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Nanolasers Based on Semiconductor Quantum Dots

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The minireview analyses fundamental experimental and theoretical research and applied applications of nanolasers based on semiconductor (including also perovskite) quantum dots. As shown, the development of nanolasers based on semiconductor and perovskite quantum dots is a consequence of long-term progress in the physics and chemistry of semiconductors. Due to the dimensional quantum limitation of the motion of quasiparticles (electrons and holes) in quantum dots, it becomes possible to vary the emission and absorption spectra by changing the sizes of quantum dots in the nanorange. This allowed semiconductor and perovskite quantum dots to demonstrate a high quantum yield and a narrow width of the emission spectrum. These properties of semiconductor (including also perovskite) quantum-dots' ensembles made it possible to develop a number of nanolasers with high optical characteristics. Current trends in laser-technology development are focused on environmental requirements, in particular, on the development of lead-free perovskite quantum dots to reduce toxicity. Hybridization of perovskite quantum dots allows passivation of the surface, reduction of defect density and increase of charge-carrier lifetime, which lowers the threshold of laser generation and increases the stability of the devices. Such hybrid systems demonstrate improved crystallinity, increased charge-carrier mobility and efficient charge transfer between layers that contributes to increasing quantum efficiency and expanding the emission spectrum from the visible range to the near-infrared range. This opens up new opportunities for the creation of highly efficient, stable and environmentally safe optoelectronic and laser devices of a new generation.

В мініогляді проведено аналізу фундаментальних експериментальних і теоретичних досліджень та прикладних застосувань нанолазерів на основі напівпровідникових (включаючи також перовськітних) квантових цяток. Показано, що розвиток нанолазерів на базі напівпровідникових і перовськітних квантових цяток є наслідком тривалого проґресу в фізиці та хемії напівпровідників. Завдяки розмірному квантовому обме-

женню руху квазичастинок (електронів і дірок) у квантових цятках стало можливим варіювати спектри випромінення та вбирання шляхом зміни розмірів квантових цяток у нанодіяпазоні. Це уможливило в напівпровідникових і перовськітних квантових цятках демонструвати високий квантовий вихід і вузьку ширину спектру випромінення. Ці властивості ансамблів напівпровідникових (включаючи також перовськітних) квантових цяток надали можливість розробити цілий ряд нанолазерів з високими оптичними характеристиками. Сучасні тенденції розвитку лазерних технологій орієнтовано на екологічні вимоги, зокрема на розробку безплюмбумових перовськітних квантових цяток для зменшення токсичности. Гібридизація квантових цяток перовськітів уможливлює пасивувати поверхню, зменшити густину дефектів і підвищити час життя носіїв заряду, що понижує поріг лазерної ґенерації та підвищує стабільність роботи пристроїв. Такі гібридні системи демонструють поліпшену кристалічність, підвищені рухливість носіїв заряду й ефективне перенесення заряду між шарами, що сприяє підвищенню квантової ефективности та розширенню спектру випромінення від видимого до близького інфрачервоного діяпазону. Це відкриває нові можливості для створення високоефективних, стабільних і екологічно безпечних оптоелектронних і лазерних пристроїв нового покоління.

Key words: perovskites, quantum dots, optical transitions, quantum energy levels, nanolasers.

Ключові слова: перовськіти, квантові цятки, оптичні переходи, квантові енергетичні рівні, нанолазери.

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1. INTRODUCTION

Nanolasers based on semiconductor (including also perovskite) quantum dots (QDs) are attracting significant attention from researchers due to the rapid advancement of nanolaser technologies driven by fundamental experimental and theoretical studies [1–20]. Their practical interest stems from their potential for creating compact photonic chips, biosensors, and single-photon sources, enabled by high photoluminescent efficiency, narrow emission bandwidth, and low lasing thresholds [20–28].

A key theoretical challenge in studying nanosystems is describing the interaction of electromagnetic fields with surface electronic states localized at the interfaces of nanosystems [11–18]. This approach requires accurately modelling interactions (Coulomb, polarization, exchange, spin–orbit, spin–spin, *etc.*) between quasiparticles (electrons, holes, and excitons) induced by electromagnetic fields at these interfaces. It is also necessary to determine the size limits of quantum objects (QDs, nanofilms, quantum wires), where the effec-

tive mass approximation remains valid [11–18].

