Editorial

Semiconductor nanomaterials for optoelectronics and the SPQEO journal

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Abstract. Semiconductor materials are vital for present-day technologies for light emitters, sensors and actuators, computation and memory devices as well as energy harvesting and storage. At the same time, nanostructures based on semiconductors trigger fast technology development and creation of materials with principally new properties due to quantum confinement effects. The SPQEO journal pays attention to the modern development of such area as physics of nanoparticles and nanostructures. During recent years, it published articles on semiconductor nanocrystals, quantum dots, thin lattices, including their growth, characterization, study of physical properties and theoretical description.

Keywords: nanomaterials, optoelectronics, nanocrystals, quantum dots, quantum confinement.

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1. Semiconductor nanostructures

Real progress of semiconductor materials runs from volume devices in 50th through micro- to nanosized ones at the beginning of 1990th [1]. With time, the creation of semiconductor nanomaterials brings a burst of the creation of new materials with unique properties and the development of electronic, optoelectronic and quantum technologies. Nowadays, semiconductor nanostructures are the most intensively investigated materials, which allow new inventions and optimization of current technologies [2,3].

The term ‘*nanomaterial*’, or ‘*nanostructure*’, is rather general and means a class of a solid, when one its external dimension is below 100 nm. Considering geometry, nanostructures are divided depending on the number of non-confined dimensions: two-dimensional (2D) quantum wells, nanofilms, flakes or sheets; 1D nanowires (NW); and 0D quantum dots (QD) or nanocrystals (NC) [1,4]. Modelling examples of such structures are presented in Fig. 1 [5]. However, a nanomaterial has properties different from its bulk counterpart only when one its dimension is lower than about 40 nm (varied upon a type of materials). This occurs due to strong quantum confinement effect –spatial confinement of electrons and holes or their pairs (excitons) in one or more dimensions within a crystal. Such condition results in increasing bandgap and discrete electronic energy levels due to the confinement of the electronic wave function to the physical dimensions of a material (Fig. 1) [2-6]. Structures with sizes of approximately 40-100 nm may have properties dissimilar compared to their bulks due to week quantum confinement effect, changes in crystal geometry, new defects, or other reasons. Microporous and nanoporous semiconductor structures, nanocavities or big nanoparticles (NPs) are also classified as nanomaterials because their structures lead to modifications of their physical properties or provide additional material capacities [7]. Nevertheless, the presented classification is rather generalized, so most kinds of nanomaterials can be divided into groups by peculiar structure, preparation method or application.

Semiconductor nanomaterials have revolutionized many areas of optoelectronics and photonics due to the discovery of new fundamental phenomena via quantum confinement effects to tailor the material bandgap and emission intensity as well as the exponential growth in technological nanodevice applications. Light-emitting nanodevices are applied for light sources of ultraviolet (UV), visible (Vis) and infrared (IR) ranges, displays, indicators, etc. Light-detecting nanostructures, such as photodiodes, photovoltaic solar cells, photoresistors and phototransistors, convert incident electromagnetic radiation into electric current or voltage with advanced performances [4].

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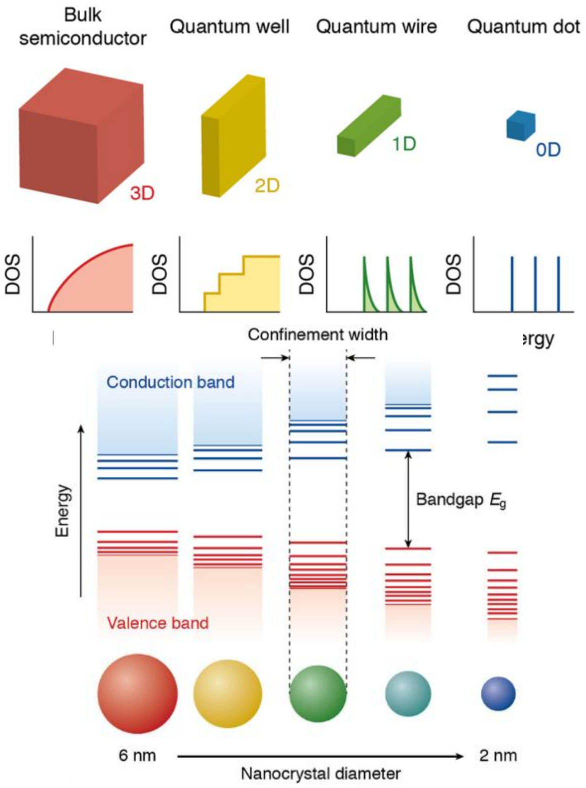

Fig. 1. Schematic illustration of the energy level structure of a bulk material and nanostructures with reduced dimensionality: 2D crystal lattice or quantum well, 1D quantum wire, 0D nanocrystal or quantum dot. DOS represents the density of electronic states. The bandgap of a semiconductor nanocrystal increases with decreasing size and discrete energy levels arise at the bandgap edges [5]. © CC BY 4.0. Open access. 2016 Springer Nature Switzerland AG.

