# Study of temperature dependences and electrical properties of thin films of $Ag_2S$ quantum dots

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**ABSTRACT**

The results of studying the electrical properties of thin films of colloidal quantum dots (QDs), $Ag_2S/SiO_2$ and $Ag_2S/SiO_2/Au$, are interesting and important for understanding the behavior of these materials. Additional studies made it possible to determine the temperature dependences of conductivity in the range from 300 to 360 K, which made it possible to study changes in the electrical properties of materials depending on temperature. Activation energy values obtained from linear approximations of current-voltage characteristics in Arrhenius coordinates have become key to determining energy barriers and conduction mechanisms in these systems. Decorating $Ag_2S$ quantum dots with plasmonic gold nanoparticles also has the potential to improve the electrical properties of materials and create new functional characteristics. The results obtained can have a wide range of applications in the field of nanoelectronics, optoelectronics, sensors and other technologies that require precise control of the electrical properties of materials at different temperatures. Decoration of $Ag_2S/SiO_2$ QDs with plasmonic gold nanoparticles leads to an increase in the band gap from 0.29 to 0.89 eV. This effect can be explained by the interaction between gold plasmons and $Ag_2S/SiO_2$ electrons, which leads to a change in the properties of the material. It has been shown that decorating $Ag_2S/SiO_2$ QDs with Au nanoparticles leads to a change in the type of conductivity. Finally, calculating the mobility of charge carriers according to the Mott-Gurney model allows for a deeper understanding of the conductivity mechanisms in the presented thin-film structures.

**Keywords:** *Quantum dots, Silver sulfide, Activation energy, Charge carrier mobility*

## 1. INTRODUCTION

Nanostructures incorporating semiconductor colloidal quantum dots (QDs) are of interest to researchers and industry. These materials have unique properties, such as quantum size effects, which can affect their electrical, optical and magnetic properties. Such nanostructures can find application in various fields, including photonics, quantum information, sensors, catalysis and other technologies [1-4]. Apart from this, quantum dots also have potential for applications in various fields such as photonics, biomedicine and quantum information science. Their unique properties make them promising materials for creating new technologies and devices. In addition, research in the field of colloidal quantum dots continues, which opens up the possibility of finding new ways and methods to control their properties in order to create even more effective and functional materials [5,6]. Therefore, colloidal quantum dots act as active elements of a new generation of photodetectors [3], IR sensors [7], solar cells [8,9], and phototransistors [4]. Various deposition methods allow control of the thickness and distribution of QDs on the substrate, which is important for various applications. For example, the spin-coating method allows the QD solution to be uniformly applied to the surface of the substrate using rotation, which ensures a uniform coating. Deep coating involves immersing the substrate in a solution and then removing it, which can also provide uniform coverage.

Langmuir-Blodgett technology allows you to control the density of the QD monolayer on the surface of the substrate by controlling the surface tension of the molecules [3,4,9]. Semiconductor colloidal silver sulfide ($Ag_2S$) quantum dots are indeed of interest for applications in modern electronics. These materials have unique optical and electrical properties that can be used to create new devices and technologies [9-11]. The use of silver sulfide-based quantum dots has a number of advantages, such as low toxicity and high efficiency. $Ag_2S$ quantum dots have a high absorption and emission coefficient of electromagnetic energy, as well as high chemical stability and a band gap from 0.9 to 1.1 eV [12,13]. Researchers have shown that changing the size of silver sulfide particles makes it possible to vary the band gap. Reducing the size of $Ag_2S$ nanoparticles (NPs), which have sizes in the range of 500 nm and 60 nm, leads to an increase in the band gap Eg from 0.88 to 1.21 eV, which can be used in photovoltaic devices [14]. A significant influence of the size effect and chemical structure on the transport of charge carriers has also been established. In addition, the quantum effect takes place in the form of laws that determine the process of excitation and decay of excitons [8]. Achieving high carrier mobility is also closely related to the choice of QD surface ligand, including the use of plasmonic nanoparticles [6,9,12]. However, studies of charge transfer processes of colloidal quantum dots are extremely rare in the literature. It is worth noting that studies of $Ag_2S$ QDs are more focused on

luminescent, optical and photocatalytic properties, while studies of the mechanisms of formation and decay of excitons and the mechanisms of conductivity in these structures are relevant and not fully understood.

