Ukrainian Journal of Physical Optics
ISSUE 1
2024

NANOMATERIALS FOR OPTOELECTRONICS: AN OVERVIEW

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Received: 09.05.2023

Abstract. Optoelectronics focuses on light-emitting and light-detecting devices and investigation of the materials used for their fabrication. Usually, the light-emitting devices are lamps, LEDs, laser diodes and gain-medium lasers, while the light-detecting devices are represented by photodiodes, photovoltaic solar cells, photoresistors, phototransistors, etc. The above field also covers the studies of emission of materials under different stimuli and interaction of light with different types of materials, mostly semiconductors and metal nanostructures. A technological progress in the materials science has instigated development of nanomaterials and optoelectronic devices on their basis. They can be divided into two-dimensional (2D) quantum wells, films or sheets, 1D nanowires and 0D quantum dots. 2D graphene-like layered materials, quantum dots and metal nanoparticles for optoelectronic applications are the most investigated. As a matter of fact, a global scientific trend associated with the nanomaterials is currently transforming our technologies and industry and represents the most ambitious course of the present and future optoelectronics.

Keywords: nanomaterials, optoelectronics, quantum confinement, emission, photovoltaics, solar energy

UDC: 539.51+ 681.7;
DOI: 10.3116/16091833/24/5/S1/2023

Optoelectronics is a particular sub-discipline of electronics, which focuses on light-emitting and light-detecting devices as well as electronic devices for the control of optical radiation and materials used for the fabrication of these devices. Naturally, it also covers the studies of emission (radiative recombination) of materials under different stimuli and interaction of light photons with different types of materials, mostly semiconductors and noble metals.

Light-emitting devices are commonly used for illumination, displays, indicators and light sources of ultraviolet (UV), visible (Vis) and infrared (IR) ranges. In its turn, IR optoelectronics, which is extensively investigated for the purposes of optics, electronics, telecommunication and even medicine, involves near-IR (NIR), shortwave-IR (SWIR), mid-IR (MIR) and far-IR (FIR) sub-fields. Most of the light-emitting devices are lamps, LEDs, laser diodes and gain-medium lasers. To generate electromagnetic radiation via different physical principles, an electric current is usually sent through an active material.

The light-detecting devices such as photodiodes, photovoltaic solar cells, photoresistors and phototransistors are designed to convert an incident electromagnetic energy into an electric current or voltage. They are used for light sensing, communications and remote control. Most materials are operated in specific sensitivity regions (or efficient absorption regions), so that photo-actuators can be divided according to their operating ranges (UV, Vis, NIR, etc).

Electronic devices for controlling optical radiation can also be referred to the optoelectronic devices. They are mostly based on liquid crystals and the materials of which optical response to external electrical stimuli is nonlinear. At the same time, they are less overlapped with nanomaterials and are out of the scope of the current overview.

Beginning from 1980s, a technological progress in the materials science has instigated a development of nanomaterials and optoelectronic devices on their basis. A term 'nanomaterial' is used whenever one of the dimensions of a system is equal to 1–100 nm. Depending on the number of non-confined dimensions, nanomaterials are divided into two-dimensional (2D) quantum wells, nanofilms or nanosheets, 1D nanowires and 0D quantum dots (QDs), as illustrated in Fig. 1 [1]. When the dimension is lower or equal to about 40 nm (depending on the types of materials), a nanomaterial reveals the properties different from its bulk counterpart due to a quantum confinement effect. The quantum confinement is a spatial confinement of electrons and holes or e–h pairs (excitons) along one or more dimensions within a material. This results in increasing bandgap and discrete electronic energy levels which appear due to a confinement of electronic wave functions (see Fig. 1) [1, 2].