In the 1960s and 1970s, despite the availability of advanced technologies (nuclear energy, semiconductor nanoheterostructures) and known perovskite materials, these materials were not used as the basis for devices (solar cells, LEDs, lasers) due to several objective reasons. Firstly, their unique optoelectronic properties, particularly those of organic–inorganic halide perovskites, which now drive fundamental and practical interest, were not yet discovered [12–18, 29–31]. Secondly, technologies for producing high-quality thin films and nanostructures with controlled parameters were unavailable, and synthesis methods were limited, preventing the creation of materials with the required purity and structure [30–32]. Additionally, there was a lack of theoretical understanding of charge transfer mechanisms, defects, stability, and interface interactions, which are critical for developing efficient devices [11–18]. Furthermore, there was no urgent need for new materials in solar energy or displays, as silicon, GaAs, and other semiconductors met the technological demands of that time [32, 33].

The development of nanolasers based on semiconductor (including also perovskite) QDs is the result of long-term progress in semiconductor physics and chemistry. In the 1980s and 1990s, the foundations for creating QDs—nanocrystals, which allow tuning of emission and absorption spectra by varying their size in the nanoscale range due to quantum confinement—were established. Classical QDs, such as CuCl, CdS, CdSe, ZnS, ZnSe, GaAs, and aluminium oxide, demonstrated high quantum yields and narrow spectral widths but faced limitations in stability and environmental safety [12–28, 34–51]. Concurrently, research on perovskite materials gained attention due to their unique properties, realized in solar cells: high absorption coefficients, long carrier diffusion lengths, and low defect concentrations [11–17, 52, 53]. A major breakthrough occurred with the synthesis of halide perovskite QDs with the formula $CsPbX_3$ (X = Cl, Br, I), which combined the advantages of classical QDs and perovskites—high photoluminescent efficiency (up to 90–100%), narrow spectral width (18–36 nm), a wide tuneable emission range (from blue to red), and high carrier mobility [53, 54]. Key contributions came from studies [6, 11, 15, 55], which first demonstrated the effectiveness of such QDs for nanolasers, providing low lasing thresholds and emission stability [53].

In study [11], the photoluminescent properties of $CsPbX_3$ QDs with average sizes of 10–12 nm were investigated. It was found that interband transitions between quantum-confined electronic states in these QDs exhibit giant dipole moments (on the order of 10 Debye) [12, 15, 17]. Such quantum-confined electronic states can lead to strong optical absorption in these QDs. Additionally, these

states were found to be long-lived (on the order of 30 ns), raising hopes for achieving Bose–Einstein condensation of excitons in these QDs [12, 15, 17].

Research has focused on optimizing the composition of perovskites (*e.g.*, fully inorganic $CsPbBr_3$), morphology, and surface ligands to enhance the stability and efficiency of nanolasers, as well as developing new compositions from simple nanocrystals to hybrid structures and laser arrays [51, 52, 54]. Encapsulation of materials in bilayer mesoporous SiO significantly improved moisture resistance and device durability, while the use of plasmonic nanostructures reduced lasing thresholds and expanded functionality for biophotonics [56]. Thus, the development of nanolasers based on semiconductor and perovskite QDs illustrates a rapid evolution from fundamental discoveries to practical applications in modern optoelectronic technologies [12–17, 51–54].

Following initial studies of halide perovskites, which exhibited high absorption coefficients (> 10 cm^{-1}) and long carrier diffusion lengths (up to 1 μm), their potential in laser technologies was recognized [52, 57]. The next step was the creation of $CsPbX_3$ (X = Cl, Br, I) QDs with sizes of 3–13 nm, which, due to quantum confinement, enabled precise tuning of emission spectra: blue ($CsPbCl_3$, 410–430 nm), green ($CsPbBr_3$, 510–520 nm), and red ($CsPbI_3$, 680–700 nm) [52, 57]. Subsequently, hybrid structures such as 'quantum-dot-in-perovskite' were developed, where colloidal QDs were integrated into a perovskite matrix, improving charge transfer and stability [58]. A significant breakthrough was the creation of nanolasers with ultralow lasing thresholds (*e.g.*, 1.9 W/cm^2 at 120 K for $CsPbBr_3$ QDs) and small mode volumes ($\cong 0.2\%$), enabling their integration into photonic chips [57]. Each step was accompanied by improvements in the physical parameters of materials and devices, facilitating the transition from laboratory samples to practical nanolasers with controllable properties [52, 56–58].