The study of plasmon-exciton interactions under temperature influences for sandwich structures with thin films of colloidal $Ag_2S$ quantum dots coated with (3-mercaptopropyl)-trimethoxysilane (MPTMS) molecules and decorated with Au nanoparticles is an interesting area of research. Using Au nanoparticles to decorate $Ag_2S$ quantum dots can improve their electrical and optical properties through plasmonic enhancement and enhancement of local electric fields. This, in turn, can lead to improvements in conductivity and other key characteristics of these materials. Research into the conduction mechanisms of $Ag_2S$ colloidal quantum dots is also important, as understanding these mechanisms can help optimize their applications in various devices and technologies, including electronics and photonics. Such research can lead to new discoveries in the field of nanoelectronics, optics and nanotechnology, as well as the development of new devices with improved characteristics and functionality. As part of this study, a further study of the electrical parameters of sandwich structures based on $Ag_2S/SiO_2$ QD and $Ag_2S/SiO_2/Au$ QD films, which were previously reported, was carried out. The results of this study expand our understanding of the operation of these structures and their potential application in various technological processes [15].

## 2. EXPERIMENTAL MATERIALS AND METHODS

The objects of research were $Ag_2S$ colloidal quantum dots prepared by aqueous synthesis methods [15,16]. The basis for the synthesis of $Ag_2S/SiO_2$ colloidal quantum dots is a technique based on the use of silver nitrate ($AgNO_3$) and MPTMS. At the beginning of the experiment, aqueous solutions of these reagents were mixed in a molar ratio of 1:2 at pH 10. This ensured optimal conditions for the formation of complexes and stable formation of colloidal particles. After this, an aqueous solution of sodium sulfide ($Na_2S$) was added to the reaction mixture in a ratio to $AgNO_3$ of 0.6:1, which corresponded to the molar ratio to $AgNO_3$. This made it possible to carry out the process of silver sulfidation and the formation of $Ag_2S$ quantum dots inside silicon dioxide, which significantly improves their stability and electrochemical properties. It follows that the described method for the synthesis of colloidal quantum dots based on $Ag_2S/SiO_2$ has a number of positive features, such as the simplicity and availability of the reagents used, the possibility of obtaining stable and highly effective materials that can be used in various fields of science and technology. With further research in this direction, we can expect the emergence of new materials with improved properties and a wide range of uses.

The steps to synthesize colloidal $Ag_2S/SiO_2$ quantum dots decorated with plasmon Au nanoparticles on the surface are as follows. Plasmon Au NPs with an average size of approximately 2–3 nm were individually synthesized. Gold nanoparticles were obtained through the reduction reaction of hydrochloric acid ($HAuCl_4$ 1 μM) and an aqueous

solution of sodium borohydride ($NaBH_4$ 0.2 mM) in the presence of cetyltrimethylammonium bromide (CTAB 40 mM) [17,18]. Decoration of the surface of $Ag_2S/SiO_2$ QDs with plasmonic Au NPs was carried out by additional functionalization of the QD interface with amino groups. In particular, an ethanol solution of (3-aminopropyl)trimethoxysilane (APTMS) was added to the colloidal solution of $Ag_2S/SiO_2$ QDs. Then, a colloidal solution of Au NPs and $Ag_2S/SiO_2$ QDs was mixed in a ratio of approximately 6:1 (hereinafter referred to as $Ag_2S/SiO_2/Au$ QDs) [17,18].

The morphology of $Ag_2S/SiO_2$ QDs, Au NPs, and $Ag_2S/SiO_2/Au$ QDs was studied using a Libra 120 transmission electron microscope (TEM) and a JEOL 2000FX high resolution TEM. The spectroscopic substantiation of the formation of plexitonic $Ag_2S/SiO_2/Au$ QD nanostructures was performed by infrared (IR) spectroscopy using a Tensor-37 IR-Fourier spectrometer.

Thin films of $Ag_2S/SiO_2$ QDs and $Ag_2S/SiO_2/Au$ QDs were formed by casting onto conductive substrates [19]. An analysis of the surface relief showed a 10% height difference, at a film thickness of about 500 nm, the maximum height difference was ∼ 50 nm. The electrical parameters of thin films of quantum dots were studied by forming Al-$Ag_2S/SiO_2$-ITO and Al-$Ag_2S/SiO_2/Au$-ITO sandwich structures (Figure 1) [20]. Conductive aluminum and indium tin (ITO) substrates were produced by magnetron sputtering. ITO had a resistivity of 16-18 Ω/sq, while aluminum had a resistivity of 20 Ω/sq. The initial solution of the test material in a volume of 0.4 ml was applied to the surface of the substrate with geometric parameters of 10 x 10 mm.

