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ИЗВЕСТИЯ

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Қазақстан Республикасы Ұлттық ғылым академиясы "ҚР ҰҒА Хабарлары. Химия және технология сериясы" ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Химия және технология сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді химиялық ғылымдар бойынша контентке адалдығымызды білдіреді.

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ABOUT MODERN RESEARCH IN THE FIELD OF COMPLEX SULFIDE COMPOUNDS (STATE AND TRENDS)

Abstract. The article provides an overview of the most significant scientific papers (from more than 600 literature sources), devoted to the studies of complex sulfides, some of which are given in this research. There are examples of research in the field of the most promising complex sulfides CdZnS, AgInS, CuInS, ZnInS and the predicted scope of their practical application in the article. The tendencies in the research for physicochemical properties of complex metal sulphides are revealed.

Key words: complex metal sulfides, doping, quantum dot, quantum transition, photoluminescence, electrochemical properties, phase transitions, traps, optical properties, solar cells, LEDs.

There are extensive series of creating new materials research based on the synthesis of complex complex sulfide compounds has been conducted over the past 3 years. It will be presented examples of research in the field of the most promising complex sulfides CdZnS, AgInS, CuInS, ZnInS.

1. Research in the field of complex sulfide CdZnS.

«Structural, optical and photovoltaic properties of Co (3%): CdZnS nanoparticles» [37]. In the present study, CdZnS and Co (3%): CdZnS nanoparticles (NPs) have been synthesized via wet chemical method at room temperature using 1-thioglycerol as a capping agent. The incident photon-to-current conversion efficiency (IPCE) measurement has been carried out for Co (5%): CdZnS for the first time in this study. The results show that Co (3%): CdZnS can be utilized as sensitizers to improve the performance of solar cells. In addition to the photovoltaic properties; structural, optical and morphological properties of Co (3%): CdZnS NPs have been investigated. The results indicate that Co (3%): CdZnS NPs can be suitable material for photovoltaic applications.

«Influence of Ce^{3+} doping on the optical and photocatalytic properties of $Zn_{0.8}Cd_{0.2}S$-ethylenediamine hybrid nanosheets» [8]. The Ce^{3+}-doped $Zn_{0.8}Cd_{0.2}S$-ethylenediamine (En) hybrid nanosheets were successfully synthesized by a simple solvothermal method and characterized by scanning electron microscope (SEM), transmission electron microscope (TEM), X-ray diffraction (XRD), UV-vis diffusion reflectance spectroscopy (UV-vis DRS) and room-temperature photoluminescence spectra (PL). The effects of Ce^{3+} doping amount on the photo-absorption properties and photocatalytic H-2 evolution rates under visible light irradiation over $Zn_{0.8}Cd_{0.2}S$-En hybrid nanosheets were also investigated. The results show that the incorporation of Ce^{3+}, existing in the form of Ce_2S_3 with uniformly distribution in sample can narrow the band gap, enhance the photo-absorption and extend the photo-absorption range of the $Zn_{0.8}Cd_{0.2}S$-En hybrid nanosheets. The photocatalytic activity tests prove that Ce^{3+}-doped $Zn_{0.8}Cd_{0.2}S$-En nanosheets have much higher photocatalytic hydrogen production activity when compared with the undoped one. Under the irradiation of visible light, the highest photocatalytic hydrogen production rate of 229.2 mu mol h(-1) is observed over 0.1 wt.% Ce^{3+}-doped $Zn_{0.8}Cd_{0.2}S$-En nanosheets, which is about 1.4

times higher than that of the undoped $Zn_{0.8}Cd_{0.2}S$-En nanosheets. The improved photocatalytic activity of Ce-doped samples ascribes to the enhanced photo-response in the visible light region and the efficient separation of electron-hole pairs due to the formation of heterojunction between $Zn_{0.8}Cd_{0.2}S$-En and Ce_2S_3.