This minireview analyses fundamental experimental and theoretical studies and applied applications of nanolasers based on semiconductor (including also perovskite) quantum dots. As shown, their applied interest stems from their potential to create compact photonic chips, biosensors, and single-photon sources, enabled by high photoluminescent efficiency, narrow emission bandwidth, and low lasing thresholds.

2. SEMICONDUCTOR QUANTUM DOTS IN NANOLASERS

The unique optoelectronic properties of semiconductor and perovskite QDs have enabled the creation of nanolasers [17, 34, 44, 50]. QDs made of cadmium and zinc sulphides/selenides, gallium arse-

nide, and perovskites such as $CsPbBr_3$ and $CsPbI_3$ exhibit low defect densities, high carrier mobility (up to 60 $cm^2/(V{\cdot}s)$), and low Auger recombination rates [59]. The bandgap energies (E_g) of such QDs range from 1.5 to 2.6 eV, allowing experimental observation of interband transitions of charge carriers (electrons and holes) across a wide range, including near-infrared and optical spectral regions [59].

Chemically, perovskites are easily synthesized by solution methods, which simplify their application in nanolasers [59, 60]. Quantum confinement in semiconductor and perovskite QDs occurs, when the radii a of the QD become smaller than the Bohr radius of the exciton $a_{ex} = \varepsilon\hbar^2 / (m_{ex}e^2)$ ($m_{ex} = m_e m_h / (m_h + m_e)$—the reduced mass of the exciton in the QD , m_e and m_h—the effective masses of the electron and hole in the QD; ε—the dielectric constant of the QD), Bohr radius of the electron $a_e = \varepsilon\hbar^2 / (m_e e^2)$ and Bohr radius of the hole $a_h = \varepsilon\hbar^2 / (m_h e^2)$, *i.e.*, the conditions must be fulfilled [11–18] as follow:

$$a < a_e, a_h, a_{ex} . \tag{1}$$

Usually, the Bohr radii of quasiparticles a_e, a_h, a_{ex} are of the order of 2–7 nm [11–18]. We will assume that the motion of quasiparticles (electrons, holes, and excitons) in QDs can be described in the effective-mass approximation [11–18]. We will describe QDs by the model of an infinite spherical-potential well. Then, the lower energy levels of the electron $E_{n_e,l_e}(a)$ in the conduction band of QDs and the hole $E_{n_h,l_h}(a)$ in the valence band of QDs are determined by the formulas [11–18]

$$E_{n_e,l_e}(a) = \hbar^2(\varphi_{n_e,l_e})^2 / (2m_e a^2) , \tag{2}$$

$$E_{n_h,l_h}(a) = \hbar^2(\varphi_{n_h,l_h})^2 / (2m_h a^2) , \tag{3}$$

where the subscripts (n_e, l_e) and (n_h, l_h) are the principal and azimuthal quantum numbers for the electron and the hole; and $\varphi_{n,l}$ are the roots of the Bessel function, *i.e.*, $J_{l+1/2}(\varphi_{n,l}) = 0$. The expressions $E_{n_e,l_e}(a)$ (2) and $E_{n_h,l_h}(a)$ (3) correctly describe the lower quantum-dimensional energy levels of the electron and hole within the QD, if their position is much lower than the depth of the QD potential well (of the order of the band gap width E_g). In this case, the conditions are satisfied as follow:

$$E_{n_e,l_e}(a), E_{n_h,l_h}(a) \ll E_g . \tag{4}$$

Fulfilment of condition (4) also allows us to consider the motion of quasiparticles within the QD, in which the conduction band and

the valence band have a parabolic shape. To observe the energy levels of an electron (2) and a hole (3) in a QD at room temperature T_0, it is necessary that the energy distance between adjacent levels,

$$\Delta E_{e(h)}(a) \ll k_B T_0 , \tag{5}$$

was much smaller than a quantum of thermal energy $k_B T_0$ [11–18].