To measure the conductivity of the structures, a four-pin method was used using a Keysight B1500A semiconductor analyzer, which eliminates the influence of contact resistance and obtains accurate results. During the experiment, data were obtained on the dependence of conductivity on temperature and voltage, which made it possible to evaluate the electrical characteristics of the samples under study. The temperature dependence study was carried out using a protective chamber (Faraday cage) placed in a muffle furnace. The measurements were carried out in the voltage range from -1 to 1 V. The temperature range was 300–360 K.
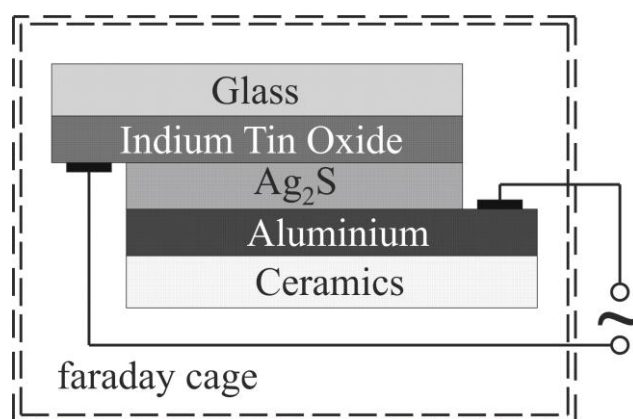


**Figure 1**. Diagram of the measuring chamber

## 3. RESULTS AND DISCUSSION

### 3.1. Morphology and Optical Characterization

For $Ag_2S/SiO_2$ QDs, a comparison of dark-field and bright-field TEM images from the same fragment of the sample showed the following discrepancy in size: in bright-field (5.0 ± 1.5 nm) and dark-field (1.8 ± 0.5 nm). The obtained data testify in favor of the formation of a $SiO_2$ shell with a thickness of ~1.6 ± 0.5 nm (Figure 2) [15].

Analysis of high-resolution TEM images (Figure 3) showed the formation of agglomerates from nanocrystals with an interplanar spacing of ~0.222 nm, corresponding to diffraction from the crystallographic plane (130) of the $Ag_2S$ monoclinic lattice and Au particles (interplanar spacing 0.2039 nm (200), FCC lattice), which confirms the decoration of $Ag_2S/SiO_2$ QDs with plasmonic Au NPs (Figure 3) [15].

The structure of $Ag_2S/SiO_2$ QD interfaces at all stages of formation of plexitonic nanostructures was established from the analysis of IR absorption spectra [15]. The formation of a $SiO_2$ shell on the surface of $Ag_2S$ QDs was confirmed in the IR spectrum by absorption peaks of siloxane vibrations (1103 cm$^{-1}$ (vas(Si-O-Si)), 1023 cm$^{-1}$ (vs(Si-O-Si) and 800 cm$^{-1}$ δ (Si-O-Si)) and silanol groups 3260 cm$^{-1}$ (ν(SiOH)) and 928 cm$^{-1}$ (δ(SiOH)) (Figure 4).
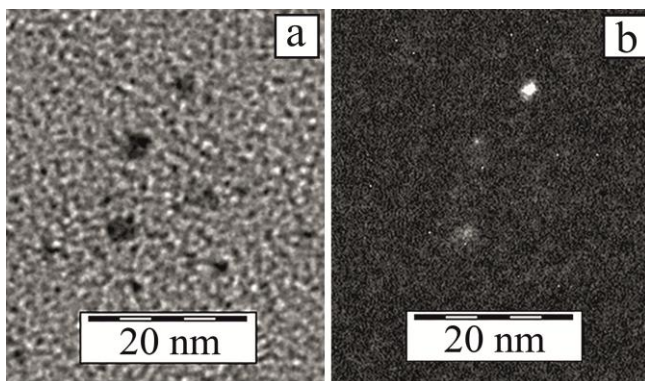


**Figure 2**. (a) Bright-field and (b) dark-field TEM images of $Ag_2S/SiO_2$ QDs
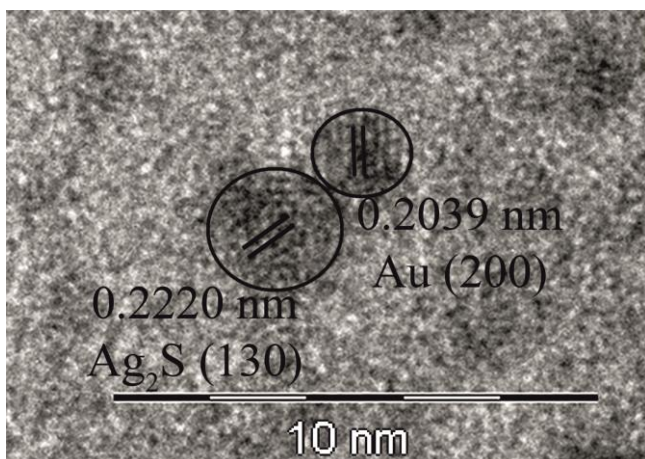


