surface and the volume is carried out and they become interdependent, which provides new properties (2D-3D). An essential point is the choice of material, where this relationship is most clearly manifested, apparently, it is extremely important for metal oxides [33, 34].

Let us consider the adsorption of a neutral water molecule on the surface of two types of nanoparticles, with large and small radii, which correspond to large and small forbidden gaps on the surface of nanoparticles (Fig. 5).

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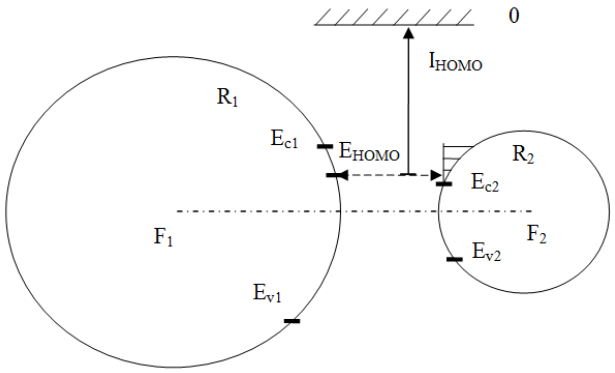


Figure 5. Diagram for the adsorption process of a water molecule on the surface of ionic nanoparticles of different radii.

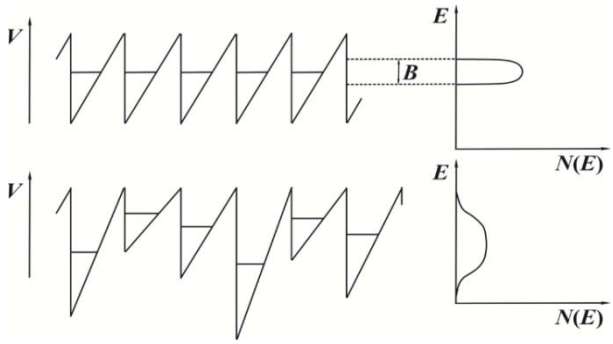


Figure 6. Schematic diagram of the electronic spectrum of contacting nanoparticles of the same size (top figure), and different random radii (bottom figure): for the lower chain of random wells the Anderson model is a suitable method for analysis.

HOMO level of the adsorbate falling into the forbidden zone (large nanoparticle) and into the region above the level of the bottom of the conduction band (small nanoparticle), as a result of which, in the second case, electron delocalization over the surface states of contacting nanoparticles of small radii is possible.

Let the highest occupied molecular orbital (HOMO) of a water molecule have energy falling into the band gap of a large nanoparticle [35]. Obviously, in the absence of a resonating level in a nanoparticle, the electronic transition from a water molecule to a nanoparticle does not occur. In contrast, for a nanoparticle with a small radius, the bottom of the wedge-shaped potential well drops below the HOMO level, resulting in an electronic transition to the allowed states of the nanoparticle surface. Thus, all wedge-shaped wells whose bottom is below the HOMO levels can receive electrons from water molecules. Now it is obvious that this situation, taking into account the random spread of the radius of nanoparticles, can be likened to the Anderson model [24, 36], each potential box of which corresponds to its wedge-shaped potential well (Fig. 6).

According to Anderson's model [36, 37], for a certain width of the allowed band formed from the states of identical boxes, divided by the spread of the random energy of the wells, situations of either delocalized, localized, or joint combining variants occur. Each of these variants has its own conduction mechanism [38] for the surface states of the entire group of powders. In the same scheme of reasoning, it is possible to formulate and answer another very important question: can the adsorption of a water molecule stimulate its decay? The answer is as follows: if the electronic states of the HOMO of a water molecule belong to the category of bonding orbitals, then the transition of an electron to a nanoparticle weakens the strength of the water molecule; but if the HOMO states belong to the antibonding class, then the indicated transition strengthens the water molecules [38,39]. These models can be verified experimentally.

V. Experimental test for the concept of variance and its results

Among the various consequences of the proposed concept, we undertook a comparison of the conclusions of Section **III** with the experiment on the character of the current-voltage characteristics of a pair of contacting powder particles with different combinations of radii.

V.1. Experimental devices and materials

The samples under study were contacts of two nanopowder compacts in the form of tablets of the composition ZrO_2-3 mol% Y_2O_3 with similar particle size: 7.5 nm (heat treatment at 400°C for 2h, sample "400–400") and different particle size: 7.5–9 nm (heat treatment 400°C for 2h and 500°C for 2h correspondingly, sample "400–500") (Fig. 7).

