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NEW POSSIBILITIES FOR USING PEROVSKITES FOR DEFENSE TECHNOLOGIES

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The mini-review discusses the innovative potential of perovskite materials in the military field. Its aim is to analyze the possibilities of these materials for creating advanced technologies, such as night vision systems, target designation, detection of chemical, biological and radiation threats, camouflage of equipment and water purification, as well as to identify key challenges and prospects for their implementation. The unique optoelectronic properties of perovskites, such as high sensitivity to weak light, wide spectral range and flexibility of integration, are considered, which make them suitable for portable devices for operation in extreme conditions. The review covers the analysis of the structural features of perovskites and their applications: sensors provide effective threat detection with high accuracy, lasers offer precise guidance, and cloaking coatings mimic background light to protect equipment. Photocatalytic systems solve the problem of water purification in the field. At the same time, limitations are noted, such as instability in humidity, lead toxicity, short charge life and heating, which require the development of protective coatings, lead-free analogues and cooling systems for stable operation of devices. Integration with drones increases mobility, but scaling up production and environmental aspects require further improvements.

This mini-review examines perovskite materials (containing quantum dots), which are currently a key area of development for military applications, due to their unique optoelectronic properties. These optoelectronic properties enable efficient operation in low-light conditions, allowing for object recognition in the dark, as well as demonstrating high sensitivity to external influences such as gases or radiation, and the ability to function in extreme conditions.

Perovskite materials are currently becoming a key direction in the development of technologies for military purposes, distinguished by unique optoelectronic properties that ensure effective operation in low light conditions, allowing to recognize objects in the dark, as well as demonstrating high sensitivity to external influences such as gases or radiation, and the ability to function in extreme conditions. These materials attract attention due to their ability to control emission, high stability and flexibility in integration with various systems, which makes them promising for cloaking equipment, target designation, monitoring of chemical, biological and radiation threats, as well as providing clean water in the field. Compounds such as $CsPbX_3$ (where X = Cl, Br, I) and methylammonium analogues ($MAPbX_3$) show exceptional potential for optoelectronic devices such as lasers and sensors, as well as for photocatalytic and photoelectrocatalytic nano systems.

The problem of water pollution by organic and bioorganic pollutants poses a serious threat in military operations, where access to clean water is crucial and traditional purification methods are often ineffective [2]. In this context, perovskites appear as an innovative alternative due to their photocatalytic and photoelectrocatalytic properties.

One of the main problems of theoretical studies of nanosystems, which contain quantum dots, is the correct description of the interactions of nanoparticles (Coulomb, polarization, exchange, spin-orbit, spin-spin) with the interfaces of nanosystems (semiconductor-dielectric-

metal). Theoretical modeling of hybrid nanosystems based on perovskite and semiconductor quantum dots, which takes into account quantum dimensional effects, allows predicting the influence of the size, shape and composition of quantum dots on the effective band gap, emission and absorption spectra, which is key to optimizing the optoelectronic properties of materials. Studies show that the interaction between nanoparticles localized above the QD surfaces in the perovskite matrix can lead to effective energy transfer, changes in the emission and absorption spectra and even to the emergence of quantum effects, such as coherence, which opens up prospects for quantum technologies. Hybrid structures of the quantum-dot-in-perovskite type provide high interface quality, which contributes to efficient charge transfer and increases the stability and diffusion length of charge carriers.

Keywords: *perovskite materials, optoelectronic properties, technologies for military purposes, photocatalytic and photoelectrocatalytic properties, quantum dots, nano systems.*

INTRODUCTION

Perovskite materials (containing quantum dots (QDs)), are currently becoming a key direction in the development of technologies for military purposes, distinguished by unique optoelectronic properties that ensure effective operation in low light conditions, allowing to recognize objects in the dark, as well as demonstrating high sensitivity to external influences such as gases or radiation, and the ability to function in extreme conditions [1]. As emphasized in [2], these materials attract attention due to their ability to control emission, high stability and flexibility in integration with various systems, which makes them promising for cloaking equipment, target designation, monitoring of chemical, biological and radiation threats, as well as providing clean water in the field. Compounds such as $CsPbX_3$ (where X = Cl, Br, I) and methylammonium analogues ($MAPbX_3$) show exceptional potential for optoelectronic devices such as lasers and sensors, as well as for photocatalytic and photoelectrocatalytic systems [3].