**Figure 3**. High-resolution TEM images of $Ag_2S/SiO_2/Au$ QDs

At the same time, the intensity of the band of symmetric valence vibrations (vs(Si-O-Si) = 1023 cm$^{-1}$) exceeds the intensity of the band of asymmetric valence vibrations of the siloxane group (vas(Si-O-Si) 1103 cm$^{-1}$), which indicates the formation of Si-O-Si chain structures characteristic of shells with a thickness of more than 1 $SiO_2$ monolayer on the $Ag_2S$ QD surface. The subsequent functionalization of the $Ag_2S/SiO_2$ QD surface with APTMS amino groups is confirmed by the appearance in the IR spectrum of characteristic vibrations of $NH_3^+$ groups (3140 cm$^{-1}$ and 3049 cm$^{-1}$ ν($NH_3^+$), 1485 cm$^{-1}$, 1450 cm$^{-1}$ and 1408 cm$^{-1}$ δas($NH_3^+$)) and $NH_2$ (3401 cm$^{-1}$ and 3233 cm$^{-1}$ ν(NH), 1658 cm$^{-1}$ δ(NH)). Adsorption of plasmonic Au NPs on the surface $Ag_2S/SiO_2$ QD occurs due to the interaction of APTMS amino groups with metal (Figure 4) [15].

### 3.2. Activation Energy Calculation

When measuring temperature under conditions of applying low-strength electric fields to the samples under study (E < $10^2$ V/cm), it was found that the temperature dependence of conductivity obeys the well-known power law [21]:

$$\sigma = \sigma_0 e^{\frac{-E_a}{2kT}} \tag{1}$$

where $Ea$ is the activation energy; $\sigma$ is the electrical conductivity of the material; $k$ is Boltzmann's constant.

The activation energy in this case is equal to:

$$E_a = \frac{2kT_1T_2}{T_2 - T_1} \ln \frac{\sigma}{\sigma_0} \tag{2}$$

where $T_1$, $T_2$ are the initial and final temperatures, respectively; $\sigma_0$ and $\sigma$ are the electrical conductivity of the material at the initial and final temperatures, respectively.

Thus, for thin-film colloidal quantum dots, the activation energy value was: $Ag_2S/SiO_2$ QDs – 0.3 eV and $Ag_2S/SiO_2/Au$ QDs – 0.87 eV. Note that decorating $Ag_2S/SiO_2$ QDs with Au plasmon nanoparticles leads to an increase in the band gap.
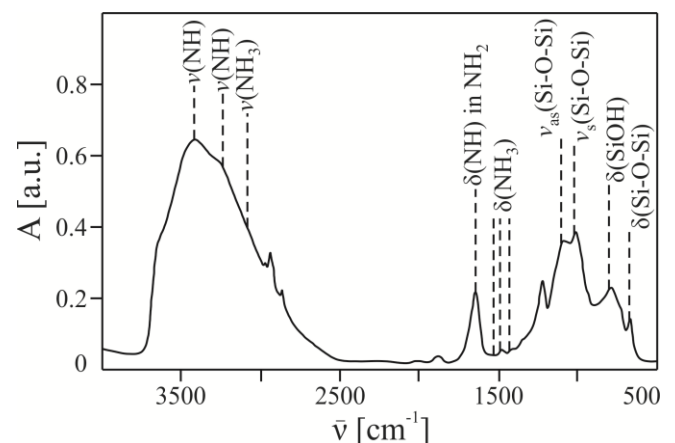


**Figure 4**. IR absorption spectrum of colloidal $Ag_2S/SiO_2/Au$ QDs

Next, let us consider the electrical properties of Ag₂S/SiO₂ and Ag₂S/SiO₂/Au QDs thin-films in the region of higher applied fields (E > 10² V/cm). In Figure 5 shows the current-voltage characteristics in the temperature range (CVCT) of Ag₂S films formed in the form of an ITO-Ag₂S/SiO₂-Al and ITO-Ag₂S/SiO₂/Au-Al sandwich structure. Note that for Ag₂S/SiO₂ QDs, a decrease in conductivity is observed with increasing temperature [Figure 5 (a)].