«Size-dependent structural phase transitions and their correlation with photoluminescence and optical absorption behavior of annealed $Zn_{0.45}Cd_{0.55}S$ quantum dots» [46]. In this paper, we investigate the effect of thermally induced structural phase transitions on the photoluminescence (PL) and optical absorption behaviour of $Zn_{0.45}Cd_{0.55}S$ nanoparticles (NPs). Analysis of X-ray diffraction (XRD) patterns and high-resolution electron microscope (HRTEM) images reveal that the as-synthesized sample possesses zinc-blende-type cubic structure. In addition, at annealing temperature (T-a) 400 degrees C, the cubic structure transforms completely into the wurtzite-type hexagonal structure. Furthermore, the second phase transition of the as-synthesized sample has observed at 700 degrees C, where the cubic structure has transformed into mixed polycrystalline phases of hexagonal ZnO, cubic CdO, monoclinic CdSO3, and orthorhombic $ZnSO_4$ structures. These new phases have also confirmed from the analysis of Raman and FTIR spectra. Analysis of UV-visible optical absorption spectra demonstrates that Increasing T-a results in the decrease of optical band gap due the improvement in crystallinity accompanied by the increase in the particle size. The PL emission bands at an excitation energy of 3.818 eV exhibit redshift and a decrease in the intensity with increasing T-a up to 500 degrees C. Meanwhile, further increase in T-a up to 700 degrees C results in the enhancement of green emission intensity. On the other hand, PL emission spectra at 3.354 eV and T. 700 degrees C, reveal a dramatic increase in the emission intensity nearly by one-order of magnitude with respect to its value of the as-synthesized sample. This behaviour is ascribed to the incorporation of oxygen-related defects via thermal annealing in air, which act as additive radiative centers. Also, we have interpreted the observed spectral blue shift of PL emission spectrum with increasing excitation energy.

A similar study of this complex sulfide is also reflected in the following works [11, 32] and in earlier studies [38, 23, 29].

2. Research in the field of complex AgInS sulfide.

«Luminescence and photoelectrochemical properties of size-selected aqueous copper-doped Ag-In-S quantum dots» [47]. Ternary luminescent copper and silver indium sulfide quantum dots (QDs) can be an attractive alternative to cadmium and lead chalcogenide QDs. The optical properties of Cu-In-S and Ag-In-S (AIS) QDs vary over a broad range depending on the QD composition and size. The implementation of ternary QDs as emitters in bio-sensing applications can be boosted by the development of mild and reproducible syntheses directly in aqueous solutions as well as the methods of shifting the photoluminescence (PL) bands of such QDs as far as possible into the near IR spectral range. In the present work, the copper-doping of aqueous non-stoichiometric AIS QDs was found to result in a red shift of the PL band maximum from around 630 nm to similar to 780 nm and PL quenching. The deposition of a ZnS shell results in PL intensity recovery with the highest quantum yield of 15%, with almost not change in the PL band position, opposite to the undoped AIS QDs. Size-selective precipitation using 2-propanol as a non-solvent allows discrimination of up to 9 fractions of Cu-doped AIS/ZnS QDs with the average sizes in the fractions varying from around 3 to 2 nm and smaller and with reasonably the same composition irrespective of the QD size. The decrease of the average QD size results in a blue PL shift yielding a series of bright luminophors with the emission color varies from deep-red to bluish-green and the PL efficiency increases from 11% for the first fraction to up to 58% for the smallest Cu-doped AIS/ZnS QDs. The rate constant of the radiative recombination of the size-selected Cu-doped AIS/ZnS QDs revealed a steady growth with the QD size decrease as a result of the size-dependent enhancement of the spatial exciton confinement. The copper doping was found to result in an enhancement of the photoelectrochemical activity of CAIS/ZnS QDs introduced as spectral sensitizers of mesoporous titania photoanodes of liquid-junction solar cells.