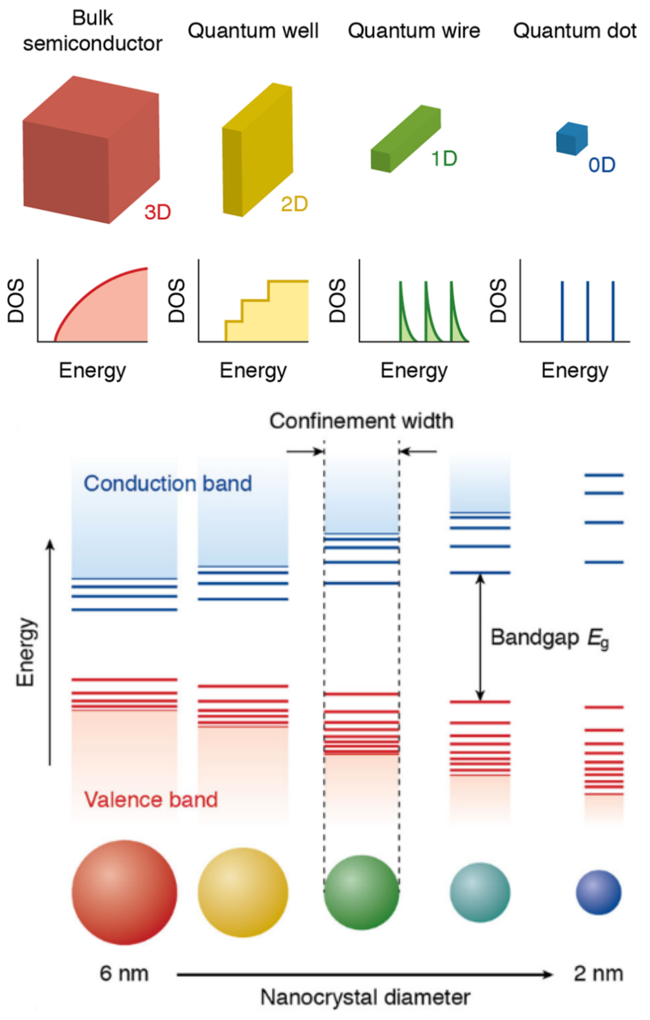

Fig. 1. Schematic illustration of energy-level structures for a bulk material and its nanostructures with reduced dimensionality: a 2D nanostructure (or a quantum well), a 1D nanostructure (or a quantum wire) and a 0D nanostructure (or a QD). DOS denotes a density of electronic states. The bandgap of a semiconductor nanocrystal increases with decreasing size and discrete energy levels arise at the band edges [1]. © CC BY 4.0. Open access. 2016 Springer Nature Switzerland AG.

Nanometre-thick semiconductor films with high crystallinity, which are known as quantum wells, have been one of the first nanomaterials used to create laser diodes [3, 4]. Somewhat later, nanoislands known as solid-state QDs have also been developed and thoroughly investigated [5–8]. Binary or ternary III–V-compound semiconductors (e.g., AlN, GaAs, GaN, AlGaN, InAs, InGaAs and InP) are mostly used to form these active solid-state materials (see Fig. 2). These materials have been successively applied in the fields related to laser diodes, displays, photodetectors, cameras and solar cells [9–13].

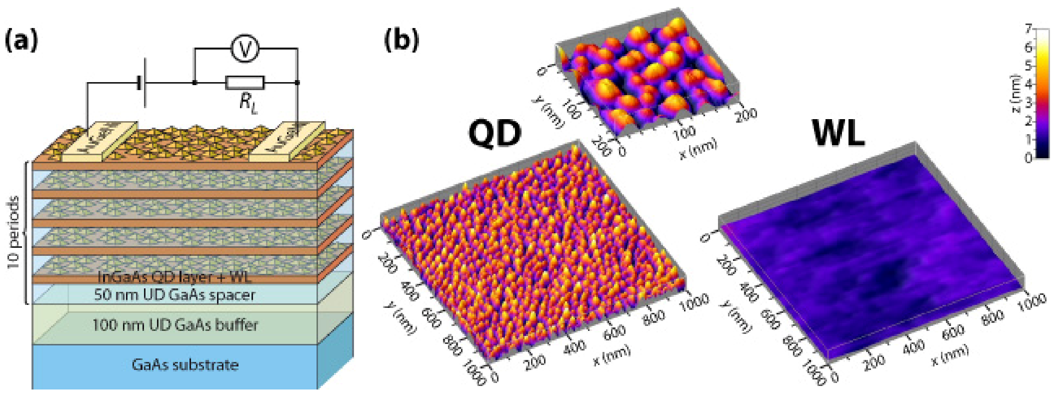

Fig. 2. (a) Scheme of heterostructure with stacked InGaAs/GaAs QDs and a connection used for photoelectric measurements. (b) 3D plots of AFM topograms for the QD and WL sample upper layers. Reprinted with permission from Ref. [7].

Colloidal 0D QDs are solution-processed semiconducting nanocrystals having a size-tunable bandgap. A great progress has been associated with a large variability of the methods for their fabrication and a wide range of their applications (see Fig. 3) [14, 15]. Colloidal QDs are synthesized based on binary or ternary semiconductors. They include II–VI (CdSe and CdS), III–V (InP, InAs, AlN and GaN), IV–VI (PbS and PbSe) and III–V ($CuInS_2$ and $CuInSe_2$) compounds, metal halide perovskites, transitional metal chalcogenides, etc. They have also found a very broad field of applications (e.g., for laser diodes, displays, photodetectors, cameras and solar cells) [16–18].