When conditions (1), (4) and (5) are met, as a result of interband transitions of an electron from quantum-dimensional energy levels $E_{n_e,l_e}(a)$ (2) to quantum-dimensional energy levels $E_{n_h,l_h}(a)$ (3) in a QD, emission (absorption) spectra are formed [11–18]:

$$\hbar\omega_{n,l}(a) = E_{n_e,l_e}(a) + E_{n_h,l_h}(a) + E_g , \tag{6}$$

where $\hbar\omega_{n,l}(a)$ is the quantum of light emitted during the transition. The selection rules allow only interband transitions, in which the quantum numbers $(n_e = n_h)$ and $(l_e = l_h)$ of the electron and hole are preserved. With a decrease in the radius a of the QD, the positions of the quantum-dimensional energy levels $E_{n_e,l_e}(a) \propto a^{-2}$ (2) of the electron and $E_{n_h,l_h}(a) \propto a^{-2}$ (3) of the hole shift upward, approaching the boundary of the QD potential well. As a result, the energy levels $E_{n_e,l_e}(a)$ (2) of the electron and $E_{n_h,l_h}(a)$ (3) of the hole are pushed out of the QD potential well. For instance, for the CdS QD with a radius $a \le 2$ nm, only two electron levels $(n_e = 1, l_e = 0)$, $(n_e = 1, l_e = 1)$ and two hole levels $(n_h = 1, l_h = 0)$, $(n_h = 1, l_h = 1)$ remain in the QD potential wells [17]. These interband transitions can be used in the operation of CdS QD nanolasers [17]. The decrease in the radius a of the QD also led to an increase in the effective band-gap width $(\hbar\omega_{n,l}(a) \propto a^{-2})$ of the QD [11–18, 61, 62]. Therefore, varying the parameters of nanosystems, such as the values of the effective masses of quasiparticles and the radii a of the QD, allows for the directed production of nanosystems with predetermined optical properties.

For $CsPbBr_3$-perovskite QDs, a size reduction from 8.5 to 4.1 nm causes an increase in the band gap from 2.37 to 2.5 eV, which is accompanied by a blue shift of photoluminescence [11, 61, 62]. In such QDs, an increased exciton binding energy is observed (for example, for $CsPbBr_3$ nanoplates, it can exceed 40 meV), which ensures efficient charge transfer and a longer lifetime of excited states compared to bulk crystals [11, 63, 64]. In two-dimensional perovskites, a decrease in the layer thickness leads to an increase in the effective mass of carriers and an increase in the exciton binding energy, which allows tuning the optical properties [65]. Quantum confinement also affects the rate and mechanisms of relaxation: for example, in $MAPbI_3$ QDs, multiexciton generation processes occur

in a few femtoseconds and radiative recombination in nanoseconds [66]. Due to these effects, perovskite QDs exhibit high photoluminescence quantum efficiency, narrow emission spectrum width, and the ability to tune precisely the colour of the glow through control of size and composition [61, 62]. This makes perovskites unique structures for creating efficient nanolasers, LEDs, and solar cells [11, 61–63].

Compact nanolasers based on perovskite and semiconductor QDs are a new class of miniature coherent light sources that combine ease of fabrication, a wide tuning range, and high optical characteristics. Perovskite QDs, in particular $CsPbBr_3$, allow the creation of lasers with extremely small dimensions (*e.g.*, 10×10 μm^2), narrow emission linewidth $\cong 0.1$ nm, and low losses due to the use of quasi-continuum-coupled states (quasi-BIC) [67]. Vertical cavity lasers based on $CsPbBr_3$ QDs demonstrate an ultralow generation threshold 0.39 μJ/cm^2, high stability of operation (over 5 hours or $1.8\cdot10$ pulses), and the ability to operate in the femtosecond regime, which is important for portable electronics and optical communications [67, 69]. Nanolasers based on perovskite QDs provide a wide range of wavelength tuning (from blue to near-infrared ones), a narrow emission band (0.1–0.2 nm), and the possibility of flexible 3*D* patterning for integration into miniature photonic chips, displays, sensors, and biomedical devices [56, 67, 70, 71]. An important advantage of these lasers over semiconductor QD lasers is also their high stability to moisture and temperature, especially in composites with SiO or liquid crystal resonators [56, 72]. Recent developments include topological lasers based on $CsPbBr_3$ QDs, which are defect-resistant and provide single-mode generation even with miniaturization [69].