«Origin and Dynamics of Highly Efficient Broadband Photoluminescence of Aqueous Glutathione-Capped Size-Selected Ag-In-S Quantum Dots» [51]. The 2-3 nm size-selected glutathione-capped Ag In S (AIS) and core/shell AIS/ZnS quantum dots (QDs) were produced by precipitation/redissolution from an aqueous colloidal ensemble. The QDs reveal broadband photoluminescence (PL) with a quantum yield of up to 60% for the most populated fraction of the core/shell AIS/ZnS QDs. The PL band shape can be described by a self-trapped exciton model implying the PL band being a sequence of phonon replica of a zero-phonon line resulting from strong electron phonon interaction and a partial conversion of the electron excitation energy into lattice vibrations. It can be concluded that the position and shape of the PL bands of MS QDs originate not from energy factors (depth and distribution of trap states) but rather from the dynamics of the electron phonon interaction and the vibrational relaxation in the QDs. The rate of vibrational relaxation of the electron excitation energy in MS QDs is found to be size-dependent, increasing almost twice from the largest to the smallest QDs.

«Synthesis of $AgInS_2$ quantum dots with tunable photoluminescence for sensitized solar cells» [14]. Synthesis of quantum dots (QDs) with high photoluminescence is critical for quantum dot sensitized solar cells (QDSCs). A series of high quality $AgInS_2$ QDs were synthesized under air circumstance by the organometallic high temperature method. Feature of tunable photoluminescence of $AgInS_2$ QDs with long lifetime and quantum yields beyond 40% has been achieved, which was mainly attributed to the donor-acceptor pair recombination, contributed above 91% to the whole emission profiles. After ligand exchange with bifunctional linker, water-soluble $AgInS_2$ QDs were adopted as light harvesters to fabricate QDSCs, achieved best PCE of 2.91% (short-circuit current density of 13.78 mA cm(-2), open-circuit voltage of 0.47 V, and fill factor of 45%) under one full sun illumination. The improved photovoltaic performance of $AgInS_2$ QDs-based QDSCs is mainly originated from broadened optoelectronic response range up to-900 nm, and enhanced photoluminescence with long lifetime and high quantum yield beyond 40%, which provide strong photoresponse similar to 40% over the window below 750 nm. The synthetic approach combined with intrinsic defects created by intentionally composition modulation introduces a new approach towards the goal of high performance QDSCs.

The research results of this complex compound are also reflected in the following works [36, 22] in earlier studies [27].

3. Research in the field of complex $CuInS_2$ sulfide.

«Defect Luminescence from Wurtzite $CuInS_2$ Nanocrystals: Combined Experimental and Theoretical Analysis» [45]. $CuInS_2$ nanocrystals with the wurtzite structure show promise for applications requiring efficient energy transport due to their anisotropic crystal structure. We investigate the source of photoluminescence in the near-infrared spectral region recently observed from these nanocrystals. Spectroscopic studies of both wurtzite $CuInS_2$ itself and samples alloyed with Cd or Zn allow the assignment of this emission to a radiative point defect within the nanocrystal. structure. Further, by varying the organic passivation layer on the material, we are able to determine that the atomic species responsible for nonradiative decay paths on the nanocrystal surface are Cu- or S-based. Density functional theory calculations of defect states within the material allow identification of the likely radiative species. Understanding both the electronic structure and optical properties of wurtzite $CuInS_2$, nanocrystals is necessary for their efficient integration into potential biological, photovoltaic, and photo catalytic applications.