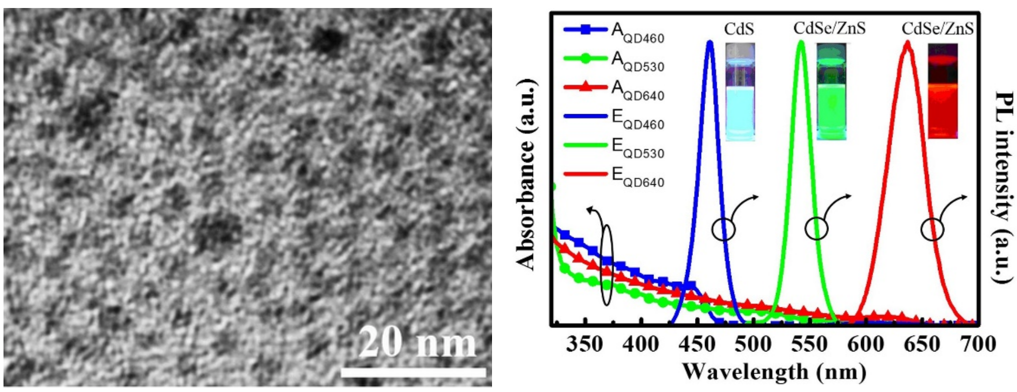

Fig 3. 0D colloidal CdSe QDs (left panel) and their emission regions and absorption/emission (photo-luminescence) spectra (right panel) [17].

A progress in the fabrication and chemistry of nanomaterials has lead to the creation of 1D nanowires, which are based upon Si and Ge (see Fig. 4), SiGe, ZnO, GaN, InAs, metal halide perovskites, transitional metal chalcogenides, etc. They have peculiar optical properties and specific conductivity and photoconductivity, which can be used for developing nanoelectrodes, anisotropic photosensors and solar cells [19–22].

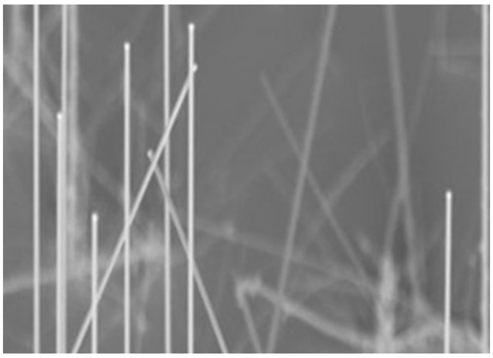

Fig. 4. Ge nanorods [22]. © CC BY 4.0. Open access. 2022 American Chemical Society.

2D layered materials are the most novel materials that originate from the invention of monolayer (1L) graphene in 2004 (Prof. A. Geim and Prof. K. Novoselov, The University of Manchester). They are represented by graphene (see Fig. 5) [23, 24], layered phosphor (black P), arsenide (black and grey As), as well as some other graphene-like compounds which are due to different structural variations of layered transitional-metal dichalcogenides MX_2 (M = Mo, W, Hf, Ni, Re, Pt, Pd, Zr; X = S, Se, Te), chalcogenides MX (M = In, Ga, Al, Sn, Ge,

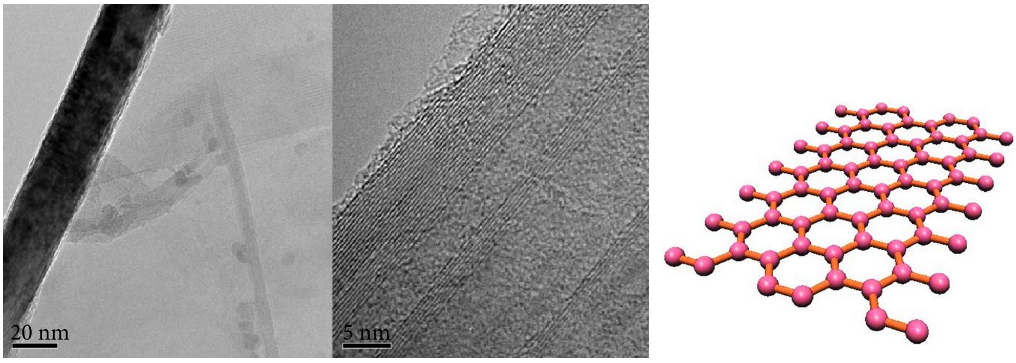

Fig. 5. High-resolution TEM image of a graphene monolayer sheet (left panel) [23] © CC BY 4.0. Open access. 2020 Hediyeh Karimi et al. Crystal structure of graphene (right panel) [24]. © CC BY 4.0. Open access. 2013 Hediyeh Karimi et al.

