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New sulfur precursor for synthesis of environmentally friendly colloidal quantum dots $CuInS_2$

© I. A. Shuklov*, A. V. Seraya, A. Y. Shalagin, V. V. Lim, T. Milenkovich, O. V. Vershinina, V. O. Yakovlev, V. S. Popov, V. V. Ivanov

Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, Moscow Region, 141701 Russia
* *E-mail: shuklov.ia@mipt.ru*

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A new sulfur precursor has been developed by dissolving the elemental sulfur in decene-1 at elevated temperatures and pressures. The synthesis of environmentally friendly colloidal quantum dots $CuInS_2$ for the visible range has been studied in details using this precursor. The influence of various reaction conditions like temperature, concentration as well as nature of indium precursor has been studied. For the obtained samples of nanoparticles, their composition and spectral characteristics have been described. The applicability of this sulfur precursor to obtain $AgInS_2$ nanoparticles has been demonstrated. Based on the materials derived, thin films have been produced and basic possiblity of photosensor preparation has been demonstrated.

Keywords: copper indium sulfide; hot injection synthesis; precursor; quantum dots.

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Opportunity for convenient directional change of the sensitivity spectrum range and of applying to substrates make the colloidal solutions of quantum dots particularly interesting for applications in electronics [1, 2]. In particular, the use of colloidal quantum dots for the visible range has already found commercial applications [3]. TV and computer monitors based on the QLED technology can be found in electronics supermarkets. This technology has been optimized to cut down the cost of devices and ensure their mass production. The synthesis of CdSe CQDs used in this technology as phosphors is well established [4]. However, a significant disadvantage of this technology is the high toxicity of cadmium compounds used in production of CdSe CQDs and risk of environmental pollution in case of damaging the devices based on them [5, 6]. This circumstance is a strong constraint to production of solar cells based on CdSe CQDs.

As an alternative to CdSe CQDs, a number of other nanocrystals absorbing in the visible range can be used. Such nanocrystals are based on less toxic and more environmentally friendly inorganic materials, for example, perovskites $CsPbX_3$ or ternary indium chalcogenides I-III-VI of type $MInZ_2$ (M = Cu, Ag, Z = S, Se, Te) having a chalcopyrite crystal structure. The perovskites

featuring good optical properties have a very low stability to hydrolysis in humid air with a relative humidity of 50 % and higher [7, 8]. High sensitivity to moisture is one of the most important and difficult problems for implementation of perovskite-based solar cells. Ternary indium chalcogenides such as $CuInS_2$ and $AgInS_2$ seem to be more attractive materials because they exhibit absorption and luminescence in the visible range while being completely unsusceptible to hydrolysis [9]. Besides, quantum dots have high potential for being used in photocatalysis for wastewater treatment and water photodecomposition [10].

$CuInS_2$ has a band gap estimated to be 1.53 eV and exciton Bohr radius of 4 nm [11]. $AgInS_2$ has a band gap estimated to be 1.87 eV for the bulk material and exciton Bohr radius of 5.5 nm.

Triple points of indium sulfides are synthesized either by solvothermal or high-temperature colloidal method. Dodecanethiol-1 is most often used as a sulfur precursor for synthesis of $CuInS_2$ nanoparticles at temperatures of 220–250 °C [12, 13]. In some cases, bis-trimethylsilyl sulfide [14], di-tert-butyl disulfide [15] and diphenylphosphine sulfide [16] were used. All the above reagents are sulfur precursors and are not produced by the Russian chemical industry, thus making the search for effective alternatives promising.

Findings and discussion

As part of our research efforts to find the alternative methods of synthesizing chalcogenide quantum dots, methods for obtaining CQDs of PbS and MTe (M = Cd, Hg, Pb, Zn) were proposed [17, 18].

To get the quantum dots of indium sulfides, it was decided to develop a sulfur precursor based on Russian-made decene-1. A precursor based on the elemental selenium dissolved in decene-1 was successfully used by us for synthesizing colloidal quantum dots of HgSe [19]. Similarly, the elemental selenium solution in decene-1 was proposed for use. Sulfur vulcanization of rubber using the elemental sulfur and its related polymerization of alkenes in the presence of sulfur are fairly well-studied processes [20]. Reagents based on sulfur solutions in a longer-chain alkene, specifically octadecene-1, were previously used for synthesizing nanoparticles of PbS [21] and $CuInS_2$ [22], CdS [23]. Unfortunately, Russian-made octadecene-1 is currently not commercially available, for which reason we used decene-1.