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One of the main problems of theoretical studies of nanosystems is the correct description of the interactions of nanoparticles (Coulomb, polarization, exchange, spin-orbit, spin-spin) with the interfaces of nanosystems (semiconductor-dielectric-metal) [5–20]. Theoretical modeling of hybrid nanosystems based on perovskite and semiconductor quantum dots, which takes into account quantum dimensional effects, allows predicting the influence of the size, shape and composition of quantum dots on the effective band gap, emission and absorption spectra, which is key to optimizing the optoelectronic properties of materials [5–20]. Studies show that the interaction between nanoparticles localized above the QD surfaces in the perovskite matrix can lead to effective energy transfer, changes in the emission and absorption spectra and even to the emergence of quantum effects, such as coherence, which opens up prospects for quantum technologies. Hybrid structures of the quantum-dot-in-perovskite type provide high interface quality, which contributes to efficient charge transfer and increases the stability and diffusion length of charge carriers [5–20].

The aim of this work is to analyze the potential of perovskites in these areas, based on their structural features and practical applications.

OPTICAL ABSORPTION ON ELECTRON STATES OF PEROVSKITE NANOCRYSTALS

Electron and exciton states with high binding energy and resistant to thermally-driven dissociation play an important role in many perspectives of perovskite nanostructured materials.

In recent years, growing interest in the electron and exciton states adjustment for controlling exciton transport processes, transitions on the heterointerface of the excitonic transistor, photoconversion, nanostructures photoluminescence, and optical properties of dielectric and semiconductor nanostructures [17, 21–26]. These devices include traps, lattices, conveyers, and ramps, which are used for studying basic properties of cold electron states, as well as electron transistors, routers, and photon storage devices, which hold the potential for creating exciton signal processing devices and exciton and electron circuits [17, 21–26].

Perovskites containing colloidal QDs $FAPbBr_3$ are promising newcomer optoelectronic materials. These nanomaterials have been used as highly absorbent nanolayers in solar cells. These newcomer optoelectronic materials have attracted increased attention because of their high energy conversion efficiency, reaching about 20% [6].

The nature of strong absorption in perovskites containing QDs $FAPbBr_3$ is not clear. Optical absorption of perovskites containing QDs $FAPbBr_3$ is poorly studied. Therefore, in Refs. [14–20], in the framework of the dipole approximation, the intraband optical absorption due to transitions between one-particle electron quantum-confined states emerging in the QDs $FAPbBr_3$ are investigated. It is shown that in a nanosystem interacting with low-intensity radiation, the optical absorption QD, as well as the polarizability QD, which reaches a maximum at the resonance frequency of the transition, assume giant values (by seven orders of magnitude) higher than the values of these quantities at other frequencies.

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STRUCTURE OF PEROVSKITES

Perovskites belong to a class of materials with the general formula ABX_3, where A is a cation (cesium or methylammonium), B is a metal (lead, iron), and X is an anion (iodine or oxygen), which can have different dimensions (0D, 1D, 2D, 3D) depending on the crystal lattice structure [27]. 0D perovskites, unlike their higher analogues, are characterized by isolated octahedral units, which provides unique optical properties, such as a wide Stokes shift and high stability [28]. These characteristics are due to strong electron-phonon coupling and self-trapped excitons. Hybrid Sn-Pb perovskites passivated with phenethylammonium iodide (PEAI) provide a wide spectral range (300–1050 nm) and low dark current [29]. $CsPbCl_3$ perovskites with four-mask synthesis technique have high selectivity to UV light [30]. The ABO_3 type structure is characterized by a crystal lattice, where the photocatalytic and photoelectrocatalytic properties depend on the electronic structure of the materials [2].

PROSPECTS FOR THE USE OF PEROVSKITES IN NIGHT VISION DEVICES

Today, perovskite materials are shaping a new direction in the development of night vision technologies due to their unique properties that ensure effective operation in low-light conditions – an important factor for camouflage and target detection during military operations. They are distinguished by high sensitivity, allowing them to recognize objects in the dark. For