Sn; X = S, Se, Te) and metal halides MX_2 (M = Pb, Be, Mg, Ca, Sr, Ba, Zn, Cd, Hg; X = I, Cl, Br) [25–31]. All these materials have unique optical and electrical properties, including an indirect-to-direct bandgap crossover, a spatial anisotropy, and high carrier mobility. To tune with high efficiency and enhance the electrical and optical properties of 2D materials, a variety of novel hybrids [32, 33] and 2D QDs (or nanoflakes) [26, 34–36] have been created. Representative 1L-MoS_2 flakes and 1L-QDs are shown in Fig. 6 [36]. A layered structure of the 2D materials permits unique hybridization between the layers of different materials via van der Waals forces or plasmonic effects in metal nanomaterials [32, 33, 36]. This enables very wide applications of the 2D materials, with the relevant examples given by extremely sensitive and flexible photodiodes and photoresistors, light sources, chemical sensors, solar cells, optical switches, displays, energy storage, fibre optical elements, lubricants, and many other applications in photobiology and medicine.

Metal nanostructures and nanoparticles (NPs) are the materials which are widely used in optoelectronics. Noble-metal (Au, Ag and Pt) nanostructures and NPs manifest strong surface plasmon interactions with light. The appropriate physical mechanism is that collective coherent excitations of free electrons in metal NPs, which are also known as a surface plasmon resonance, lead to enhanced local electric fields in the vicinity of nanostructure surface [37, 38]. If compared to highly symmetric structures (in the shapes of spheres, cubes and discs), lower-symmetry non-spherical metal NPs (nanorods, nanostars and nanotriangles) and the nanostructures with sharp edges and tips provide the highest plasmonic enhancement. Relevant samples of these NPs are shown in Fig. 7. A success achieved with the nonspherical metal NPs comes from their good surface plasmon resonance originated from their edges or tips, which provides a significant local-field enhancement. Variations of their size and shape enable highly tuned absorption properties of the metal NPs. This stimulates their investigations and applications aimed at enhancing photodetecting and emitting properties [33, 39–43].