«Interplay between Surface Chemistry, Precursor Reactivity, and Temperature Determines Outcome of ZnS Shelling Reactions on $CuInS_2$ Nanocrystals» [10]. ZnS shelling of I-III-$VI_{(2)}$ nanocrystals (NCs) invariably leads to blue-shifts in both the absorption and photoluminescence spectra. These observations imply that the outcome of ZnS shelling reactions on I-III-VI_2 colloidal NCs results from a complex interplay between several processes taking place in solution, at the surface of, and within the seed NC. However, a fundamental understanding of the factors determining the balance between these different processes is still lacking. In this work, we address this need by investigating the impact of precursor reactivity, reaction temperature, and surface chemistry (due to the washing procedure) on the outcome of ZnS shelling reactions on $CuInS_2$ NCs using a seeded growth approach. We demonstrate that low reaction temperatures (150 degrees C) favor etching, cation exchange, and alloying regardless of the precursors used. Heteroepitaxial shell overgrowth becomes the dominant process only if reactive S- and Zn-precursors (S-ODE/OLAM and ZnI_2) and high reaction temperatures (210 degrees C) are used, although a certain degree of heterointerfacial alloying still occurs. Remarkably, the presence of residual acetate at the surface of CIS seed NCs washed with ethanol is shown to facilitate heteroepitaxial shell overgrowth, yielding for the first time CIS/ZnS core/shell NCs displaying red-shifted absorption spectra, in agreement with the spectral shifts expected for a type-I band alignment. The insights provided by this work pave the way toward the design of improved synthesis strategies to CIS/ZnS core/shell and alloy NCs with tailored elemental distribution profiles, allowing precise tuning of the optoelectronic properties of the resulting materials.

The research results of this complex compound are also reflected in the following works [31] in earlier studies [3, 24, 40, 18, 19, 13, 9, 28, 35, 12].

4. Research in the field of complex ZnInS sulfide.

«Improving the emission of ultrasmall Mn-doped ZnInS quantum dots via Ag-induced trap state energy level» [39]. For ultrasmall Mn-doped quantum dots (QDs), the energy transfer of the exciton to the Mn is the key factor for Mn emission. Herein, the Ag-induced electron trap state energy level, which is an intermediate energy level between the conduction band (CB) and T-4(1) of Mn, is proposed for improving the energy transfer. After doping the Ag and forming Ag&Mn:ZnInS QDs, most excitons will first be captured by the intermediate energy level and then be transferred to Mn d-states, leading to enhanced photoluminescence (PL) quantum yields (QY) of the QDs from the original 17% (Mn:ZnInS QDs) to 30% (Ag&Mn:ZnInS QDs).

«Dopant-controlled photoluminescence of Ag-doped Zn-In-S nanocrystals» [50]. In this work, we reported the growth of cadmium-free Ag-doped Zn-In-S nanocrystals (NCs) with effective photoluminescence (PL) via a hot-injection strategy. The effects of the nucleation temperatures, reaction times, and Ag-doping concentrations on the PL properties of Ag-doped Zn-In-S NCs were investigated systematically. The as-synthesized NCs exhibit color-tunable PL emissions covering a broad visible range of 472-585 nm. After being passivated by a protective ZnS shell, the PL quantum yield (QY) of the resultant NCs was greatly improved up to 33%. With the increase of the Ag-doping level, the PL is significantly intensified due to the improved concentration of Ag ions which provides more holes to recombine with electrons from the bottom of the conduction band. This also makes the emission via the dopant energy level become a powerful, competitive advantage for the NCs with higher Ag-doping levels, resulting in a longer lifetime and higher PL QY. These results suggest that tailoring the Ag-doping level can be a powerful strategy to control the optical properties of Ag-doped Zn-In-S NCs.