example, a sensor as shown in [1] based on $FA_{0.8}Cs_{0.2}Pb_{0.5}Sn_{0.5}I_3$ achieves a sensitivity of 56.35 A/W and captures light at an intensity of 0.01 mW/cm², which is equivalent to moonlight, while a camera [31] developed on the basis of PFL (Perovskite Full Layer) and PPL (Perovskite Partial Layer) perovskite layers with the addition of halogens (I, Br, Cl) has a sensitivity of 22.6 mA/W at 650 nm and recognizes signals at the level of 0.3 μW/cm², surpassing traditional RGB detectors with a threshold of 0.7 μW/cm². Such indicators are key for detecting camouflaged objects, drones or enemy soldiers in complete darkness. The fast response time – from 2.75 ns as shown in [1] to 350 ps in [32] and down to microseconds [31] – ensures instantaneous response, which is critical for radars, optical sights, and guidance systems where delay can cost the target. The cutoff frequency of 3 GHz [32] and 12.7 MHz [33], which indicates the maximum frequency of signal processing without distortion, provides high analysis speed, for example, for tracking enemy drones or vehicles, where delay in information about the monitored object is critical.

Based photodetectors and sensors is achieved by the absence of an external electrical bias [33, 34], an additional voltage that is usually used in traditional devices for activation, which reduces power consumption and simplifies the design. This effect is enhanced by a linear dynamic range of 70.4 dB [34], which reflects the ability of the device to recognize different levels of illumination, and a zero dark current of up to 10–50 nA/cm² [33], the current that occurs in photosensitive elements in the dark, which is minimized here, which reduces noise and increases accuracy in low-light conditions. Such characteristics make it possible to create devices that are lightweight and suitable for portable use, unlike traditional IR detectors that require additional power supply. The wide spectral range from UV-VIS to NIR (400–1100 nm) in sensors [1, 35], such as retiniform sensors and photodetectors based on gradient perovskite crystals, and the thermal imaging range of 3 – 5 μm in photodetectors [36] with a detection capability of 10^8 Jones allow them to “see” through smoke, leaves, or camouflage coatings, surpassing the limited range of silicon sensors (400–1000 nm). It should be noted that scalable production—that is, the ability to stably synthesize perovskite materials in significant volumes, exceeding 10 grams per cycle [36] – is an important step for the mass production of devices such as photodetectors or sensors. This threshold (10 g) indicates a transition from laboratory conditions, where they usually work with milligrams, to an industrial scale, which allows to meet the needs of the army in thousands of units. The flexible design of photodetectors and sensors [32], in particular flexible sensor arrays, contributes to the rapid deployment of production, since elastic and lightweight materials easily adapt to different shapes and sizes, simplify integration into military equipment and withstand mechanical loads. This approach outperforms slow and expensive traditional methods, such as photolithography for silicon sensors, providing savings in time and resources.

Despite these advantages, perovskites have limitations for military use. The stability of materials, particularly photodetectors [1, 32], when exposed to moisture or mechanical damage is a weak point compared to silicon sensors that can withstand extreme conditions. The need to optimize pixels <10 μm [1] and the decrease in stability in humidity can cause material degradation in the field. Noise, particularly 1/f noise in photodetectors [35, 36] with a noise equivalent power of ≈70 $pW/Hz^{1/2}$, and limited bandwidth (up to 46.4 kHz [35] and 40 Hz [36]) make it difficult to process images of moving targets, while the high cutoff frequency (~3 GHz [32] and 12.7 MHz [33]) theoretically supports fast processing, but noise interference reduces its efficiency. The need for thermal management for perovskite LEDs [37], which serve as light sources in some systems, involves temperature control for stable operation at currents of 2800 mA/cm² and luminances of 226 $W \cdot sr^{-1} \cdot m^{-2}$, which makes their use more difficult compared to passive IR detectors without active cooling. The low resolution of RGB detectors <5.4 μW/cm² [31] can degrade the clarity of images of small objects in the dark, although the overall sensitivity of perovskites to low light exceeds that of traditional devices.

THE POTENTIAL OF PEROVSKITE LASERS IN MILITARY TARGETING SYSTEMS

Perovskite materials show exceptional potential for the development of lasers and targeting systems for military applications. Their key properties – high photoluminescence quantum yield (PLQY, up to 90%) [38], indicating efficient conversion of excitation energy into radiation, low lasing thresholds (from 1.37 to 81.8 μJ/cm²) [3, 39], providing energy savings, a wide spectral range (420–778 nm) [3], allowing adaptation to various conditions, and ease of fabrication through solution processing techniques – make them attractive for modern defense technologies. Current research reflects the evolution of these materials from experimental prototypes to practical solutions, such as laser rangefinders for determining the distance to the target, high-precision sights for small arms, and guidance systems for unmanned aerial vehicles, which require compactness and efficiency.