Then, with increasing temperature, the conductivity of Ag₂S/SiO₂/Au QDs increases. This may be due to thermal excitation of charge carriers and the manifestation of plasmonic excitonic interactions in the Ag₂S/SiO₂/Au QD system [Figure 5 (b)].

Previously, we showed that colloidal Ag₂S/SiO₂/Au QDs have almost linear current-voltage characteristics at a temperature of 300 K, and this property is determined by the ohmic conductivity of this structure. The transition from ohmic to barrier conductivity may be key for the application of these structures, which is associated with exposure to electromagnetic radiation in the visible range. These are interesting results that indicate that colloidal Ag₂S/SiO₂/Au quantum dots have unique conductive properties that can change when exposed to certain radiation [15].

In this work, we observe a similar manifestation of a change in the type of conductivity of the ITO-Ag₂S/SiO₂/Au-Al sandwich structure. As in previous studies, we observe identical, almost linear current-voltage characteristics at a temperature of 300 K, but when the structure is heated, an increase in the nonlinearity of the characteristics is observed. Nonlinear current-voltage characteristics indicate the formation of a barrier structure in which the flowing current is determined by the injection of charge carriers through the barrier. Therefore, we can conclude that in the ITO-Ag₂S/SiO₂/Au-Al sandwich structure a Schottky barrier also appears at the Al - Ag₂S/SiO₂ contact boundary, similar to the ITO-Ag₂S/SiO₂-Al structure. The conduction mechanism of the Schottky emission type [22,23] is described by equation (3):

$$J = A^*T^2 \exp\left\{ \frac{-e\left[ \varphi_b - \sqrt{eE/(4\pi\varepsilon_r\varepsilon_0)} \right]}{kT} \right\} \tag{3}$$

where $J$ is the current density, describes the volumetric current through the material; $A^*$ - the effective Richardson constant characterizes the ability of a material to emit electrons when heated ($m^*$ is the effective mass of charge carriers, plays a role in determining the electronic parameters of the material; $h$ is Planck's constant); $T$ – absolute temperature characterizing the degree of heating of the material; $e$ – electron charge; $\varphi_b$ – the height of the Schottky barrier, determines the behavior of electrons when passing through the boundary between materials; $E$ – electric field strength, describes the force of the electric field on charges in the material; $\varepsilon_r$ – dynamic dielectric constant, characterizes the interaction of electric fields in the material; $\varepsilon_0$ – dielectric constant; $k$ – Boltzmann's constant, associated with the distribution of thermal energy in materials, and

$$A^* = 4\pi em^*k^2/h^3 \tag{4}$$

To determine the conduction mechanism, we construct the CVCT in Schottky coordinates ($lnJ(E)^{1/2}$) (Figure 6) [24, 25]. The slope of the linear approximations of the CVCT changes with temperature.

Based on the slope value of the linear approximation in Schottky coordinates, this value $\varepsilon_r$ can be calculated using equation (5) [26].

$$\varepsilon_r = \frac{e^3}{4\pi\varepsilon_0 b^2 k^2 T^2} \tag{5}$$

where $b$ is the slope ratio of linear approximations of CVCT in the Schottky coordinates.

Equation (6) is used to describe the current caused by thermal excitation of charge carriers in the membrane structure. This equation allows one to estimate the magnitude of the current caused by thermal excitation of charge carriers under various conditions and structural parameters [27, 28].

$$J = A^*T^2 \exp\left( \frac{-E_a}{kT} \right) \tag{6}$$

where $E_a$ is the energy of activation of charge carriers. Having taken the logarithm of Eq. (6), we obtain:
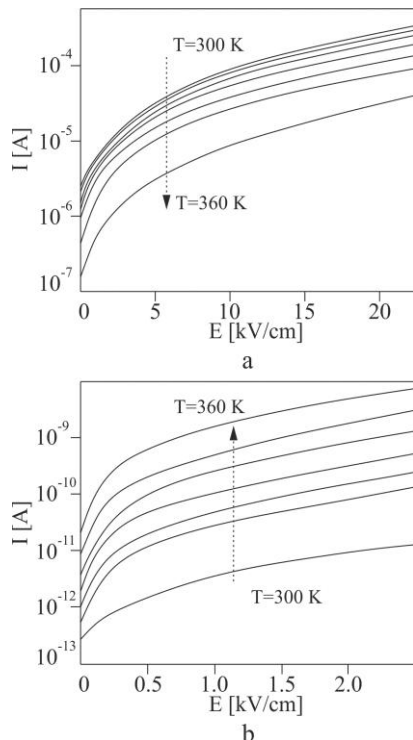
$$\ln J = \ln(A^*T^2) - \frac{E_a}{kT} \tag{7}$$