«Highly bright and stable white-light-emitting cadmium-free Ag, Mn co-doped Zn-In-S / ZnS quantum dots and their electroluminescence» [55]. Optimized white light emitting Ag, Mn:Zn-In-S quantum dots (QDs) were synthesized via a simple, scalable, reproducible, and low-cost one-pot non-injection synthetic approach. After coating a thick ZnS shell (similar to 12 monolayers) on the core QDs, high photoluminescence (PL) quantum yield (QY) up to 76% was achieved and high emission efficiency was retained even when the initially oil-soluble QDs were transferred into aqueous media by ligand replacement. Moreover, both thermal stability and photostability of thick shell-Ag, Mn:Zn-In-S/ZnS QDs were significantly enhanced as compared with those of Ag, Mn:Zn-In-S core QDs due to the suppressed surface defects resulting from the passivation of the dense ZnS layers. White quantum dot light-emitting diodes (QD-LEDs) were fabricated using thick shell Ag, Mn:Zn-In-S/ZnS QDs as single QDs emitter, showing good performance with maximum current efficiency of 1.86 cd A(-1)corresponding to external quantum efficiency (EQE) of 0.82% at a current density of 0.065 mA cm(-2), color rendering indices (CRI) of 83, Commission International d'Eclairage (CIE) coordinates of (0.344, 0.393) and correlated color temperature (CCT) of 5156 K.

«Doping concentration-dependent photoluminescence properties of Mn-doped Zn-In-S quantum dots» [15]. In this report, doping concentration-dependent photoluminescence (PL) properties of Mn-doped ternary Zn-In-S quantum dots (QDs) were studied by using steady-state and time-resolved PL spectroscopy. The QDs PL was firstly significantly intensified with the increasing Mn doping concentration and then decreased after the doping concentration increased up to 7.5 at.%. However, their decay lifetimes exhibit a monotone decrease with Mn doping concentration ranged from 0 to 10 at.%. It can be concluded that the PL intensity was mainly determined by two factors: one was the increased efficiency of energy transfer from host excitons to Mn^{2+} ion accepter, and the other was the decreased efficiency of the emission from a Mn^{2+} ion, which was caused by the increased component of exposed Mn^{2+} ions on QDs surface and the accelerated interaction between adjacent dopants. The competition of above two exciton relaxation dynamics processes determined the trend of the PL intensity, while the latter was responsible for the monotonously decreased lifetime of the Mn^{2+} ion emission with the increasing Mn doping concentration.

The research results of this complex compound are also reflected in the following works [16, 17] in earlier studies [25, 26, 34,1, 2].

Note that other complex compounds of complex ternary sulfides such as CdPbS [7], HgPbS [20], BaPbS [21], CdCoS [4], PbZnS [5], PbCoS [6], HgCdS [30], CdSnS [33], PbCaS [49], CdPbS [52], PbSnS [53], ZnMnS [41], CdMnS [43], ZnCoS [42], CdFeS [54], CdNiS [44], MnZnS [48] were studyed.

Research in the field of sulfides was also carried out by domestic scientists. For example, studies for ZnS sulfides are reflected in [56, 57], and the study for the physicochemical properties of CdS sulfides is described in [58, 59]. Practical applications of complex sulfides are described in [60].

Findings

There a clear tendency of doping the basic sulfide material with various chemical elements that are not part of them is followed from the analysis of the vast majority of modern works (on the synthesis and s tudy of complex sulfides) shown in the literature review. This operation significantly changes the physico - chemical properties of complex sulfide, which, as a result, leads to a significant expansion of their practical application in science and technology.

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КҮРДЕЛІ СУЛЬФИДТІ ҚОСЫЛЫСТАР САЛАСЫНДАҒЫ ЗАМАНАУИ ЗЕРТТЕУЛЕР ТУРАЛЫ (ЖАҒДАЙЫ ЖӘНЕ БЕТАЛЫСЫ)

Аннотация. Мақалада күрделі сульфидтерді зерттеу бойынша бір бөлігі мақалада келтірілген 600 аса әдебиеттік көздердің ең маңызды ғылыми еңбектеріне шолу жасалынды. Ең перспективалы күрделі сульфидтер CdZnS, AgInS, CuInS, ZnInS саласына мысалдар және олардың тәжірибелік қолданылатын болжамды ауқымы келтірілді.