Sulfur may be inserted into the C-H bond at lower temperatures than selenium. Sulfur is actually completely dissolved in decene-1 as early as at a temperature of 120 °C. Polysulfides prevail in resulting sulfur solution, which is confirmed by the chemical behaviour and spectral characteristics of resulting solutions. Thus, upon cooling the solutions made at 150 °C, the elemental sulfur is released to pass into solution again upon heating (Fig. 1). Temperature increase to 170 °C leads to irreversible dissolution of sulfur and getting solutions with a more intense color. Simultaneously, colored products can be observed in the absorption spectrum, the spectra of these products being similar to those of the described organic polysulfides [24, 25]. The absorption edge shifts to the region of longer waves during the reaction.

To study the formation of $CuInS_2$ nanoparticles, a precursor formed by dissolving 0.4 M of sulfur in 10 ml of decene-1 at 150 °C was selected. Russian-made decane and cetane were tested as high-temperature apolar solvents. The use of decane (T_{boil} = 174 °C) allows synthesizing at temperatures up to 150 °C, while the use of cetane (T_{boil} = 286 °C) – at temperatures up to 250 °C. Higher synthesis temperatures are not achievable because initiating a reaction in the argon flow results in removal of the solvent with an inert gas flow from the reaction mixture at temperatures approaching boiling points. Indium halides ($InCl_3$ and InI_3) and

indium stearate were tested as indium starting reagents. Due to their high hygroscopicity, indium halides are less convenient as metal precursors. For all tested systems, the mixture of copper chloride and indium salts forms homogeneous solutions in the oleylamine+alkane mixture at temperatures of about 100 °C. $CuInS_2$ CQD were synthesized by injecting the sulfur precursor into a mixture of metal precursors (see Table 1).

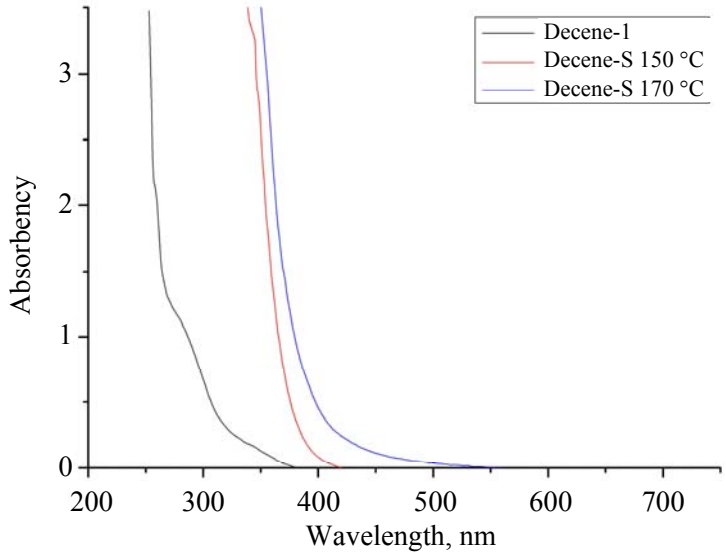


Fig. 1. Absorption spectra of decene and 0.4 M of elemental sulfur solution in 1-decene at different dissolution temperatures

Table 1

Syntheses of $CuInS_2$, variations of indium precursors

In precursor	Solvent	Temperature, °C	Particle size, nm	Standard size deviation, nm
$InCl_3$	decane	150	9.0	2.07
$InCl_3$	cetane	150	14.3	2.05
InI_3	decane	150	4.9	0.84
$In(OOCC_{17}H_{33})_3$ ($InSt_3$)	decane	150	19	3.30

Indium chloride, indium iodide and indium stearate were studied as indium precursors. When synthesizing $CuInS_2$ under the same conditions at 150 °C with the reaction terminated after 90 minutes, the average particle size strongly depends on the metal precursor. The size and structure characteristics of quantum dots were determined by the transmission electron microscopy. The smallest average diameter equaling to 5 nm was determined for the particles obtained with indium iodide. While indium stearate was found to have the highest average particle size of 19 nm. The influence of the medium on the average particle size was also investigated, and syntheses were carried out in decane and cetane with indium chloride as a precursor. Cetane allows synthesizing at higher temperatures.

In decane, nanoparticles of a smaller average size of 9 nm were obtained, while in cetane, under similar conditions, the average size of dots was 14 nm. This may be caused by the large difference in viscosity of these two alkanes, specifically 0.850 mPa·s for decane and 3.03 mPa·s for cetane. In a more viscous solvent, larger nanoparticles were obtained [26]. The larger the nanoparticles,