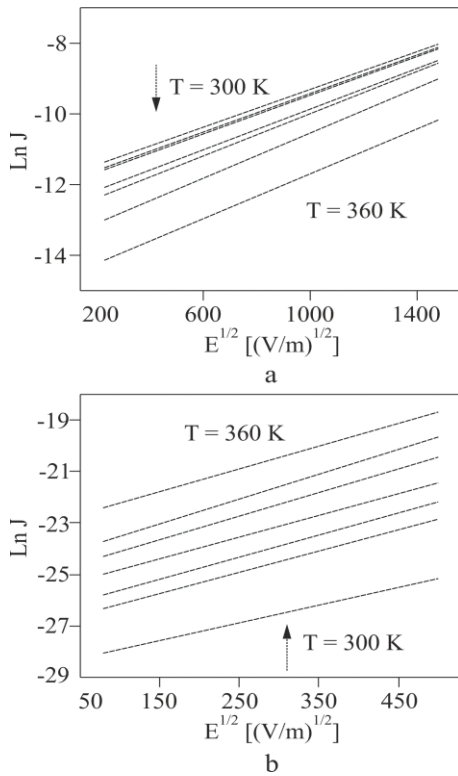**Figure 5**. CVCT of (a) Ag₂S/SiO₂ QDs and (b) Ag₂S/SiO₂/Au QDs

**Figure 6**. CVCT of (a) Ag$_2$S/SiO$_2$ QDs and (b) Ag$_2$S/SiO$_2$/Au QDs in Schottky coordinates



**Figure 7**. CVCT of (a) Ag$_2$S/SiO$_2$ QDs and (b) Ag$_2$S/SiO$_2$/Au QDs in Arrhenius coordinates

The *lnJ* and $(kT)^{-1}$ coordinates are referred to as Arrhenius coordinates (Figure 7) [24]. The slope of linear approximations of CVCT in Arrhenius coordinates gives the values of the activation energy of charge carriers.

In essence, the energy of activation is the effective height of the Schottky barrier [29] and described by the equation:

$$E_a = e\varphi_b - \sqrt{e^3 E / (4\pi\varepsilon_r\varepsilon_0)} \tag{8}$$

The activation energy values for charge carriers of thin-film colloidal QDs, calculated from linear approximations of the CVCT in Arrhenius coordinates, were: Ag$_2$S/SiO$_2$ QDs – 0.29 eV and Ag$_2$S/SiO$_2$/Au QDs – 0.89 eV. Note that the activation energy values obtained from the linear approximation of the CVCT in Arrhenius coordinates correlate with the results obtained using the power law (Equation 1).

### 3.3. Determination of the Dominant Conduction Mechanism

Investigate into the ideality figure η in natural materials can move forward the generation of electronic gadgets such as sun powered cells, OLED shows and transistors. The properties and conductivity of natural materials play an imperative part within the improvement of modern advances and gadgets. Based on these contemplations, the value of η was calculated, which was decided from the slant of the direct portion of the forward uprooting of the ln (*I*) – *V* chart and was calculated from the connection [30]:
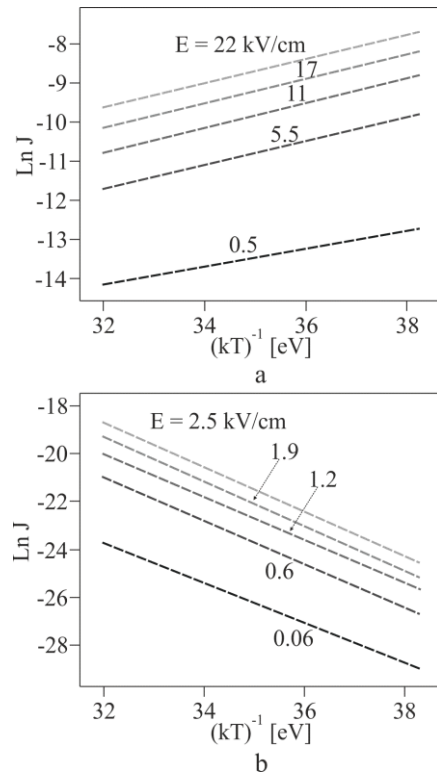
$$\eta = \frac{e}{kT}\frac{dV}{d(\ln I)} \tag{9}$$

The ideality factor $\eta$ generally describes how efficiently thermionic emission occurs in a material. For an ideal diode, in which thermionic emission mechanism is dominant, this factor is equal to unity. However, if for the studied Ag$_2$S film structures the values of the ideality factor are greater than unity, this indicates a more complex mechanism of conduction of these compounds. Such an increase in value may indicate additional processes affecting the conductivity of the material, in addition to thermionic emission [31].