Осылайша, CdZnS күрделі сульфид саласындағы зерттеулер бойынша жарық энергиясын электр тогына түрлендіру тиімділігі анықталды, бұл осы қосылысты күн элементтерінің сипаттамаларын жақсарту үшін сенсибилизатор ретінде пайдалану туралы айтуға мүмкіндік береді. Ce_2S_3 түріндегі Ce^{3+}-ді тегіс бөліп қосу тыйым салынған аймақтың енін тарылтып, $Zn_{0.8}Cd_{0.2}S$ гибридті наножапырақтардың фото сіңіру диапазонын ұлғайтуы және кеңейтуі мүмкін. $Zn_{0.45}Cd_{0.55}S$ нанобөлшектерді оптикалық сіңіру және фотолюминесценциясына термиялық индукцияланған құрылымдық фазалық ауысулардың әсері зерттелді.

AgInS аралас сульфид саласындағы зерттеулерде мыспен легирленуі сұйық өтумен күн элементтеріндегі титан диоксидінің мезокеуекті фотоанодтардың спектрлік сенсибилизаторлары ретінде енгізілген CAIS/ZnS кванттық нүктелерінің фотоэлектрохимиялық белсенділігінің жоғарылауына алып келетіні байқалған. Кванттық нүктелердің фотолюминесценция жолақтарының орналасуы мен пішіні энергетикалық факторлармен емес (тұзақтардың тереңдігімен және жай-күйінің таралуымен), электрондардың фонондармен өзара әрекеттесу динамикасымен және кванттық нүктелерде тербелмелі релаксациямен байланысты екендігі туралы қорытынды жасалады. Жоғары фотолюминесценциялы кванттық нүктелердің синтезі күн элементтері үшін шешуші мәнге ие болатыны атап көрсетілді.

$CuInS_2$ күрделі сульфид саласындағы зерттеулер бойынша жұмыстарда $CuInS_2$ вюрциттің өзін және Cd немесе легирленген Zn үлгілердің спектроскопиялық зерттеулері бұл сәулеленуді нанокристаллдағы радиациялық нүктелік ақауға жатқызуға мүмкіндік беретіні дәлелденген. Өңдеу әдісімен $CuInS_2$ нанокристаллдарындағы ZnS қабыршықтану реакцияларының қорытынды мәселесі прекурсордың реакциялық қабілеттілігінің, реакция температурасының және беттің химиялық құрамының әсерлерін зерттеу арқылы шешіледі.

ZnInS аралас сульфидті зерттеу кезінде легирленген Mn аса аз кванттық нүктелер үшін экситонмен энергияны Mn-ге тасымалдау негізгі фактор болып табылады. Ыстық инжекция әдісімен тиімді фотолюминесценциясы бар, құрамында кадмий жоқ легирленген Ag-ң ZnInS нанокристаллдарының өсуі зерттелді. Ақ жарық сәуле шығаратын оңтайландырылған кванттық нүктелер Ag, Mn белгіленді: ZnInS инжекциясыз қарапайым, масштабталған, жаңғыртылған және қымбат емес синтетикалық тәсіл арқылы синтезделді. Спектроскопияны пайдалана отырып, Mn легирленген ZnInS-ң фотолюминесцентті қасиеттері, үштік кванттық нүктелері зерттелді.

Шолуда келтірілген әдеби көздерді талдаудан, күрделі сульфидтерді синтездеу және зерттеу жөніндегі қазіргі заманғы жұмыстардың басым көпшілігінде сульфидтің негізгі материалын олардың құрамына кірмейтін әртүрлі химиялық элементтермен қоспалау үрдісі айқын байқалады. Бұл операция өз кезегінде

ғылым мен техникада практикалық қолдану аясын айтарлықтай кеңейтуге әкелетін күрделі сульфидтің физика-химиялық қасиеттерін айтарлықтай өзгертеді.

Түйін сөздер: металдардың күрделі сульфидтері, қоспалау, кванттық нүкте, кванттық ауысу, фотолюминесценция, электрохимиялық қасиеттері, фазалық ауысулар, тұтқыштар, оптикалық қасиеттері, күн батареялары, жарық диодтары.