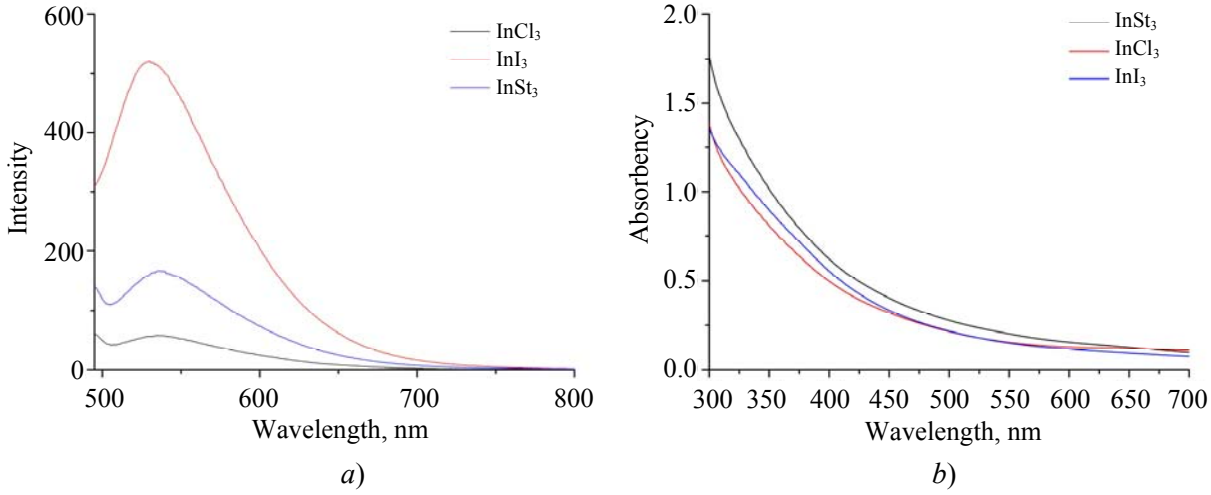
the higher the values of standard size deviations of nanoparticles are. It is worth noting that since indium halides are highly hydroscopic, it is difficult to weigh these salts in the normal atmosphere, while using indium stearate does not require special conditions for weighing.

The obtained quantum dots exhibit a clearly distinct luminescence maximum at 540 nm with all the precursors that have been studied, as well as at all studied temperatures from 110 °C to 150 °C with $InCl_3$ as a precursor (Fig. 2*a*). Similar behaviour was described previously for $CuInS_2$ nanoparticles synthesized by the solvothermal method [27]. This is explained by the fact that the size of the obtained nanoparticles exceeds the Bohr exciton radius for the given material. The luminescence intensity depends on the reaction conditions.

The shape of the absorption spectrum depends on the maximum particle size and size distribution with an absorption edge of about 650 nm (Fig. 2*b*). Analysis of TEM images (Fig. 3*a*) showed that the obtained $CuInS_2$ nanoparticles have the shape of tetrahedron and truncated tetrahedron, which is typical for this material. The size distribution (Fig. 3*b*) is approximated by the lognormal function, the average particle size is about 9 nm.

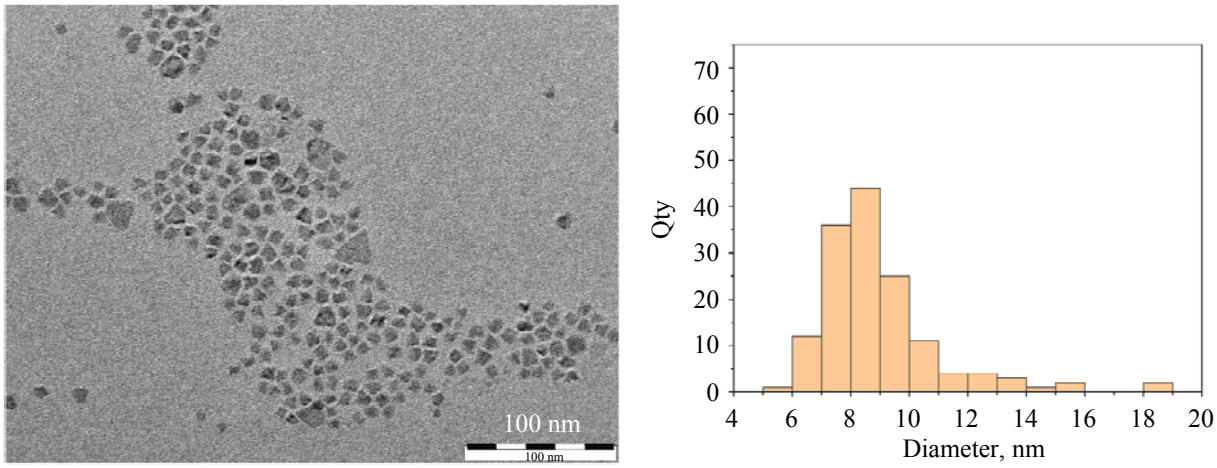
Selected area electron diffraction (SAED) patterns obtained from the nanoparticles (Fig. 4*a*) indicate the presence of a crystalline phase of chalcopyrite $CuInS_22$ with tetragonal syngony. The diffraction pattern contains reflections (112), (204), (312), which correspond to interplanar distances of 3.196, 1.959, 1.666 Å. The transmittance spectrum shows signals of stretching vibrations of C-H groups at 2923 cm^{-1} (methylene) and 2853 cm^{-1} (methyl), as well as deformations of CH_2 group at 1464 cm^{-1}. Also a very broad absorption signal can be observed in the IR range, which is probably associated with an intraband transition in nanocrystals.