Perovskite lasers are characterized by compactness and low power consumption, which is critical for portable military devices such as hand-held target designators or drone modules. The topological laser, an innovative design that uses boundary states between photonic crystals with different topological phases to create resonators that are resistant to manufacturing defects [40], based on $CsPbBr_3$ provides single-mode emission in the green spectrum (519–532 nm) with a threshold of 6.8 μJ/cm² and a divergence of 4.6°, which guarantees high accuracy of target designation in daylight conditions due to a sharp focus of the beam. Manufacturing defects are various defects that occur during the manufacturing process of optical devices, such as surface irregularities caused by uneven material deposition (e.g., by spin coating or deposition), cracks caused by mechanical stresses or thermal expansion during processing, inhomogeneities in layer thickness due to inaccuracies in the technological processes, and impurities introduced into the material due to contamination of raw materials or equipment. They are the result of imperfections in manufacturing methods such as casting, printing, or vapor deposition, and can significantly degrade optical performance, for example by scattering light or reducing the efficiency of the resonator. Topological design helps to compensate for these defects while maintaining radiation stability.

Microcavity arrays – structures with numerous small resonators created by inkjet printing [39] – have achieved a threshold of 1.37 μJ/cm² at 528 nm with a flexibility of 0.40 mm^{-1} and a density of 635 dpi, allowing their integration into mobile platforms such as drones where lightness and adaptability are required. Vertical cavity surface-emitting lasers (VCSELs) – vertical cavity surface-emitting lasers that provide uniform emission [41] – based on $CH_3NH_3PbI_3$ with a threshold of 7.6 μJ/cm² and a divergence of <3° offer high beam sharpness, ideal for targeting in limited visibility conditions. So-called random lasers – devices where resonance occurs due to random scattering of light in an inhomogeneous medium, such as an optical fiber [42], with a threshold of 32.3 μJ/cm² and a grain contrast of 0.05 provide a grain-free image that optimizes the detection of targets in fog or smoke.

The tunability of the spectrum and the ability to change the wavelength of the emission by changing the halide composition, for example, $CsPbCl_xBr_{3-x}$ (420–530 nm) [3], allows lasers to be adapted to tasks from daytime guidance to infrared systems for night use, expanding their functionality in various combat scenarios. Stability, expressed in the possibility of delivering more than 1.8×10^6 pulses for chiral microlasers – devices with helical symmetry that affects the polarization of light, providing unique optical properties [3] – guarantees reliability in long-term operations, such as continuous artillery guidance. Integration with VCSEL [40] and fiber systems [42] opens up possibilities for autonomous guidance systems with high accuracy, for example, for missile trajectory correction or laser target illumination for guided munitions.

One of the key advantages of these perovskite devices is their low generation threshold (1.37–81.8 μJ/cm², [3, 39]), which significantly reduces power consumption compared to traditional II–VI/III–V lasers [36], enabling long-term battery operation in the field. Inkjet

printing [17] and topological design [40] technologies simplify mass production, avoiding expensive methods such as electron beam lithography, which reduces costs and speeds up the development of these devices. The flexibility of substrates, such as PDMS polymers, allows for the creation of devices of various shapes and sizes, adapted to individual needs, such as integration into armored vehicles or individual equipment. Optimization of crystallization with binary solvents (DMSO: NMP) increases PLQY and carrier lifetime (up to 29.28 ns [39]), which ensures durability in harsh climatic conditions such as humidity or high temperature. Annealing and printing technologies [43] improve crystal morphology, reducing defects and facilitating large-scale production, which is critical for military needs.