Following, we characterize the prevailing conductivity instrument by showing the current-voltage characteristics on a logarithmic scale (Figure 8). In this case, a commonplace control law I ~ V$^m$ [32], where m is the incline esteem for each locale of the connected voltage characterizes energy of charge carriers portrays the reliance of the current on the connected voltage.

Considering the sandwich structure of ITO-Ag$_2$S/SiO$_2$-Al, at a temperature T = 300 K, three locales characterizing the energy of charge carriers can be recognized [Figure 8 (a)]. The resistive conduction component, characterized by coefficient m, compares to the voltage run from to 0.125 V (coefficient m$_1$ in Table 1). Current mode with space charge restricted conduction (SCLC) [30] works within the voltage run from 0.125 to 0.7 V (coefficient m$_2$ in Table 1). The third extend, comparing to charge exchange due to the trap charge constrained conduction (TCLC) component, works at voltages over 0.7 V (coefficient m$_3$ in Table 1) [30].

Analyzing the ITO-Ag$_2$S/SiO$_2$/Au-Al sandwich structure, it was previously shown that at a temperature T = 300 K, the dominant conduction mechanism is the resistive mechanism. When plotting the dependence of current

density on voltage on a logarithmic scale, we also obtain a linear characteristic, which is determined by ohmic conductivity. In turn, heating of Ag₂S/SiO₂/Au QDs is accompanied by an increase in the nonlinearity of the current-voltage characteristic - the formation of a barrier. In this regard, let us consider the conductivity mechanisms of the ITO-Ag₂S/SiO₂/Au-Al sandwich structure at a temperature T = 360 K [Figure 8 (b)]. Three regions can be distinguished with different inclination angles. The resistive conductivity component of Ag₂S/SiO₂/Au QDs compared to the voltage run from to 0.175 V (coefficient $m_1$ in Table 1). The SCLC instrument wins within the voltage run from 0.175 to 0.675 V (coefficient $m_2$ in Table 1). Charge exchange due to the TCLC instrument works at voltages over 0.675 V (coefficient $m_3$ in Table 1).

The space charge constrained conduction portability parameter concurring to the Mott-Gurney demonstrate [31] can be depicted as:

$$J_{SCLC} = \frac{9}{8} \varepsilon_0 \varepsilon_r \mu_{eff} \frac{V^2}{d^3} \qquad (10)$$

where $\varepsilon_0$ is the free-space dielectric consistent; $\varepsilon_r$ is the relative dielectric permittivity of a material; $d$ is the film thickness; $V$ is the connected voltage and $\mu_{eff}$ is the viable charge portability. The compelling charge portability of colloidal Ag₂S/SiO₂ and Ag₂S/SiO₂/Au QDs movies are appeared in Table 2.

As a comparative analysis, we present the results for condensates of colloidal Ag₂S QDs, passivated with thiol-containing molecules (thioglycolic acid and L-cysteine) (Ag₂S/TGA QDs and Ag₂S/L-Cys QDs) [33]. These materials were synthesized using a similar method, and similar studies of their electrophysical properties were conducted. Note that the formation of QDs shells using various condensates significantly affects the properties of the final material.

## 4. CONCLUSION

As a result of the study of the electrical characteristics of colloidal quantum dots Ag₂S/SiO₂ and Ag₂S/SiO₂/Au, interesting patterns were identified that indicate a change in the type of conductivity depending on the structure and composition of the nanoparticles. Specific consideration is given to the decoration of colloidal Ag₂S/SiO₂ QDs with plasmonic gold nanoparticles and its impact on the electrical properties of the material. Studies have shown that when Ag₂S/SiO₂ is decorated with plasmonic gold nanoparticles, the type of conductivity changes from barrier to ohmic. This proposes that plasmonic gold nanoparticles have a noteworthy impact on the electrical properties of the material and help improve its conductivity. In expansion, amid the consider it was found that the temperature impact on the ITO-Ag₂S/SiO₂/Au-Al sandwich structure leads to nonlinearity of the current-voltage characteristic and a change in the type of conductivity of the sandwich structure from ohmic to barrier. This proposes that temperature changes can significantly affect the material's conductivity and electrical properties. It has been appeared that the