Based on the obtained sol, the creation of thin films of CQDs was studied. When applied on glass surfaces or on gold interdigitated electrodes on oxidized silicon, thin layer samples with a ligand shell substituted by thiocyanate anions were obtained using NH_4SCN in isopropanol (Fig. 5). According to AFM data, the obtained films have a smooth, even and uniform surface without pronounced edge effects with an observed average roughness of 10 nm at the film thickness of about 100 nm.



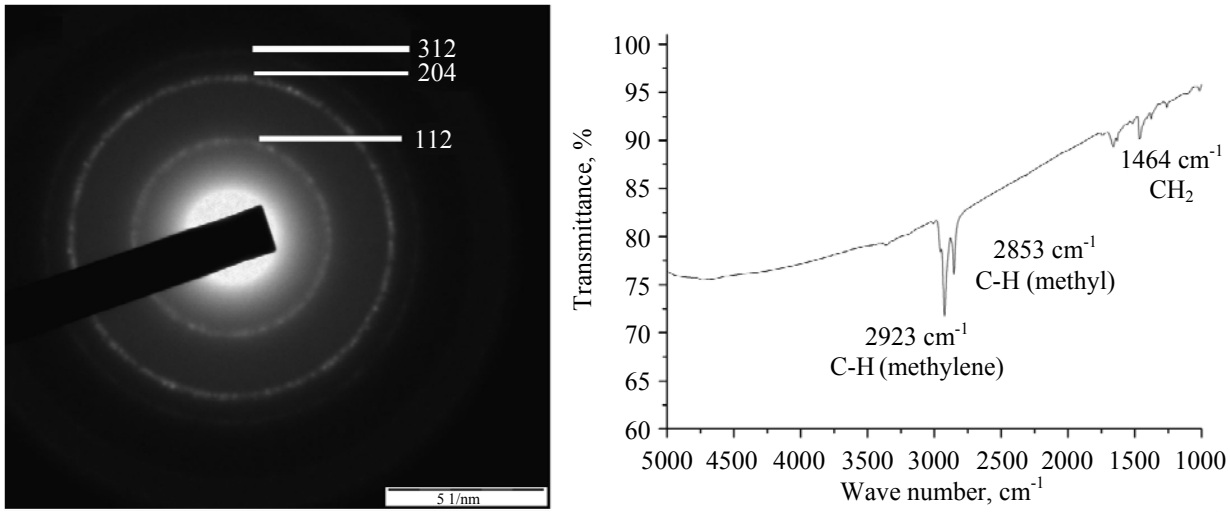
a) *b*)

Fig. 2. Spectra of a) luminescence and b) absorption (visible range, 300–700 nm) of $CuInS_2$ CQDs obtained using different precursors at 150 °C in decane



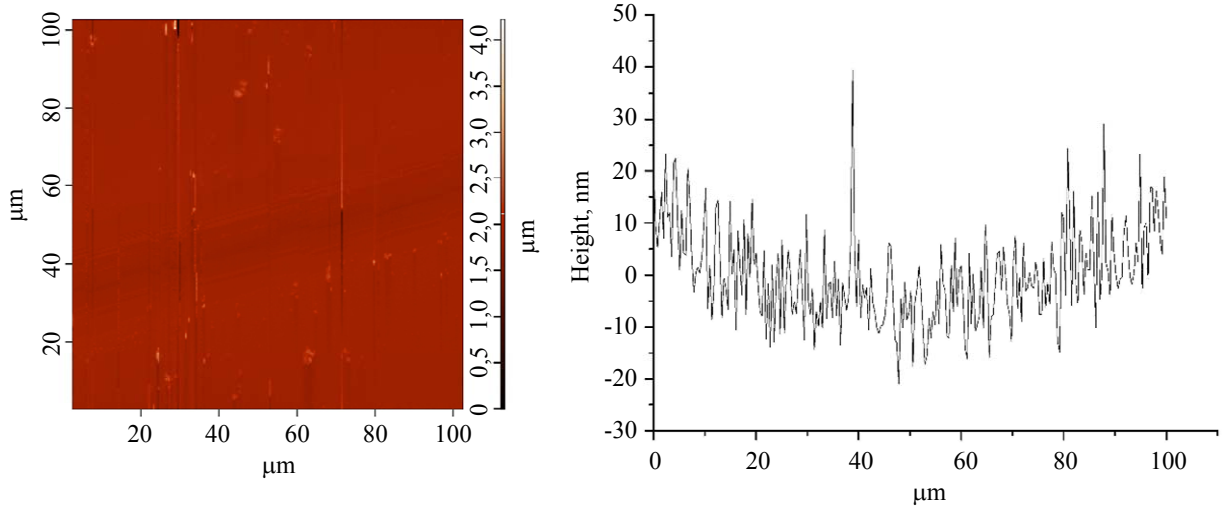
a) *b*)