However, perovskite lasers face significant challenges in field applications. Instability to moisture, heat, and UV radiation causes photodegradation [41], where nanosecond pumping degrades thermal stability by heating the active medium, potentially leading to device failure during combat use. The toxicity of lead in $CsPbX_3$ [39, 40] poses environmental and safety risks to soldiers and the environment, requiring the development of encapsulation technologies or lead-free alternatives such as $CsSnX_3$. The low thermal conductivity makes continuous pumping difficult (thresholds up to 3.8 kW/cm² at 77 K [3]), which exceeds optical pumping, limiting the duration of operation in intensive modes. The lack of reliable electrical pumping [44, 45] hinders the transition to practical devices, as optical pumping is less convenient in combat conditions. The problems of Joule heating and Auger recombination [46], which lead to energy loss at high voltages, as well as the short lifetime of optical amplification, require interface engineering [47] to improve efficiency. Joule heating occurs due to heat loss when an electric current passes through the material, causing a local temperature increase, leading to degradation of the perovskite structure and reducing its optical properties, especially during long-term pumping. Auger recombination is a process in which the energy of excited charge carriers is transferred to another carrier instead of emitting a photon, leading to unwanted loss of light signal and increasing the generation threshold, especially at high current densities. The short lifetime of optical amplification, due to rapid energy dissipation through defects or non-radiative recombination, limits the duration of effective laser radiation. Creating interfaces, such as adding protective layers or optimizing the boundaries between materials, can reduce these effects, improving heat dissipation and stabilizing charge carriers, which is key to practical use in combat systems.

POSSIBILITIES OF USING PEROVSKITES AS SENSORS OF CHEMICAL, BIOLOGICAL COMPOUNDS AND RADIATION EXPOSURE IN A COMBAT ZONE CHEMICAL THREATS

Devices equipped with perovskite sensors are capable of detecting hazardous chemicals, such as toxic gases (e.g., nitrogen dioxide NO_2, sulfur dioxide SO_2, or hydrogen sulfide H_2S) and volatile organic compounds (VOCs), which can indicate the presence of chemical weapons or explosives. One example, using the oxide perovskite $LaFeO_3$ as a sensor, with gold (Au) and chlorine (Cl) added to enhance its properties, demonstrates the detection of ethanol with a limit of detection (LOD) of 88 parts per billion (ppb) at an operating temperature of 120°C [48]. This means that the sensor can detect very small amounts of ethanol, a substance that is sometimes present in mixtures with VOCs on the battlefield. The gold helps the sensor better recognize the target gas among others, and the chlorine promotes the adsorption of molecules to the surface, which facilitates the analysis of air in conditions where mixed gases create interference.

Another example is the porous $PrFeO_3$ nanofibers produced by the electrospinning method, which detect acetone with a LOD of 141.3 ppb at an operating temperature of 180°C [48]. Their porous, sponge-like structure increases the sorption surface area for gases, which allows for the effective detection of acetone, a compound present in traces of explosives. These fibers can withstand up to 1000 detection cycles, which indicates their durability, but the high

operating temperature (180°C) requires an additional power source, which may complicate their use in the field. Another perovskite-based sensor, Ag-$LaFeO_3$, where silver is added to increase sensitivity, selectively responds to xylene with a LOD of 10 ppm at an operating temperature of 125°C and maintains its operational efficiency even at humidity levels up to 70% [48]. Silver acts as a catalyst, improving the bond with xylene, making this sensor suitable for operation in rainy or humid operating conditions.

For the detection of toxic gases such as SO_2, the perovskite $LaSmFeO_3$ provides an LOD of 0.017 ppm at room operating temperature [48]. This extremely low sensitivity threshold allows the detection of sulfur dioxide gases, also associated with chemical weapons, without additional heating, which simplifies the design of the device. In contrast, the $LaFeO_3$ sensor detects hydrogen sulfide (H_2S) with an LOD of 4 ppm at temperatures of 150–300°C, using the principle of the change in electrical resistance that occurs when H_2S molecules are adsorbed on the surface [48]. This wide temperature range allows the sensor to be adapted to various conditions, but high temperatures can complicate the creation of portable devices, as an additional heating element is required. A single-component sensor on The $MAPbI_3$ perovskite sensor exhibits a response to ammonia (NH_3) at 30 ppm with a response time of 8 seconds [49]. This is because ammonia changes the conductivity of the sensor, allowing it to be rapidly detected as a possible marker for sarin, a chemical weapon. This speed is critical for responding to enemy attacks in real time.