3. THEORETICAL MODEL OF AN OPTICAL NANOLASER ON HEAVY HOLE TRANSITIONS

The optical properties of quasi-0*D* structures consisting of spherical semiconductor (or dielectric) nanocrystals (NCs) (or QDs) of radius $a \cong 1$–10 nm, grown in transparent dielectric (or semiconductor) matrices, are currently being intensively studied [11–18]. Optical and nonlinear optical properties of heterophase nanosystems are determined by the energy spectrum of spatially limited electron–hole pairs (EHP) (or excitons) [11–18]. Quantum size effects have been detected in the energy spectra of electrons and excitons in such quasi-0*D* structures using optical spectroscopy [11–18].

The motion of charge carriers in NC, like in QDs, is limited in three directions. Therefore, the energy spectrum of charge carriers is discrete in NC with linear dimension of the order 1–10 nm [12,

15, 17, 34, 44, 50]. This property can be used to create optical nanolasers or optical computers [37, 44, 50]. In this context, we point out that the size (*i.e.*, radius) a of a QD should be in the range of a few nm in order to provide that the difference, *i.e.*, energy splitting $\Delta E_{e(h)}$, between electron and hole levels are of the order of a few $k_B T_0$ at the room temperature T_0. In Ref. [17], it was discussed theoretically the prospect of using semiconductor NCs for designing nanolasers.

The energy spectrum of an EHP

$$E_{n_e, l_e=0, t_h}(S) = \\ = E_g + \pi^2 n_e^2 S^{-2} Kb + S^{-1}\left(Z_{n_e,0} + P_{n_e,0} + \varepsilon_2/\varepsilon_1\right) + \omega(S, n_e)\left(t_h + 3/2\right), \tag{7}$$

in the quantum state $(n_e l_{e=0}, t_h)$; (n_e, l_e) are the principal and orbital quantum numbers of the electron, and t_h are the principal quantum number of the hole in a spherical NC with permittivity ε_2, submerged in a dielectric matrix with ε_1 such that $\varepsilon_2 >> \varepsilon_1$ was obtained in Ref. [17] within the adiabatic approximation ($m_e << m_h$, where m_e and m_h are the effective masses of an electron and a hole in the NC) using only the first-order perturbation theory in the functions of a spherical-potential well of infinite depth. Here, $t_h = 2n_r + l_h = 0, 1, \ldots$ (n_r is the hole radial quantum number and l_h is the orbital quantum number of a hole), $S = a/a_h$ is the dimensionless radius of the NC, and a_h and E_g—the Bohr radius of the hole and the band gap in an infinite semiconductor with permittivity ε_2, respectively. The energy in Eq. (1) is measured in the units of $Ry = \hbar^2/(2m_h a_h^2)$, the coefficient $K = 0.67$ accounts for the variance of the NCs with respect to the radii a [17], and the parameter $b = m_e/m_h$. The parameters $Z_{n_e,0}$ and $P_{n_e,0}$ were determined in Refs. [17]:

$$Z_{n_e,0} = 2\int_0^1 dx (1 - x^2)^{-1} \sin^2(\pi n_e x), \tag{8}$$

$$P_{n_e,0} = 2Ci(2\pi n_e) - 2\ln(2\pi n_e) - 2\delta + \varepsilon_2/\varepsilon_1 - 1, \tag{9}$$

where $Ci(y)$ is the cosine integral and $d = 0.577$—the Euler constant.

The EHP spectrum (7) was obtained for NCs whose sizes a are limited by the condition

$$a_0 << a_h << a \le a_e, \tag{10}$$

where a_e are the Bohr radius of the electron in an infinite semiconductor with permittivity ε_2, and a_0 is a characteristic length of the order of the interatomic distance. When this condition is satisfied, the polarization interaction of an electron and a hole with the sur-

face of the NC plays a large role in the potential energy of the EHP. The condition (10) also makes it possible to study the motion of an electron and a hole in the NC in the effective-mass approximation.