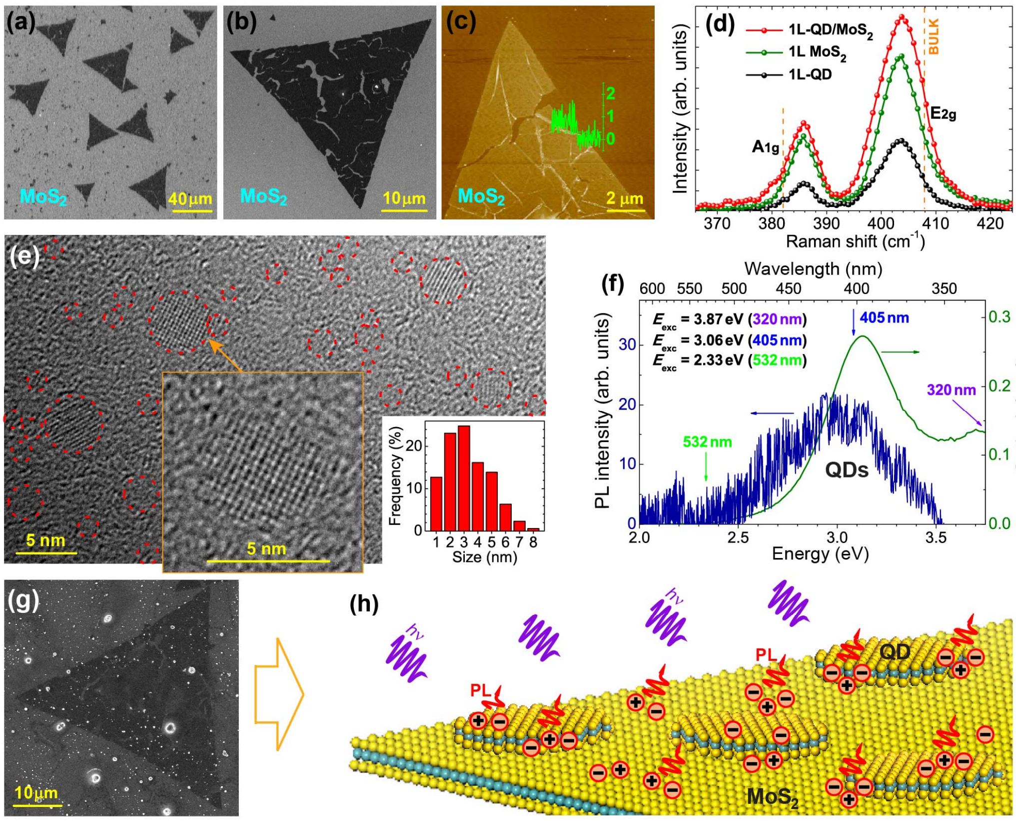

Fig. 6. Morphology, structure and properties of a 1L-QD/MoS_2 hybrid: SEM images of a large area (a) and a triangular flake (b); AFM topogram and a height profile (c); room-temperature μ-Raman spectra for 1L-QD/MoS_2 hybrid, 1L flake and 1L-QDs (d); HRTEM image of 1L-QDs and QD-size distribution (e); photoluminescence and absorption spectra of 1L-QDs (f); SEM image (g) and scheme (h) of a flake decorated with 1L-QDs, and explanation of the interaction mechanism. Reprinted with permission from Ref. [36]. © 2022 Elsevier B.V. All rights reserved.

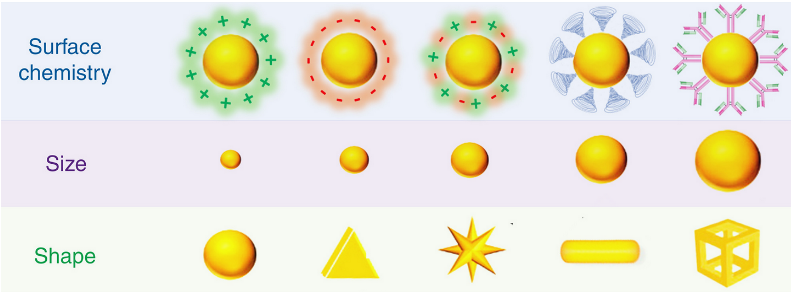

Fig. 7. Gold NPs can be tailored with a wide variety of sizes, shapes and surface chemistries [39]. © CC BY-NC 4.0. Open access. 2018 John Wiley & Sons, Inc.

The field of optoelectronics focuses on the light-emitting and light-detecting devices and the studies of materials used to fabricate these devices. This field also covers the studies of the emission of materials under different stimuli and the interaction of light with different types of materials, primarily semiconductors and metal nanostructures. The technological progress in the materials science has stipulated tremendous steps in development of the nanomaterials and the optoelectronic devices on their basis. They are divided into 2D quantum wells, films or sheets, 1D nanowires and 0D QDs. Among them, 2D graphene-like layered materials, colloidal QDs and noble-metal nanostructures or NPs are the most investigated for optoelectronic applications. The success in application of the nanomaterials is based on their simple integration with circuits and silicon-based technologies. It is also linked with fibre and flexible optics and sub-micron electronics. On the other hand, the properties of the above materials can be tuned in a very wide range, using different approaches. As a matter of fact, a global scientific trend associated with the nanomaterials is currently transforming our technologies and industry. It represents the most ambitious course in the present-day and future optoelectronics.