Nanohybrids combining graphene with $Cs_3Cu_2Br_5$ perovskite show high sensitivity to dimethylmethylphosphonate (DMMP), a compound that also mimics sarin, with a LOD of 305 ppb and a limit of quantification (LOQ) of 1019 ppb [50, 51]. These sensors are fabricated by a hot solution injection method, which results in the formation of nanocrystals with a size of less than 10 nm, providing a large surface area for contact with gases. Their sensitivity is 4 times higher than that of sensors based on $Cs_2AgBiBr_6$ perovskite and 12 times higher than that of pure graphene [50], due to the synergistic cooperation of the two components of the structure: graphene conducts electricity and perovskite adsorbs DMMP. The sensor returns to its initial active state after 300 seconds of exposure at a pumped air flow of 100 ml/min, which allows it to be used repeatedly [50]. The Cs_2SnBr_6 perovskite in the sensor is capable of recognizing diethylcyanophosphonate (DECPF, as an imitation of VX war gas) at 20–25°C with an LOD in the range of 600 ppb – 2.1 ppm [51], but aggregation of nanocrystals and oxidation in air reduce the stability of this sensor, so protective layers such as SiO_2 are required for its continuous operation [51]. Also, the sensitivity of these sensors is reduced by 15–20% due to humidity in the air, which requires additional activated carbon filters [50, 51].

Doping of $LaFeO_3$ perovskite with Y ions increases its sensitivity to ethanol to LOD 50 ppb, by creating active sites for adsorption [48], and $ErFeO_3$ nanofibers achieve LOD 35 ppb for ethylene glycol detection, using a large surface area to detect traces of explosives components [27]. The $FASnI_3/SnO_2$ composite provides LOD 65 ppb for formaldehyde (HCHO) with a response time of 10 seconds due to the SnO_2 improving conductivity [49]. Doping of A-sites (sites where A cations are located), e.g. Sr^{2+} in $LaCoO_3$, creates oxygen vacancies that activate reactions with nitrites (LOD 0.5 μM), associated with chemical weapons [52]. However, the high temperature (up to 650°C for NO_2) is the operating temperature required for optimal sensor performance, and instability in humid conditions makes long-term operation difficult [48]. Scaling up the synthesis to industrial production levels with perovskite cooling at 1.5 K/day [53] could reduce costs by gradually lowering the temperature for better crystallization, but this requires automated systems to control the process, and this is especially relevant for sensor manufacturers seeking to reduce the cost of mass production.

BIOLOGICAL THREATS: DETECTION OF BIOMARKERS AND PATHOGENS

Perovskite sensors are also used to detect biological threats, such as pathogens or biomarkers of injury. For example, a $CsPbBr_3$ sensor detects Cu^{2+} ions with a LOD of 0.1 nM and Hg^{2+} ions with a LOD of 0.124 nM due to luminescence quenching, and trypsin with a LOD of 0.1 μg/mL in PMMA composites [48]. PMMA (polymethyl methacrylate) is a plastic that strengthens the perovskite, allowing it to stably immobilize trypsin, an enzyme that can signal biological agents. Cu^{2+} and Hg^{2+} attenuate the luminescence of the sensor, allowing these toxic ions to be accurately detected. The perovskite-based Sr_2PdO_3 sensor detects glucose with a LOD of 0.202 μM and p-phenylenediamine with a LOD of 0.17 μM in a neutral medium (pH 7) using an electrochemical mechanism: Pd^{2+} promotes the oxidation of these compounds, generating an electrical signal [48]. This is useful for monitoring glucose as an indicator of stress or fatigue in soldiers, helping to assess their condition, particularly through blood or sweat analysis, where glucose concentration can reflect physical condition.

Flexible photodetector on The $Cs_{0.1}(MA_{0.17}FA_{0.83})_{0.9}Pb(I_{1-x}Br_x)_3$ perovskite in a tubular form recognizes CdTe quantum dots with an LOD of 0.43–0.85 nm for wavelengths of 545, 625, and 730 nm with a deviation of less than 10% [54]. The tubular design collects light from all sides with an efficiency of 90%, in contrast to flat sensors (30–40%), which allows for the simultaneous analysis of multiple biomarkers, for example, for infection diagnosis. The photoelectric response of 21.5 μA at 530 nm, due to the gradient zones that absorb light better, allows for accurate concentration determination, which is critical for rapid assessment of the condition in the field. CdTe quantum dots are provided as model objects that mimic fluorescent biomarkers to test the sensor's sensitivity to various signals generated by the detection of biological agents, although they are not themselves target substances for analysis.

A $CsPbBr_2I$ microfluidic chip sensor (500×500 μm channel) detects glucose (3.9–11.1 mM) and lactate (0.5–2.2 mM) with a LOD of ~23 nM in liquid samples such as blood or sweat using light-induced polarization, which creates a potential of up to 0.65 V at 6.25 mW/cm² [55]. This allows the sensor to operate without batteries, which is important for portable devices in places where electricity is not available. This approach helps detect biomarkers of fatigue or injury in soldiers, as well as assess the effects of biological agents such as anthrax, a bacterial infection caused by Bacillus anthracis that can be used as a biological weapon in war zones.