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О СОВРЕМЕННЫХ ИССЛЕДОВАНИЯХ В ОБЛАСТИ СЛОЖНЫХ СУЛЬФИДНЫХ СОЕДИНЕНИЙ (СОСТОЯНИЕ И ТЕНДЕНЦИИ)

Аннотация. В статье сделан обзор наиболее значимых научных работ по исследованию сложных сульфидов из более 600 литературных источников, часть которых приведена в статье. Приведены примеры исследований в области наиболее перспективных сложных сульфидов CdZnS, AgInS, CuInS, ZnInS и прогнозируемая сфера их практического применения.

Так, по исследованиям в области сложного сульфида CdZnS выявлена эффективность преобразования световой энергии в электрический ток, что позволяет судить об использовании этого соединения в качестве сенсибилизатора для улучшения характеристик солнечных элементов. Отмечается, что включение Ce^{3+}, существующего в форме Ce_2S_3 с равномерным распределением в образце может сузить ширину запрещенной зоны, увеличить и расширить диапазон фотопоглощения гибридных нанолистов $Zn_{0.8}Cd_{0.2}S$. Исследовано влияние термически индуцированных структурных фазовых переходов на фотолюминесценцию и оптическое поглощение наночастиц $Zn_{0.45}Cd_{0.55}S$.

В исследованиях в области смешанного сульфида AgInS отмечается, что легирование медью приводит к повышению фотоэлектрохимической активности квантовых точек CAIS / ZnS, введенных в качестве спектральных сенсибилизаторов мезопористых фотоанодов диоксида титана в солнечных элементах с жидким переходом. Делается вывод о том, что положение и форма полос фотолюминесценции квантовых точек обусловлены не энергетическими факторами (глубиной и распределением состояний ловушек), а, скорее, динамикой взаимодействия электронов с фононами и колебательной релаксацией в квантовых точках. Отмечено, что синтез квантовых точек с высокой фотолюминесценцией имеет решающее значение для солнечных элементов.

В работах по исследованиям в области сложного сульфида $CuInS_2$ доказано, что спектроскопические исследования как самого вюрцита $CuInS_2$, так и образцов, легированных Cd или Zn, позволяют отнести это излучение к радиационному точечному дефекту в нанокристалле. Проблема исхода реакций шелушения ZnS на нанокристаллах $CuInS_2$ методом травления решается исследованием влияния взаимодействий реакционной способности прекурсора, температуры реакции и химического состава поверхности.

При исследованиях смешанного сульфида ZnInS выявлено, что для сверхмалых квантовых точек, легированных Mn, передача энергии экситоном в Mn является ключевым фактором. Исследован рост нанокристаллов ZnInS, легированных Ag, не содержащих кадмия с эффективной фотолюминесценцией методом горячей инжекции. Отмечено, что оптимизированные излучающие белый свет квантовые точки Ag, Mn: ZnInS были синтезированы с помощью простого, масштабируемого, воспроизводимого и недорогого синтетического подхода без инжекции. Изучены фотолюминесцентные свойства, тройных квантовых точек ZnInS, легированных Mn, с использованием спектроскопии.

Из анализа литературных источников, приведённых в обзоре, следует, что в подавляющем большинстве современных работ по синтезу и исследованию сложных сульфидов явно прослеживается тенденция легирования основного материала сульфида различными химическими элементами, не входящих в их состав. Эта операция заметно изменяет физико-химические свойства сложного сульфида, что, как следствие, в свою очередь приводит к значительному расширению сферы их практического применения в науке и технике.

Ключевые слова: сложные сульфиды металлов, легирование, квантовая точка, квантовый переход, фотолюминесценция, электрохимические свойства, фазовые переходы, ловушки, оптические свойства, солнечные батареи, светодиоды.

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