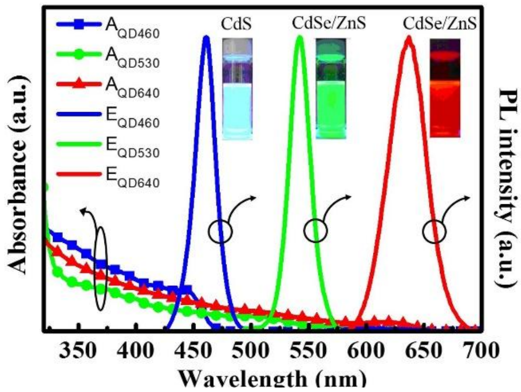

Fig. 2. Colloidal QD absorption/emission range variability over the whole visible region [10]. © CC BY 4.0. Open access. 2014 Springer Nature Switzerland AG.

2. Semiconductor quantum dots and nanocrystals

Semiconductor clusters such as QDs or NCs are fragments of crystals consisting of hundreds to many thousands of atoms with the bulk bonding geometry and with surface states eliminated by enclosure in a material that has a larger bandgap due to quantum confinement effect. Their optical and electrical properties are strongly size-dependent [1,4].

QDs are mostly colloidal 0D NCs, which are solution-processed and of rather ideal spherical shape with sizes below 20 nm. They have a size-tunable bandgap of very broad range, resulting in the emission variation in a very wide range (Fig. 2) [8,9]. Colloidal QDs can be synthesized from different compounds, such as II–VI (CdS, CdSe), III–V (InAs, InP, AlN, GaN), IV–VI (PbS, PbSe) and III–V ($CuInS_2$, $CuInSe_2$), transitional metal chalcogenides, metal halide perovskites, etc. Their application field covers from laser diodes, displays, photodetectors, and cameras to solar cells and energy storage devices [10-12]. Yet, depending on their preparation method, the size and shape can be far from ideal ones and such structures are mostly classified as NCs or NPs.

The SPQEO journal focuses on this type of 0D nanomaterials, thus, some reports should be mentioned. Most recent articles are devoted to II–VI Cd-based QDs and NCs with chemical formulas of CdS [13], CdCuS [14,15], CdZnS [16], and CdTe [17]. The article on small-size QDs (about 5 nm) and optically detected magnetic resonance study of relaxation/emission processes in the NC-polymer composite may be highlighted [13]. Moreover, the impact of semiconductor QDs bandgap and their dispersion on reabsorption and the loss of luminescent quanta in luminescent solar concentrators is studied theoretically in [18,19] using CdS, CdSe, CdTe, InP, InAs and PbSe QDs as an example.

A few reports describe properties of metal oxide NPs such as ZnO [20,21], AgO [22], TiO_2 [23], $BaTiO_3$ [24] and SnO_2 [25]. Several articles report green synthesis of metal oxide NPs using plant extracts and their characterizations [20-23]. The authors of Ref. [26] observed IR light absorption oscillations in 2D macroporous Si with CdTe, ZnO and CdS surface NCs and proposed a high-coherent optical quantum computer based on ZnO NCs on macroporous Si surface. SiO_2 nanocomposite films are also fabricated and characterized [27-29]. Nanostructured SiC as a promising material for the cold electron emitters is studied [30]. The authors of Ref. [30] proposed a novel cold electron emitter based on self-assembled SiC nanotips grown on a Si substrate by a simple and cost-effective manufacturing process based on a standard microelectronics-grade Si wafers with no ultra-high vacuum required and no complicated chemical deposition processes or toxic chemicals involved. There is also a comprehensive review on luminescent properties of the structures with embedded Si nanoclusters focusing on the influence of technology, doping and annealing [31].

Nanoislands, known as solid-state QDs, are highly investigated during last three decades [32-35]. Binary or ternary III-V compounds, such as InAs, InGaAs, GaAs, InP, GaN, AlGaN, AlN, and others are used to grow these nanostructures. They are successively applied in laser diodes, displays, photodetectors, cameras and solar cells [36,37]. The reports on In(Ga)As/GaAs QDs published in SPQEO are focused on the defects created in such nanostructures due to the mismatch between the QD material and embedding layers [38,39].

3. One-dimensional nanowires

Semiconductor 1D NWs are a new class of semiconductors with typical cross-sectional dimensions that can be tuned from 1–100 nm and lengths spanning from hundreds of nanometers to millimeters [40]. They can be made from Si, Ge, SiGe, CdS, ZnO, GaN, InAs, perovskites, transitional metal chalcogenides, etc. NWs have peculiar optical properties and specific conductivity and photoconductivity that can be used for nanoelectrodes, anisotropic photodetectors, photocatalysts and solar cells [41-44].
In SPQEO, the electrophysical properties of Si NW arrays synthesized using the metal-assisted chemical etching and suitable for application in chemical sensors and solar cells are studied in [46]. Studies of optimal regimes of growing Si self-assembled NWs by means of metal-enhanced CVD technology as well as mechanical strains inevitably arising in such structures are reported [47,48]. A few other articles report on optical properties of NWs of CdS synthesized by vapor–liquid–solid growing were investigated as the function from such technological parameter as overpressure of sulfur vapor at the synthesis process or sulfurization post-processing [45,49,50]. They have characteristic structure of NRs and luminescence in the visible range (Fig. 3).