The last term in the EHP spectrum (7) gives the hole spectrum $\mu_{n_e, l_e=0, t_h}(S)$ in oscillator form [17]:

$$\mu_{n_e, l_e=0, t_h}(S) = P_{n_e,0} S^{-1} + \omega(S, n_e)\left(t_h + 3/2\right), \tag{11}$$

$$\omega(S, n_e) = 2.232\left(1 + (2/3)\pi^2 n_e^2\right)^{1/2} S^{-3/2}, \tag{12}$$

where $\omega(S,n_e)$ is the frequency of the hole-oscillator vibrations, in an adiabatic electronic potential [17]. The second term in Eq. (7) (kinetic energy of the electron), which is due to the purely spatial limitation of the quantization region, makes the main contribution to the EHP spectrum (1) obtained within the adiabatic approximation, and the last two terms, which are associated with the Coulomb and polarization of the electron and the hole with the surface of the NC, appear only as corrections.

Thus, the polarization interaction of an electron and a hole with the surface of a NC, just as the quantization of the charge carriers, contributes to the renormalization of the energy gap (8) of the NCs.

In Ref. [17], interband absorption spectra of CdS NC ($\varepsilon_2 = 9.3$) of sizes varying from 1 to 10 nm dispersed in a transparent dielectric matrix of silicate glass were investigated. The effective masses of electrons and holes in CdS were ($m_e/m_0 = 0.205$) and ($m_h/m_0 = 5$), respectively (*i.e.*, $m_e << m_h$).

In the experiment reported in Refs. [16, 34, 44, 50], an energy structure consisting of an equidistant series of levels was found in the region of transitions to the lower level of dimensional quantization of the electron ($n_e = 1$). The above structure is caused by quantization of the hole energy spectrum in the adiabatic potential of the electron.

From the comparison of formula (6) (for $n_e = 1$) with the experimental dependence of the splitting magnitude of the NC size a obtained in Refs. [17], it follows that, for NC of radii $1.5 \le a \le 3.0$ nm, the splitting $\omega(S, n_e)$ (12) is in good agreement with the experimental data [34, 44, 50] and differs from the latter only slightly ($\le 4\%$) [17].

Based on the presented results, a scheme of operation of a laser developed on the basis of CdS NCs grown in boric–silicate glass matrices was formulated [17] as follow.

1. Pumping: the hole transition from energy level $\mu_{n_e=1, l_e=0, t_h=1}(S)$ (11) to electron state ($n_e = 1, l_e = 0$) (1*s* state) (7) in conduction band with energy

$$\hbar\omega_1(S) = E_g + E_{n_e=1,l_e=0}(S) + \mu_{n_e=1,l_e=0,t_h=1}(S). \quad (13)$$

2. Creation of inverse population on the hole level ($t_h = 0$ by means of electron transition from the energy level $E_{n_e=1,l_{e=0}}(S)$ (1), with spin flip [50], to the hole energy level $\mu_{n_e=1,l_e=0,t_h=1}(S)$ (5). The energy of this transition

$$\hbar\omega_2(S) = E_g + E_{n_e=1,l_e=0}(S) + \mu_{n_e=1,l_e=0,t_h=0}(S). \quad (14)$$

3. Lasing step: transition of the hole in the valence band between equidistant levels $(t_h = 0) \rightarrow (t_h = 1)$ separated by the energy

$$\Delta\omega(S, n_e = 1) = \hbar\omega(S, n_e = 1); \quad (15)$$

for NC of the radius $a = 2$ nm, $\Delta\omega \cong 54$ meV (15) is several times greater than the thermal energy $k_B T$.

Thus, in a nanolaser on CdS NCs, the pumping energy $\hbar\omega_1 \cong 3.12$ eV (7) would correspond to visible light, and lasing at energy $\Delta\omega \cong 54$ meV (9) would occur in the infrared range.

4. APPLICATION OF NANOLASERS IN OPTICAL INTERCONNECTS

Due to their unique properties, nanolasers based on perovskite and semiconductor QDs fined a variety of applications. In each specific application (for example, optical interconnects, photonics, biophotonics), not all general properties of perovskite and semiconductor QDs are used, namely those that are critical to achieving the desired functions and efficiency of the device. Properties such as band gap width, emission wavelength, generation threshold, carrier transfer rate, and moisture stability are not just universal characteristics, but those that are specially selected and optimized for a specific field of application.