Declaration of competing interest. The authors declare no competing financial interests or personal relationships with respect to the present paper.

Data availability. The reported data can be available on request to the author.

References

1. Rabouw, F.T., de Mello Donega, C. (2016). Excited-State Dynamics in Colloidal Semiconductor Nanocrystals. *Topics in Current Chemistry (Z)* 374, 58.
2. de Mello Donegá, C. (2011). Synthesis and properties of colloidal heteronanocrystals. *Chemical Society Reviews*, *40*(3), 1512-1546.
3. Holonyak, N., Kolbas, R., Dupuis, R., & Dapkus, P. (1980). Quantum-well heterostructure lasers. *IEEE Journal of Quantum Electronics*, *16*(2), 170-186.
4. Krispin, P., Lazzari, J. L., & Kostial, H. (1998). Deep and shallow electronic states at ultrathin InAs insertions in GaAs investigated by capacitance spectroscopy. *Journal of applied physics*, *84*(11), 6135-6140.
5. Michler, P., Kiraz, A., Becher, C., Schoenfeld, W. V., Petroff, P. M., Zhang, L., Hu, E., & Imamoglu, A. (2000). A quantum dot single-photon turnstile device. *Science*, *290*(5500), 2282-2285.
6. Semenova, E. S., Zhukov, A. E., Mikhrin, S. S., Egorov, A. Y., Odnoblyudov, V. A., Vasil'ev, A. P., Nikitina, E. V., Kovsh, A. R., Kryzhanovskaya, N. V., Gladyshev, A. G., Blokhin, S. A., Musikhin, Y. G., Maximov, M. V., Shernyakov, Y. M., Ustinov, V. M. & Ledentsov, N. N. (2004). Metamorphic growth for application in long-wavelength (1.3–1.55 µm) lasers and MODFET-type structures on GaAs substrates. *Nanotechnology*, *15*(4), S283.
7. Golovynskyi, S., Datsenko, O. I., Seravalli, L., Trevisi, G., Frigeri, P., Gombia, E., Babichuk, I., Lin, D., Li, B., & Qu, J. (2020). Near-infrared lateral photoresponse in InGaAs/GaAs quantum dots.