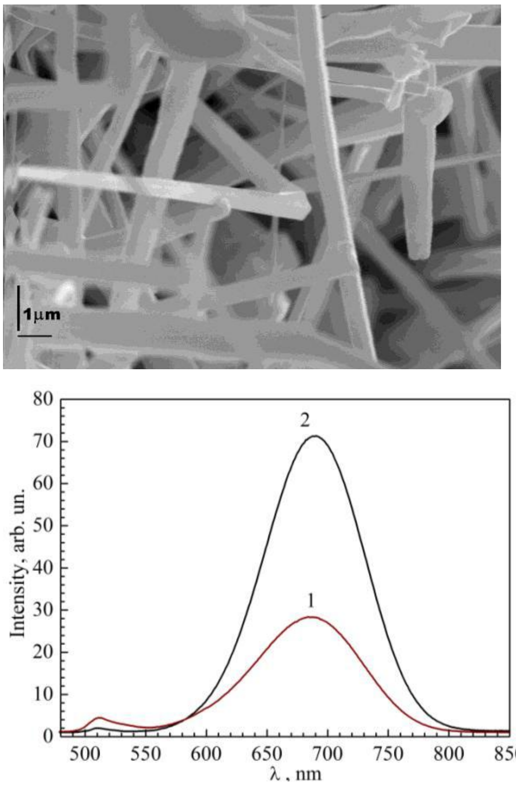

Fig. 3. Scanning electron microscopy images of CdS nanowires and their luminescence spectra [45]. © CC BY 4.0. Open access. 2023 Publisher PH "Akademperiodyka" of the NAS of Ukraine.

4. Two-dimensional nanostructures and quantum wells

Nanometer-thick semiconductor lattices with a high crystallinity, known as QWs, are one of the first created nanomaterials. They are mostly known by using in first laser diodes [51,52]. In SPQEO, current and electroluminescence intensity oscillations under bipolar lateral electric transport in double-GaAs/InGaAs/GaAs QWs [53] as well as the emission spectra of electron beam irradiated InGaN/GaN white LEDs with QWs [54] are measured. Moreover, narrow-band controllable sources of IR emission based on multilayer magneto-optical photonic structures containing a III-V semiconductor layer are simulated in Ref. [55]. Electrical properties inherent to ZnO nanofilms prepared using the sol-gel method with potential applications in the fields of electronics, photoelectronics and sensor technologies are studied as well [56].

2D nanostructures of graphene or layered semiconductors are currently ones of the most studied matters. There are not many articles devoted to them in SPQEO. Up to now, an increase in the efficiency of copper indium gallium selenide (CIGS) solar cells due to the reduced graphene oxide field layer of the back surface is reported in Ref. [57]. Moreover, a comprehensive review article on 2D MoS_2 for photonic applications was published [58].

Conclusions

The SPQEO journal covers main trends in the physics and technology of semiconductor nanomaterials used in modern nanoelectronics, optoelectronics, photonics, photovoltaics and sensorics. These nanostructures include QWs, QDs (or NCs and NPs) based on Si, SiC, II-VI, III-V and IV-VI semiconductor compounds and their solid solutions as well as metal oxides. The basic properties of nanostructures of different dimensions, preparation of semiconductor nanostructures and some of their electrical and optical properties are discussed.

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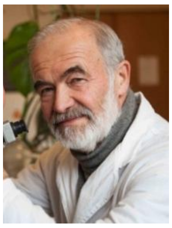

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Напівпровідникові наноматеріали для оптоелектроніки та журнал SPQEO

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Анотація. Напівпровідникові матеріали є життєво важливими для сучасних технологій для випромінювачів світла, датчиків і приводів, обчислювальних пристроїв і пристроїв пам'яті, а також для збору та зберігання енергії. У той же час наноструктури на основі напівпровідників сприяють швидкому розвитку технологій і створенню матеріалів з принципово новими властивостями завдяки ефектам квантового розміру. Журнал SPQEO приділяє увагу сучасному розвитку такого напряму, як фізика наночастинок і наноструктур. Протягом останніх років журнал публікував статті про напівпровідникові нанокристали, квантові точки, тонкі ґратки, включаючи їх зростання, характеристику, дослідження фізичних властивостей і теоретичний опис.

Ключові слова: наноматеріали, оптоелектроніка, нанокристали, квантові точки, квантовий розмір.