In this case, the chemical technology of co-precipitation with the use of physical effects was used (see details in [45]). The dependence of the current on the voltage at the contact (VAC) was obtained in a linear sweep mode (from –6V to +6V) on the R-20 device ("Elinns") in a moisture saturation mode at 86%. The saturation time for the samples at each humidity level was at least 2 hours (until the adsorption equilibrium was established in the working volume-salt-sample system) with an accuracy of 5%.

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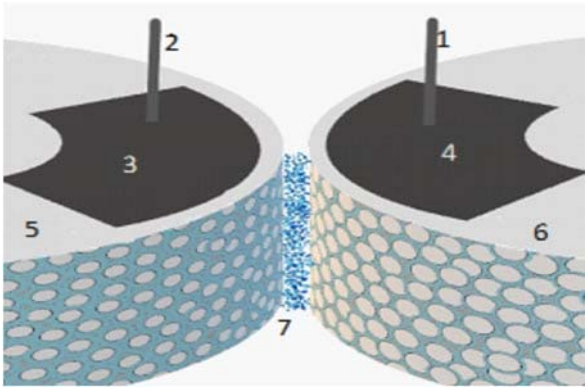


Figure 7. The scheme of the experiment, where 1 – anode, 2 – cathode, 3, 4 – contact pads; 5 – a tablet of a powder with a smaller particle size, 6 – a tablet of a powder with a large particle size, 7 – a hydration layer.

V.2. Experiments on the contact of different sized nanoparticles

Figure 8 shows the current versus voltage dependence obtained at an atmospheric humidity of 85%. It can be seen that the dependence of the current on the voltage for the contact of systems with the same particle size (curve 400–400) has a linear character on a given scale, while a similar dependence for the contact of systems with different sizes of nanoparticles (curve 400–500) has a pronounced "diode" character in the voltage range (–5V÷+2V). The forward branch of the semiconductor junction with the used arrangement of the electrodes is in the third octant, the reverse branch is in the first one (Fig. 8).

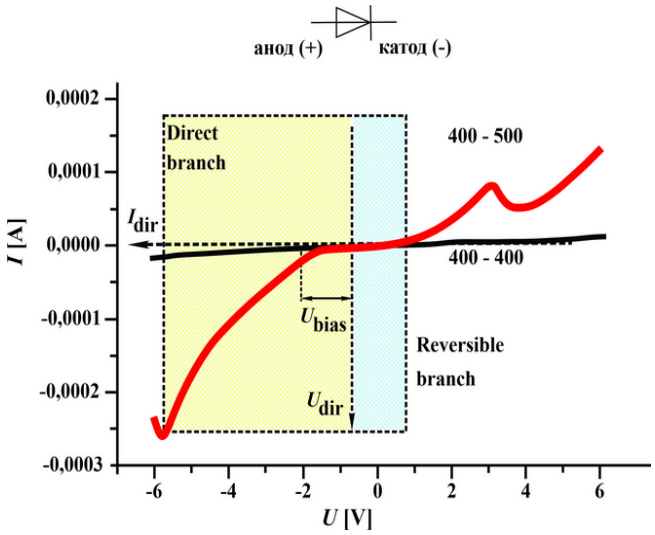


Figure 8. *V-I* curves of contacts of chemically identical samples (ZrO_2–3 mol% Y_2O_3) with identical size of particles (curve 400–400) and samples with different size of particles (curve 400–500) at humidity (85%).

The linear nature of the heterojunction between compacts with the same particle size (400–400) indicates a relatively low current (up to 20 μA) through the contact (400–400) at the specified humidity. The contact of compacts of different-sized particles at the same humidity exhibits an order of magnitude higher (up to 250 μA) current. The working range of the obtained heterojunction is from about 5 V in the forward branch to 2 V in the reverse one. After exceeding these values, the loss of its straightening properties occurs. The curve (400–500) is offset from zero to negative values. It can be assumed that the presence of a bias voltage of –2V is due to the polarization of the media near the contact or electrodes [40].

VI. Conclusion

An analysis of the contacts of two nanopowders revealed several possibilities for the appearance of a contact potential difference between them and the mechanism of the formation of a contact potential difference in nanoparticles of different radii, but ligated with the same impurity.

For the generalized Seitz-Madelung model, applied successively to the near-surface regions of ionic-bonded nanoparticles, it is shown that the graded-gap state in the forbidden band can be realized in the case of chemical homogeneity.