Semiconductor Science and Technology, *35*(5), 055029.
8. Seravalli, L. (2023). Metamorphic InAs/InGaAs quantum dots for optoelectronic devices: A review. *Microelectronic Engineering*, 111996.
9. Lee, S. J., Ku, Z., Barve, A., Montoya, J., Jang, W. Y., Brueck, S. R. J., Sundaram, M., Reisinger, A., Krishna, S., & Noh, S. K. (2011). A monolithically integrated plasmonic infrared quantum dot camera. *Nature communications*, *2*(1), 286.
10. Mukherjee, S., Maiti, R., Katiyar, A. K., Das, S., & Ray, S. K. (2016). Novel colloidal MoS_2 quantum dot heterojunctions on silicon platforms for multifunctional optoelectronic devices. *Scientific reports*, *6*(1), 29016.
11. Babichuk, I. S., Semenenko, M. O., Golovynskyi, S., Caballero, R., Datsenko, O. I., Babichuk, I. V., Li, J., Xu, G., Qiu, R., Huang, C., Hu, R., Golovynska, I., Ganus, V., Li, B., Qu, J., & Leon, M. (2019). Control of secondary phases and disorder degree in Cu_2ZnSnS_4 films by sulfurization at varied subatmospheric pressures. *Solar Energy Materials and Solar Cells*, *200*, 109915.
12. Liu, Z., Lin, C. H., Hyun, B. R., Sher, C. W., Lv, Z., Luo, B., Jiang, F., Wu, T., Ho, C. H., Kuo, H. C., & He, J. H. (2020). Micro-light-emitting diodes with quantum dots in display technology. *Light: Science & Applications*, *9*(1), 83.
13. Kwoen, J., Imoto, T., & Arakawa, Y. (2021). InAs/InGaAs quantum dot lasers on multi-functional metamorphic buffer layers. *Optics Express*, *29*(18), 29378-29386.
14. Zhao, H., & Rosei, F. (2017). Colloidal quantum dots for solar technologies. *Chem*, *3*(2), 229-258.
15. Liu, M., Yazdani, N., Yarema, M., Jansen, M., Wood, V., & Sargent, E. H. (2021). Colloidal quantum dot electronics. *Nature Electronics*, *4*(8), 548-558.
16. Wood, V., & Bulović, V. (2010). Colloidal quantum dot light-emitting devices. *Nano reviews*, *1*(1), 5202.
17. Han, H. V., Lin, C. C., Tsai, Y. L., Chen, H. C., Chen, K. J., Yeh, Y. L., Lin, W. Y., Kuo, H. C. & Yu, P. (2014). A highly efficient hybrid GaAs solar cell based on colloidal-quantum-dot-sensitization. *Scientific reports*, *4*(1), 5734.
18. Zhao, J., Chen, L., Li, D., Shi, Z., Liu, P., Yao, Z., Yang H, Zou, T., Zhao, B., Zhang, X., Zhou, H., Yang, Y., Cao, W., Yan, X., Zhang, S., & Sun, X. W. (2021). Large-area patterning of full-color quantum dot arrays beyond 1000 pixels per inch by selective electrophoretic deposition. *Nature Communications*, *12*(1), 4603.
19. Hsu, Y. F., Xi, Y. Y., Djurišić, A. B., & Chan, W. K. (2008). ZnO nanorods for solar cells: hydrothermal growth versus vapor deposition. *Applied Physics Letters*, *92*(13), 133507.
20. Wen, S., Liu, Y., Wang, F., Lin, G., Zhou, J., Shi, B., Suh, Y. D., & Jin, D. (2020). Nanorods with multi-dimensional optical information beyond the diffraction limit. *Nature communications*, *11*(1), 6047.
21. Wang, J., Liu, L., Chen, S., Qi, L., Zhao, M., Zhao, C., Tang, J., Cai, X., Lu, F., & Jiu, T. (2022). Growth of 1D nanorod perovskite for surface passivation in $FAPbI_3$ perovskite solar cells. *Small*, *18*(3), 2104100.
22. Laumier, S., Farrow, T., van Zalinge, H., Seravalli, L., Bosi, M., & Sandall, I. (2022). Selection and Functionalization of Germanium Nanowires for Bio-Sensing. *ACS omega*, *7*(39), 35288-35296.
23. Huang, G., Lv, C., He, J., Zhang, X., Zhou, C., Yang, P., Tan. Y., & Huang, H. (2020). Study on preparation and characterization of graphene based on ball milling method. *Journal of Nanomaterials*, *2020*, 1-11.
24. Karimi, H., Yusof, R., Rahmani, R., & Ahmadi, M. T. (2013). Optimization of DNA sensor model based nanostructured graphene using particle swarm optimization technique. *Journal of Nanomaterials*, *2013*, 789454
25. Mak, K. F., Lee, C., Hone, J., Shan, J., & Heinz, T. F. (2010). Atomically thin MoS_2: a new direct-gap semiconductor. *Physical review letters*, *105*(13), 136805.
26. Li, Z., Ye, R., Feng, R., Kang, Y., Zhu, X., Tour, J. M., & Fang, Z. (2015). Graphene quantum dots doping of MoS2 monolayers. *Advanced Materials*, *27*(35), 5235-5240.
27. Shu, Y., Guo, J., Fan, T., Xu, Y., Guo, P., Wang, Z., Wu, L., Ge, Y., Lin, Z., Ma, D., Wei, S., Li, J., Zhang, H., & Chen, W. (2020). Two-dimensional black arsenic phosphorus for ultrafast photonics in near-and mid-infrared regimes. *ACS Applied Materials & Interfaces*, *12*(41), 46509-46518.
28. Golovynskyi, S., Datsenko, O. I., Dong, D., Lin, Y., Irfan, I., Li, B., Lin, D., & Qu, J. (2021). Trion binding energy variation on photoluminescence excitation energy and power during direct to indirect bandgap crossover in monolayer and few-layer MoS_2. *The Journal of Physical Chemistry C*, *125*(32), 17806-17819.
29. Golovynskyi, S., Dong, D., Lin, Y., Datsenko, O. I., & Li, B. (2021). Hexagram bi-layer MoS_2 flake: The impact of polycrystallinity and strains on the exciton and trion photoluminescence. *Surfaces and Interfaces*, *26*, 101343.
30. Usman, M., Golovynskyi, S., Dong, D., Lin, Y., Yue, Z., Imran, M., Li, B., Wu, H., & Wang, L. (2022).