Fig. 3. a) TEM image and b) size distribution of $CuInS_2$ CQDs



a) *b*)

Fig. 4. a) SAED image; b) IR spectra in the range of 5000–1000 cm^{-1}; of $CuInS_2$ nanoparticles



a) *b*)

Fig. 5. Surface image and cut profile of $CuInS_2$ CQD film obtained by substitution of ligands

Photoresponses were measured using a proprietary setup, comprising Keithley 2636 B source measurement unit, with the sample illuminated orthogonally from a LED at the wavelength of 405 nm. During measurements, the cell containing the sample was blown with argon to eliminate effects induced by the surrounding atmosphere. In the course of measurements, the current flowing through a single photoresistor was measured over time at the constant voltage on the sample equaling to 1 V. The illumination duration was 30 s with a duty cycle of 2 (Fig. 6).

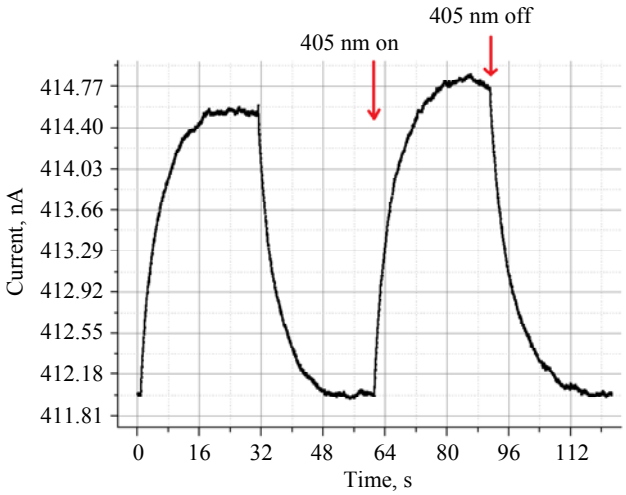


Fig. 6. Typical current vs. time dependence when switching the illumination on and off from the 405 nm source

The average photocurrent amplitude for the sample was 2.5 nA. The ampere-watt responsivity averaged to 19.5 μA/W. Photocurrent rise time (time required for the photocurrent to increase from 10% to 90% of the maximum) and fall time (time required for the photocurrent to decrease from 90% to 10% of the maximum) of:

$$t_{0.1–0.9} = 10.8 \text{ s}$$
$$t_{0.9–0.1} = 9.21 \text{ s}$$

The obtained high values of rise and fall times are generally not typical for detection processes based on the photon mechanism and may be contributed from thermal processes occurring in parallel.

The method developed for synthesizing $CuInS_2$ nanoparticles was used for synthesis of $AgInS_2$ nanoparticles. The method was established to be less general when applied to silver than when applied to copper. It is impossible to use indium halides as a precursor for the synthesis of these nanoparticles, since they form insoluble silver halides in the reaction conditions. When a mixture of indium stearate and silver is used, colloidal nanoparticles of $AgInS_2$ with an absorption peak maximum at 585 nm can be obtained. Changing the reaction time allows varying the optical properties of the resulting nanocrystals (Fig. 7).

It is planned to additionally research the use of this precursor for synthesizing nanocrystals of ABS_2 chalcopyrites, where A = Cu, Ag; B = Ga, In, Bi.

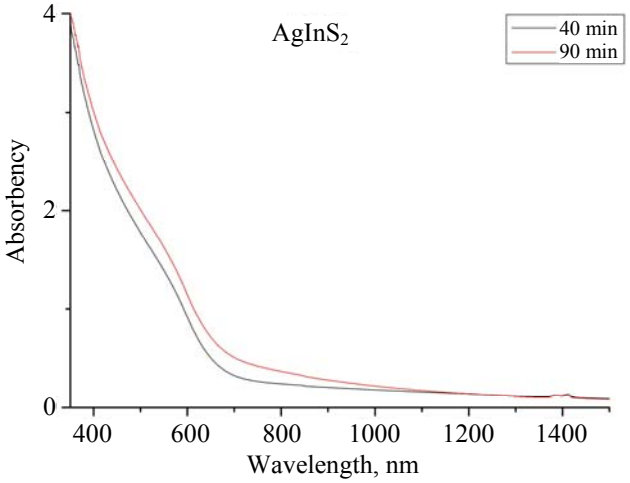


Fig. 7. Absorption spectra of $AgInS_2$ obtained at 150 °C

Experimental section

Chemicals.