**Table 1.** Conduction mechanism of Ag₂S/SiO₂ QDs and Ag₂S/SiO₂/Au QDs

|  | Ag₂S/SiO₂ QDs | Ag₂S/SiO₂/Au QDs |
|---|---|---|
| Slope value $m_1$ | 1.14 | 1.09 |
| Slope value $m_2$ | 1.45 | 1.44 |
| Slope value $m_3$ | 2 | 2.24 |
| $U_{m1}$ (V) | 0 – 0.125 | 0 – 0.175 |
| $U_{m2}$ (V) | 0.125 – 0.7 | 0.175 – 0.675 |
| $U_{m3}$ (V) | > 0.7 | > 0.675 |

**Table 2.** Activation energy, ideality factor and charge carrier mobility of Ag₂S/SiO₂ and Ag₂S/SiO₂/Au QDs

|  | Ag₂S/SiO₂ QDs | Ag₂S/SiO₂/Au QDs |
|---|---|---|
| $E_a$ (eV) | 0.29 | 0.89 |
| Ideality factor $\eta$ | 3.39 | 1.37 |
| $\mu_{eff}$ (m²V⁻¹s⁻¹) | 3.81×10⁻⁷ | 1.25×10⁻¹⁰ |

**Table 3.** Activation energy, ideality factor and charge carrier mobility of Ag₂S/TGA and Ag₂S/L-Cys QDs

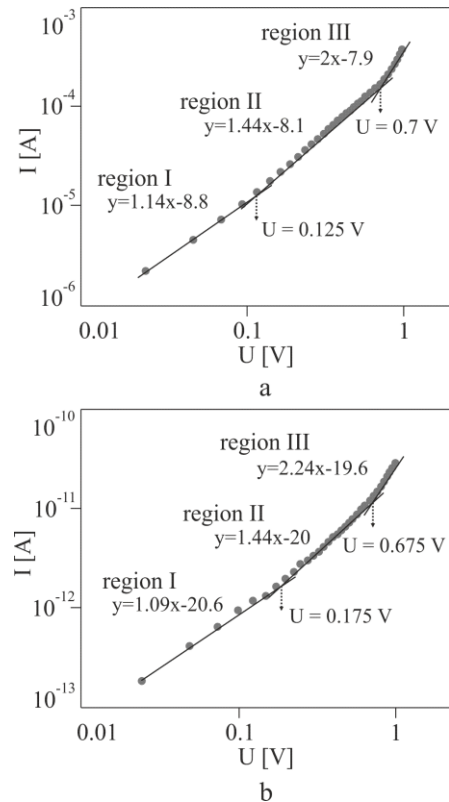|  | Ag₂S/TGA QDs | Ag₂S/L-Cys QDs |
|---|---|---|
| $E_a$ (eV) | 0.2 | 0.66 |
| Ideality factor $\eta$ | 4.21 | 1.41 |
| $\mu_{eff}$ (m²V⁻¹s⁻¹) | 9.77×10⁻⁸ | 2.57×10⁻⁹ |



**Figure 8**. Logarithmic current density as a function of logarithmic applied voltage under negative bias of (a) Ag₂S/SiO₂ QDs and (b) Ag₂S/SiO₂/Au QDs

conductivity of the ITO-Ag$_2$S/SiO$_2$-Al and ITO-Ag$_2$S/SiO$_2$/Au-Al sandwich structures is decided by the Schottky barrier at the Ag$_2$S QDs film - Al interface. Using two methods, the activation energy of the process of thermal excitation of charge carriers was calculated. It has been shown that decorating Ag$_2$S/SiO$_2$ QDs with Au plasmon nanoparticles leads to an increase in the band gap from 0.29 to 0.89 *eV*. This fact may be due to the manifestation of small traps of plasmon-exciton interaction in the Ag$_2$S/SiO$_2$/Au QDs system, which is indirectly confirmed by a decrease in charge carrier mobility from $3.81 \times 10^{-7}$ to $1.25 \times 10^{-10}$ m$^2$V$^{-1}$s$^{-1}$. The results obtained indicate the possibility of developing model diode structures based on Ag$_2$S/SiO$_2$ and Ag$_2$S/SiO$_2$/Au colloidal QDs. In this way, the results of this study confirm the significance of the interaction of different nanoparticles in colloidal systems and their impact on the electrical properties of materials.

## ACKNOWLEDGMENTS

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