Thus, in the field of optical interconnects, nanolasers based on perovskite and semiconductor QDs are used as sources of coherent light for ultrafast data transfer between chips. The most common perovskite QDs used for this purpose are methylammonium lead bromide ($MAPbBr_3$), methylammonium lead iodide ($MAPbI_3$), and caesium lead bromide ($CsPbBr_3$). QDs often have the formula $CsPbX_3$, where X is Cl, Br or I [56, 57, 73, 74]. They are used to create integrated photonic circuits, sensors, spectroscopic systems, and optical computers. High quantum efficiency, a wide emission spectrum, and the ability to tune precisely the wavelength make these materials versatile for such photonic applications [1, 56, 74]. For example, $CsPbBr_3$ perovskite QDs embedded in a two-layer mesoporous silica

matrix demonstrate efficient two-photon excitation and moisture resistance, which allows them to be used in biophotonics and sensors. Such nanolasers are characterized by high optical quality factor, high carrier transfer rate and bright emission even in the near infrared range [56, 73]. Experiments have shown that photoelectrons and holes generated in a perovskite matrix with a significant band gap (of the order of 2.5 eV) are transferred to the QD with an efficiency of up to 80%, where intense light emission occurs [73]. Thus, nanolasers based on perovskite QDs (*e.g.*, $MAPbBr_3$, $CsPbBr_3$, $CsPbX_3$) characterized by a band gap of 1.5–2.3 eV, a radiation wavelength of 520–800 nm, an ultralow generation threshold (up to 1.9 W/cm^2), and a high optical *Q*-factor have the potential for effective integration into optical interconnects and photonic devices [57, 73–76].

5. APPLICATION OF NANOLASERS IN BIOMARKET DETECTION, SENSING AND DIAGNOSTICS

Promising nanolasers for use in biomarker detection, sensing and diagnostics are created based on perovskite QDs with the general formula ABX_3, where *A* is an organic or inorganic cation (*e.g.*, Cs^+, MA^+—methylammonium, FA^+—formamidine), *B* is a metal (usually PbI^+), *X* is a halogen (Cl^-, Br^-, I^-). Typical examples are $CsPbBr_3$, $MAPbBr_3$, and $CsPbI_3$.

The quantum dimensional effect in QDs with sizes of 2–10 nm makes it possible to tune precisely the values of the effective band gap and emission spectra by changing the particle size [12–18, 61, 75, 77]. Perovskite QDs used in nanolasers are characterized by high photoluminescence quantum efficiency (PLQY > 90%), narrow emission bandwidth ($FWHM \cong 15$–30 nm), wide wavelength tuning range (400–800 nm) and low lasing threshold ($I\_th \cong 10$–100 $\mu J/cm^2$) [61, 74, 75, 77], existence of long-lived edge-dimensional electronic states with lifetime $\tau \cong 20$–50 ns [12–18, 61, 77]. Due to high defect tolerance and ease of synthesis, such QDs demonstrate stable luminescence even without additional surface passivation [61, 75]. CdSe, InP-based QDs, as well as perovskite QDs (*e.g.*, $CsPbIX_3$, where $X = Cl$, Br, I) are used for cell biomarkers, protein and DNA sensing, and for the creation of highly sensitive biosensors [74, 77]. In biomedical applications, perovskite QDs are encapsulated in biocompatible shells (*e.g.*, SiO_2, polymers), which ensures stability in aqueous media and minimizes toxicity [61, 75]. Thus, $CsPbBr_3$@SiO QDs are used for high-resolution cell labelling and for sensing metal ions and biomolecules due to changes in luminescence intensity upon interaction with the analyte [61, 74]. In laser biosensors based on perovskite QDs, a generation threshold of < 100 $\mu J/cm^2$ is

achieved that allows them to be used for point sensing of biological objects [77]. Thus, nanolasers based on perovskite QDs (ABX_3, in particular, $CsPbBr_3$, $MAPbBr_3$) and QDs (CdSe, InP, $CsPbBr_3$), which have found application in this field combine high photoluminescence, narrow emission band, low generation threshold and the possibility of biofunctionalization, which makes them ideal for modern biomarkers, sensing and diagnostics [61,74, 75, 77].