The following chemicals were used for synthesis of $CuInS_2$ and $AgInS_2$ CQDs without further purification: copper chloride (99%, Lankhit), indium chloride (99%, Lankhit), indium iodide (99%, Lankhit), sulfur (99.99999%, Reakhim), decene-1 (90%, Vekton), silver nitrate (reagent grade, Vekton), hexane (99% HPLC grade, MacronFineChemicals) and ethanol (reagent

grade, Khimmed), decane (high purity, reagent grade), cetane (high purity, reagent grade), oleylamine (80–90 %, Acros), which was dried by heating (100 °C) under reduced pressure (1 mbar). Indium stearate was produced from metallic indium according to the method described in the literature [28]. Silver stearate was produced from silver nitrate [29].

Characterization.

The size, morphology and structure of nanoparticles was studied using JEM-2100 transmission electron microscope (TEM) by JEOL (Japan) featuring the accelerating voltage of 200 kV. The crystal structure was analyzed by comparing the interplanar distances measured on the obtained SAED images to the values from the database of crystal structures. The optical properties were evaluated by spectrophotometry methods using a spectrophotometer (JASCO V-770, JACSO) and by spectrometry using an IR Fourier spectrometer (Spectrum 100, PerkinElmer) equipped with a multiple attenuated total internal reflection (MATIR) attachment fitted with Ge and ZnSe prisms (incidence angle – 45°, number of reflections – 25), Keithley 4200A-SCS source measurement unit, 405 nm laser. The surface morphology of thin films was studied using NT-MDT Solver-PRO atomic force microscope in the tapping mode.

Preparation of the sulfur precursor

The elemental sulfur (0.4 mmol (128 mg)) was placed in a thick-walled glass reactor together with 10 ml of 1-decene. The reaction mixture was heated at 150 °C in an oil bath while stirring it for 1 hour. The resulting light-yellow solution was used as a sulfur precursor for synthesizing nanocrystals.

General method for synthesis of $CuInS_2$ CQDs based on indium halides.

CuCl (2.97 mg, 0.03 mmol) and InX_3 (0.03 mmol, 6.7 mg of $InCl_3$ or 14.8 mg of InI_3) were dissolved in a mixture of 0.2 ml of oleylamine and 5 ml of decane. The resulting mixture was heated in the argon flow at 110 °C for 60 min to form a homogeneous solution. The resulting mixture was diluted with decane to 30 ml and heated to 150 °C. A sulfur solution in decene-1 (7 ml) was injected at the specified temperature.

After the sulfur precursor was injected, the temperature of the reaction mixture drops and is maintained at the required level of the synthesis temperature. The reaction mixture turns brown as the reaction runs. After 90 minutes the flask is immersed in an ice bath. $CuInS_2$ nanoparticles are released by triple re-precipitation. CQDs were released and purified by adding a 1:2 methanol:isopropanol mixture followed by centrifugation and re-dispersion in tetrachloroethylene for characterization purpose.

Method for synthesis of $CuInS_2$ CQDs based on indium stearate.

CuCl (2.97 mg, 0.03 mmol) and indium stearate (0.03 mmol, 6.7 mg of $InCl_3$ or 14.8 mg of InI_3) were dissolved in a mixture of 0.2 ml of oleylamine and 5 ml of decane. The resulting mixture was heated in the argon flow at 110 °C for 60 min to form a homogeneous solution. The resulting mixture was diluted with decane to 30 ml and heated to 150 °C. A sulfur solution in decene-1 (7 ml) was injected at the specified temperature.

After the sulfur precursor was injected, the temperature of the reaction mixture drops and is maintained at the required level of the synthesis temperature. The reaction mixture turns brown as the reaction runs. After 90 minutes the flask is immersed in an ice bath. $CuInS_2$ nanoparticles are released by triple re-precipitation. CQDs were released and purified by adding a 1:2 methanol:isopropanol mixture followed by centrifugation and re-dispersion in tetrachloroethylene for characterization purpose.

Method for synthesis of $AgInS_2$ CQDs.

Silver stearate (11.8 mg, 0.03 mmol) and indium stearate (29.1 mg, 0.03 mmol) were dissolved in a mixture of 0.6 ml of oleylamine and 2 ml of decane. The resulting mixture was heated in the argon flow at 110 °C for 60 min to form a homogeneous solution. The resulting mixture was diluted with 22 ml of decane and heated to 150 °C. A sulfur solution in decene-1 (0.4 M, 6 ml) was injected at 150 °C. After the sulfur precursor was injected, the temperature of the reaction mixture drops and is maintained at the required level of the synthesis temperature. The reaction mixture turns brown as the reaction runs. After 90 minutes the flask is immersed in an ice bath. $AgInS_2$ nanoparticles are released by triple re-precipitation. CQDs were released and purified by adding a 1:2 methanol:isopropanol mixture followed by centrifugation and re-dispersion in n-hexane.