With a random set of nanoparticles with different radii, it is possible to simulate their collective properties basing on the Anderson model with all the richness of its consequences (in this case, each potential pit of the Anderson model corresponds to a wedge-shaped pit of the nanoparticle surface). Electronic transitions from HOMO of water molecules to wedge-shaped potential pits of nanoparticles can either destabilize water molecules, or strengthen them (depending on the binding or loosening character of HOMO, respectively).

The electronic structure of the local states of the surface of nanoparticles with different radii demonstrates possible surface states depending on the energy range of their electrons: within the energy gap and above the energy of the end of the graded-gap. The properties of these local conduction bands close to the upper boundary of the graded-gap have new properties that are not inherent to the Tamm states [41].

Studying the features of the adsorption of a neutral water molecule on nanoparticles of different radii, new situation was revealed, when the HOMO levels locate higher than the band gap, which leads to

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an electronic transition from the molecule water into a nanoparticle.

As an experimental test of the theoretical concept, we chose the study of the volt-ampere dependence of two doped (with Yttrium impurity) powder particles with unequal radii, which showed the presence of properties characteristic for a rectifying contact, in accordance with the general theory. It should be noted that the formation of a contact potential difference in the case of complete mirror symmetry of two nanopowders does not contradict the Curie-Prigogine principle, since the situations considered go beyond the region of weak nonequilibrium [28].

The choice of the electronic concept of "bands", as the basis for the theoretical analysis of the new phenomenon of homovarizonicity, made it possible to widen the class of effects and expand the area of their implementation beyond the limits of such a standard object as zirconium dioxide. This would have been hardly possible using the "bond" proton approach, which is not free from contradictions in the field of implementation of charge carrier tunneling processes [43].

As a prospect of the obtained results, the following should be noted. If the analyzed ionic crystal belongs to the class of superionics, then for the region above the critical temperature of the superionic transition all conclusions remain valid, however, with the correction that all terms of the Coulomb sums must be multiplied by the factor $(1+\Delta^2/(R^2\ (x,y,z))$, where Δ/R is the ratio of the distance between the nearest equivalent half-empty position to the distance from the origin of coordinates to a light mobile ion moving along new split positions.

The discovered nonlinearity of current-voltage characteristics can later become an experimental test for the found theoretical dependence, which consists in the symbatism of the contact potential difference and the difference in the size of nanoparticles.

The obtained experimental and theoretical data allow us to reliably predict the use of these results to develop a new field of nanoelectronics based on unusual molecular processes in chemically homogeneous homovarizonic systems of nanoparticles.

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Оксидли материалларнинг кимёвий жиҳатдан бир ҳил нанозаррачалари юзасига яқин соҳаларда электрон тузилманинг ўзгариши ва унинг цирконий диоксид кукунига сувнинг кимёсорбция энергиясини ўзгартиришдаги роли

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Махсус турдаги оксид нанозаррачаларининг сиртга яқин соҳаларининг электрон тузилиши ва шу асосда контактнинг ўзига хос текислаш хусусиятларини олиш имконияти назарий жиҳатдан ўрганиляпти, кейин эса тажрибада текшириляпти. Тамм типидаги сирт ҳолатларининг моделлари Кулоннинг узоқ масофали ўзаро таъсирини ҳисобга олган ҳолда тузилган. Аниқланган дисперсия ва унинг нанозаррачалар юзасининг эгрилигига боғлиқлиги бир хил радиусли (синергетик эффект), турли радиусли (легирланган ва легирланмаган вариантлар) нанозарралар ҳолатлари учун контакт потенциаллар фарқини шакллантириш шартларини моделлаштиришга имкон беради, шунингдек, Андерсон модели доирасида берилган материалдан қилинган кукун зарралари гуруҳини тасвирлаш имкониятини кашф қилиш. Таклиф этилаётган концепциянинг баъзи оқибатлари тажриба доирасида турли хил радиус бирикмаларига эга бўлган бир жуфт контактли кукун зарраларининг вольт-ампер характеристикаларининг табиати бўйича ўрганилди ва улар текисловчи контактга хос хусусиятлар мавжудлигини кўрсатди. Таклиф этилаётган назариядан келиб чиқадиган кейинги тажриба синовлари учун истиқболлар илгари суриляпти.

Калит сўзлар: сферик оксид нанозаррачалари, электронлар зоналарининг дисперсияси, маҳаллий сирт даражалари, контакт потенциаллар фарқи, кимёсорбция энергиясини ўзгартириш.

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