6. APPLICATIONS IN QUANTUM AND NEUROMORPHIC TECHNOLOGIES

Nanolasers based on perovskite QDs (ABX_3, *e.g.*, $CsPbBr_3$, $CsPbI_3$) and semiconductor QDs (CdSe, InP, PbS) demonstrate unique physical properties, which makes them promising for quantum and neuromorphic technologies (systems whose architecture and operating principles are similar to the biological brain). The main physical parameters, which give them promise in such applications, are the bandgap widths (from 1.7 to 2.3 eV); photoluminescence quantum efficiency (PLQY) can exceed 90–99% even without additional passivation; emission bandwidth (*FWHM*)—15–30 nm; excited state lifetime—10–100 ns; QD sizes are of 4–12 nm (strong quantum confinement) [11, 12, 15, 17, 34, 44, 50, 61, 77].

For quantum technologies, the important properties are single-photon emission, narrow spectral line, spin control and coherence: for example, $CsPbBr_3$ QDs demonstrate emission coherence up to 80 ps, as well as the possibility of spin control through size and composition [61, 77]. In quantum computing and cryptography, such QDs are used as single-photon sources for quantum communications, as well as for multistimulus optical coding and 3*D* optical memory [61, 74, 77].

In neuromorphic technologies, hybrid structures based on $CsPbBr_3$ QDs/graphene or QDs/carbon nanotubes provide photonic synapses with energy consumption on the order of tens of attojoules, simulation of short- and long-term memory, and associative learning [61]. Promising transistors based on perovskite QDs demonstrate high carrier mobility (up to 10 $cm^2/(V{\cdot}s)$), an extended hysteresis window, and stability under multiple switching [61]. Highly confined $CsPbBr_3$ QDs with dimensions (4–8 nm) are a source of single photons for quantum computing, with high colour purity and stability [77]. Hybrid perovskite/QD structures are used for optical memory, where the information storage time can reach several hours, and recording/erasing is performed by a laser pulse [61, 77]. QDs in photonic neuromorphic sensors provide sensitivity up to 10^{-15} Joules, which allows us to recognize weak signals and simulate synaptic transmission [61].

7. PROSPECTS FOR THE DEVELOPMENT OF LASER-TECHNOLOGY RESEARCH

One of the main problems of theoretical research on nanosystems is the correct description of the interactions of nanoparticles (Coulomb, polarization, exchange, spin–orbit, spin–spin ones) with the interfaces of nanosystems (semiconductor–dielectric–metal) [12–18]. Theoretical modelling of hybrid nanosystems based on perovskite and semiconductor QDs, which takes into account quantum-dimensional effects, allows us to predict the influence of the size, shape and composition of QDs on the effective band gap, emission and absorption spectra that is key to optimizing the optoelectronic properties of materials [12–18, 78, 79]. Studies show that the interaction between nanoparticles localized above the QD surfaces in the perovskite matrix can lead to efficient energy transfer, changes in the emission and absorption spectra (*e.g.*, red and blue shifts) and even to the emergence of quantum effects such as coherence, which opens up prospects for quantum technologies [73, 78]. Hybrid structures of the 'quantum-dot-in-perovskite' type provide high quality interfaces, which contribute to efficient charge transfer and increase the stability and diffusion length of charge carriers [73, 78].

Current trends in the development of laser technologies are focused on environmental requirements, in particular, on the development of lead-free perovskites and QDs to reduce toxicity [12–18, 31, 44, 50, 79, 80]. Hybridization of perovskite QDs allows passivation of the surface, reduction of defect density and increase of charge carrier lifetime, which lowers the threshold of laser generation and increases the stability of the devices [11–17, 78, 81]. Such hybrid systems demonstrate improved crystallinity, increased charge carrier mobility and efficient charge transfer between layers, which contributes to the increase of quantum efficiency and expansion of the emission spectrum from the visible to the near infrared range [12–18, 73, 78, 81]. This opens up new opportunities for the creation of highly efficient, stable and environmentally safe optoelectronic and laser devices of a new generation [78, 79, 80].

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