Method of manufacturing a photoresistor based on $CuInS_2$ CQDs

50 μl of $CuInS_2$ colloidal quantum dots sol of the 10 mg/ml concentraion in hexane were deposited onto interdigital electrodes using spin-coating (speed – 4000 rpm, time 45 s). Ligands were substituted by applying 100 μl of the prepared solution of ammonium thiocyanate of the 20 mg/ml concentration in isopropanol to a fixed substrate, followed by acceleration to 4000 rpm by the spin-coating method (time 45 s). Excess of thiocyanate and reaction products were removed by applying 100 μl of isopropanol to the substrate by the spin-coating method (speed – 4000 rpm, time – 45 s). To achieve the required thickness, the application and substitution procedure was repeated.

Conclusion

For the first time, a sulfur precursor was obtained by dissolving sulfur in decene-1 at an elevated temperature. Its optical properties and composition were studied by the spectrophotometry method. The new sulfur precursor was shown to be fit for preparation of colloidal quantum dots of indium chalcopyrites ($CuInS_2$ and $AgInS_2$) The resulting colloidal nanocrystals have a potential to replace environmentally-unsafe CQDs of cadmium selenide used in monitors and other photoelectronic devices, as well as for photocatalytic applications.

As an indium precursor, it is more practical to use indium stearate, due to its very low hygroscopicity as compared to indium halides. The resulting $CuInS_2$ nanocrystals feature a maximum in the emission spectrum in the visible range at 540 nm. On the basis of the resulting nanocrystals, photosensitive elements of the photoresistive type were created, with an ampere-watt responsivity of 19.5 μA/W, with the sample illuminated at a wavelength of 405 nm.

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REFERENCES

1. Ponomarenko V. P., Popov V. S., Shuklov I. A., Ivanov V. V. and Razumov V. F., Russ. Chem. Rev. **93** (4), RCR5113 (2024).

2. Shuklov I. A. and Razumov V. F., Russ. Chem. Rev. **89** (3), 379 (2020).

3. Shu Y., Lin X., Qin H., Hu Z., Jin Y. and Peng X., Angewandte Chemie **132** (50), 22496–22507 (2020).

4. Pu Y., Cai F., Wang D., Wang J.-X. and Chen J.-F., Industrial & Engineering Chemistry Research. **57** (6), 1790–1802 (2018).

5. Chakraborty D., Ethiraj K. R., Chandrasekaran N. and Mukherjee A., Environmental Pollution **270**, 116049 (2021).

6. Sharma V. K., McDonald T. J., Sohn M., Anquandah G. A. K., Pettine M. and Zboril R., Chemosphere **188**, 403–413 (2017).

7. Kore B. P., Jamshidi M. and Gardner J. M., Materials Advances. **5** (6), 2200–2217 (2024).

8. Zhou C., Tarasov A. B., Goodilin E. A., Chen P., Wang H. and Chen Q., Journal of Energy Chemistry. **65**, 219–235 (2022).

9. Yang W., Gong X. and Chang J., Journal of Nanoscience and Nanotechnology **16** (3), 2172–2183 (2016).

10. Coughlan C., Ibáñez M., Dobrozhan O., Singh A., Cabot A. and Ryan K. M., Chemical Reviews **117** (9), 5865–6109 (2017).

11. Czekelius C., Hilgendorff M., Spanhel L., Bedja I., Lerch M., Müller G., Bloeck U., Su D.-S. and Giersig M., Advanced Materials **11** (8), 643–646 (1999).

12. Zhong H., Zhou Y., Ye M., He Y., Ye J., He C., Yang C. and Li Y., Chemistry of Materials **20** (20), 6434–6443 (2008).

13. Rahman A., Jennings J. R. and Khan M. M., Materials Science in Semiconductor Processing **169**, 107930 (2024).

14. Niezgoda J. S., Harrison M. A., McBride J. R. and Rosenthal S. J., Chemistry of Materials **24** (16), 3294–3298 (2012).

15. Norako M. E., Franzman M. A. and Brutchey R. L., Chemistry of Materials **21** (18), 4299–4304 (2009).

16. Yu K., Ng P., Ouyang J., Zaman M. B., Abulrob A., Baral T. N., Fatehi D., Jakubek Z. J., Kingston D., Wu X., Liu X., Hebert C., Leek D. M. and Whitfield D. M., ACS Applied Materials & Interfaces **5** (8), 2870–2880 (2013).