Raman scattering and exciton photoluminescence in few-layer GaSe: Thickness-and temperature-dependent behaviors. *The Journal of Physical Chemistry C*, *126*(25), 10459-10468.

31. Golovynskyi, S., Datsenko, O. I., Usman, M., Pérez-Jiménez, A. I., Chaigneau, M., Bosi, M., Seravalli, L., Hidouri, T., Golovynska, I., Li, B., & Wu, H. (2023). Free exciton and bound excitons on Pb and I vacancies and O and I substituting defects in PbI_2: Photoluminescence and DFT calculations. *Applied Surface Science*, *624*, 157128.
32. Lai, G. J., Lyu, L. M., Huang, Y. S., Lee, G. C., Lu, M. P., Perng, T. P., Lu, M. Y., & Chen, L. J. (2021). Few-layer WS_2–MoS_2 in-plane heterostructures for efficient photocatalytic hydrogen evolution. *Nano Energy*, *81*, 105608.
33. Irfan, I., Golovynskyi, S., Yeshchenko, O. A., Bosi, M., Zhou, T., Xue, B., Li, B., & Seravalli, L. (2022). Plasmonic enhancement of exciton and trion photoluminescence in 2D MoS_2 decorated with Au nanorods: Impact of nonspherical shape. *Physica E: Low-dimensional Systems and Nanostructures*, *140*, 115213.
34. Golovynskyi, S., Bosi, M., Seravalli, L., & Li, B. (2021). MoS_2 two-dimensional quantum dots with weak lateral quantum confinement: Intense exciton and trion photoluminescence. *Surfaces and Interfaces*, *23*, 100909.
35. Park, K. H., Jung, S., Kim, J., Ko, B. M., Shim, W. G., Hong, S. J., & Song, S. H. (2021). Boosting photovoltaic performance in organic solar cells by manipulating the size of MoS_2 quantum dots as a hole-transport material. *Nanomaterials*, *11*(6), 1464.
36. Golovynskyi, S., Datsenko, O. I., Dong, D., Lin, Y., Golovynska, I., Jin, Z., Li, B., & Wu, H. (2022). MoS_2 monolayer quantum dots on a flake: Efficient sensitization of exciton and trion photoluminescence via resonant nonradiative energy and charge transfers. *Applied Surface Science*, *601*, 154209.
37. Muskens, O. L., Giannini, V., Sánchez-Gil, J. A., & Gómez Rivas, J. (2007). Strong enhancement of the radiative decay rate of emitters by single plasmonic nanoantennas. *Nano letters*, *7*(9), 2871-2875.
38. Ziegler, J., Djiango, M., Vidal, C., Hrelescu, C., & Klar, T. A. (2015). Gold nanostars for random lasing enhancement. *Optics express*, *23*(12), 15152-15159.
39. Li, B., & Lane, L. A. (2019). Probing the biological obstacles of nanomedicine with gold nanoparticles. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, *11*(3), e1542.
40. Lee, K. C., Chen, Y. H., Lin, H. Y., Cheng, C. C., Chen, P. Y., Wu, T. Y., Shih, M. H., Wei, K. H., Li, L., & Chang, C. W. (2015). Plasmonic gold nanorods coverage influence on enhancement of the photoluminescence of two-dimensional MoS_2 monolayer. *Scientific reports*, *5*(1), 16374.
41. Yeshchenko, O. A., Kudrya, V. Y., Tomchuk, A. V., Dmitruk, I. M., Berezovska, N. I., Teselko, P. O., Golovynskyi, S., Xue, B., & Qu, J. (2019). Plasmonic nanocavity metasurface based on laser-structured silver surface and silver nanoprisms for the enhancement of adenosine nucleotide photoluminescence. *ACS Applied Nano Materials*, *2*(11), 7152-7161.
42. Irfan, I., Golovynskyi, S., Bosi, M., Seravalli, L., Yeshchenko, O. A., Xue, B., Dong, D., Lin, Y., Qiu, R., Li, B., & Qu, J. (2021). Enhancement of Raman scattering and exciton/trion photoluminescence of monolayer and few-layer MoS_2 by Ag nanoprisms and nanoparticles: shape and size effects. *The Journal of Physical Chemistry C*, *125*(7), 4119-4132.
43. Yaremchuk, I., Pidluzhna, A., Stakhira, P., Kuntyi, O., Sus, L., Savaryn, V., Stakhira, P., Kostruba, A., Fitio, V., & Bobitski, Y. (2021). Surface-localized plasmon resonance in a system of randomly arranged gold nanorods on a dielectric substrate. *Ukrainian Journal of Physical Optics*, *22*(2), 69-82.

Golovynskyi S. 2023. Nanomaterials for optoelectronics: An Overview. Ukr. J. Phys. Opt. 25, 01045 – 01053. doi: 10.3116/16091833/24/5/S1/2023

Анотація. *Оптоелектроніка зосереджена на світловипромінювальних і світлодетекторних пристроях і дослідженні матеріалів, які використовуються для їх виготовлення. Зазвичай світловипромінювальними пристроями є лампи, світлодіоди, лазерні діоди та лазери із середовищем підсилення, тоді як світлодетекторними пристроями є фотодіоди, фотоелектричні сонячні елементи, фоторезистори, фототранзистори тощо. Вищезазначена сфера також охоплює дослідження випромінювання матеріалів під різним збудженням та взаємодію світла з різними типами матеріалів, переважно напівпровідниками та металевими наноструктурами. Технологічний прогрес у матеріалознавстві спонукав до розробки наноматеріалів та оптоелектронних пристроїв на їх основі. Їх можна розділити на двовимірні (2D) квантові* *ями, плівки або листи, 1D нанодроти та 0D квантові точки. 2D-графеноподібні шаруваті матеріали, квантові точки та металеві наночастинки для оптоелектронних застосувань є найбільш дослідженими. По суті, глобальна наукова тенденція, пов'язана з наноматеріалами, наразі трансформує наші технології та промисловість і представляє найбільш амбітний курс сучасної та майбутньої оптоелектроніки.*

Ключові слова*: наноматеріали, оптоелектроніка, квантовий розмір, випромінювання, фотовольтаїка, сонячна енергія*