17. Shuklov I. A., Mardini A. A., Skabitsky I. V., Dubrovina N. V., Perepukhov A. M., Lizunova A. A. and Razumov V. F., Nano-Structures & Nano-Objects **35**, 101020 (2023).

18. Shuklov I. A., Toknova V. F., Lizunova A. A. and Razumov V. F., Materials Today Chemistry **18**, 100357 (2020).

19. Shuklov I. A., Milenkovich T., Majorova A. V., Vershinina O. V., Ivanova V. A., Pavlova V. D. and Popov V. S., Applied Physics, No. 1, 43–50 (2024) [in Russian].

20. Mutlu H., Ceper E. B., Li X., Yang J., Dong W., Ozmen M. M. *and* Theato P., Macromol. Rapid Commun. **40** (1), 1800650 (2019).

21. McPhail M. R. and Weiss E. A., Chem. Mater. **26** (11), 3377–3384 (2014).

22. Xia C., Winckelmans N., Prins P. T., Bals S., Gerritsen H. C. and de Mello Donegá C., Journal of the American Chemical Society **140** (17), 5755–5763 (2018).

23. Li Z., Ji Y., Xie R., Grisham S. Y. and Peng X., J. Am. Chem. Soc. **133** (43), 17248–17256 (2011).

24. Nakabayashi T., Tsurugi J. and Yabuta T., The Journal of Organic Chemistry **29** (5), 1236–1238 (1964).

25. Field L. Disulfides and Polysulfides. Organic Chemistry of Sulfur. Oae S. Boston, MA: Springer US, 1977, pp. 303–382.

26. Kim Y. H. and Lee J.-S., ACS Omega **7** (49), 45277–45286 (2022).

27. Li T.-L. and Teng H., Journal of Materials Chemistry **20** (18), 3656–3664 (2010).

28. Dou Q. and Ng K. M., Powder Technology **301**, 949–958 (2016).

29. Malik W. U., Jain A. K. and Jhamb O. P., J. Chem. Soc. A 1514–1517 (1971).

About authors

Ivan Alekseevich Shuklov, Leading Research Assistant, Associate Professor, Dr. rer. nat., Moscow Institute of Physics and Technology (National Research University) (141701, Russia, Moscow Region, Dolgoprudny, Institutsky Per., 9). E-mail: shuklov.ia@mipt.ru SPIN code 4060-7233, Author ID 1146575

Alexandra Valerievna Seraya, Engineer, Moscow Institute of Physics and Technology (National Research University) (141701, Russia, Moscow Region, Dolgoprudny, Institutsky Per., 9). E-mail: seraiaaleksandra@gmail.com SPIN code 8568-5395, Author ID 1288527

Vladimir Valerievich Lim, maintenance man, bachelor, Moscow Institute of Physics and Technology (National Research University) (141701, Russia, Moscow Region, Dolgoprudny, Institutsky Per., 9). E-mail: lim.vv@mipt.ru

Aleksandr Yurevich Shalagin, maintenance man, bachelor, Moscow Institute of Physics and Technology (National Research University) (141701, Russia, Moscow Region, Dolgoprudny, Institutsky Per., 9). E-mail: shalagin.au@mipt.ru SPIN code 9769-2552

Teodora Milenkovich, Junior Research Assistant, graduate student, Moscow Institute of Physics and Technology (National Research University) (141701, Russia, Moscow Region, Dolgoprudny, Institutsky Per., 9). E-mail: tmilenkovich@mail.ru

Olesya Valerievna Vershinina, Junior Research Assistant, graduate student, Moscow Institute of Physics and Technology (National Research University) (141701, Russia, Moscow Region, Dolgoprudny, Institutsky Per., 9). E-mail: seraia.ov@phystech.edu

Viktor Olegovich Yakovlev, Junior Research Assistant, master, Moscow Institute of Physics and Technology (National Research University) (141701, Russia, Moscow Region, Dolgoprudny, Institutsky Per., 9). E-mail: iakovlev.vo@mipt.ru

Viktor Sergeevich Popov, Head of Laboratory, Leading Research Assistant, Associate Professor, Candidate of Chemical Sciences, Moscow Institute of Physics and Technology (National Research University) (141701, Russia, Moscow Region, Dolgoprudny, Institutsky Per., 9). E-mail: popov.vs@mipt.ru SPIN code 1128-2332, Author ID 625948

Viktor Vladimirovich Ivanov, Senior Research Assistan, Professor, Doctor of Physics and Mathematics, Corresponding Member of the Russian Academy of Sciences. Moscow Institute of Physics and Technology (National Research University) (141701, Russia, Moscow Region, Dolgoprudny, Institutsky Per., 9). E-mail: Ivanov.vv@mirt.ru SPIN code 1856-3914, Author ID 19128