$SrTiO_3$@RGO nanosensors achieve a sensitivity of 9.11 $\mu A/\mu M^{-1}\cdot cm^{-2}$ for tryptophan, and Au on $SrPdO_3$ composites achieve a sensitivity of 9.11 $\mu A/\mu M^{-1}\cdot cm^{-2}$ for glucose at pH 7, where gold catalyzes the oxidation of glucose to gluconic acid, generating an electrical signal) [52] Nanocubes are a form of perovskite material used to enhance sensor efficiency, and their inclusion in the analysis is justified by their role in improving conductivity. These sensors, like Sr_2PdO_3, help analyze glucose as a biomarker of stress, providing accurate data for medical monitoring. Integration of sensors with drones for biomonitoring allows for real-time detection of anthrax or other biological threats [52, 53]. However, the toxicity of lead and its instability in water (>50% humidity) hinder the use of perovskite sensors in the field, especially in rainy regions [48]. Despite the instability in liquids, glucose and other components have been studied under controlled conditions using sealed microfluidic chips that protect the sensor from direct contact with water, preserving its functionality.

RADIATION THREATS: X-RAY AND GAMMA DETECTORS

Perovskites have been shown to be effective for radiation monitoring. A perovskite $(HIS)BiI_5$ sensor achieves a sensitivity of 1230 μC Gy/cm³ air and a LOD of 36 nGy/s air at 50 V (this is the operating voltage applied to the detector to ensure its sensitivity), absorbing 97% of X-ray photons at 50 keV (a measure of the material's ability to capture X-rays, due to the N–H···I hydrogen bonds that hold the perovskite crystal structure) [53]. The C bonds stabilize the material, allowing it to detect low doses of radiation from radioactive materials in cargo, for

example during border inspections, where the sensor can identify even weak sources such as uranium or caesium isotopes. The perovskite $FAPbI_3$, synthesized from γ-valerolactone (an environmentally friendly solvent) at temperatures up to 90°C with subsequent annealing at 150°C, exhibits a sensitivity of 2.16×10^6 μC Gy^{-1} cm^{-2} and an LOD of 2 nGy/s, which enables the detection of small objects, such as peanut seeds, at 12 nGy/s (an indicator that demonstrates the ability of the sensor to distinguish small details under the influence of radiation) [56]. The low production temperature and environmentally friendly solvent reduce the harmfulness of the process, and the high sensitivity of the sensor is useful for scanning in conflict zones, for example, to detect radioactive waste in.

The vacuum-deposited $CsPbI_2Br$ perovskite provides a sensitivity of 1.2 C Gy^{-1} cm^{-3} and a LOD of 25.69 nGy/s, withstanding 3000 X-ray images with a loss of 3.6% over 10 months due to smooth 1 μm-thick layers [57]. The high charge carrier mobility (18.804 cm^2 s^{-1} V^{-1}) helps to efficiently collect charge, which is beneficial for long-term use. The MDABCO-$CsBr^3$ perovskite achieves a sensitivity of 4124 μC Gy^{-1} cm^{-2} and a LOD of 0.45 μGy/s, remaining stable at 60% humidity for 90 days due to a migration energy of 828 meV (this energy, which hinders the movement of ions, keeps the sensor stable, not more sensitive) [58]. Hydrogen bonds reduce this motion, ensuring reliability. Hybrid detectors of $MAPbI_3$ and $Cs_2AgBiBr_6$ achieve μτ $>10^{-4}$ cm^2/V (a measure of charge mobility and lifetime) and a resolution of 12.6-line pairs per millimeter (lp/mm) (these are measures of charge collection efficiency and image sharpness, which are critical for radiation detection, and are cheaper than the traditional CdTe – cadmium telluride detector used as the standard) [59]. The low cost (within 10–20% of CdTe) and high resolution are useful for mass production of portable radiation scanners.

The perovskite $LaFeO_3$ in microspheres increases the porosity of the material, which improves gamma-ray capture [52], allowing for compact sensors for radiation detection. Stability after 180 days of operation [53] and low dark current drift (2.3 picoamperes [56]) (this is residual electrical noise in the absence of light) make the sensors suitable for scanning cargo for radioactive materials.

THE USE OF PEROVSKITES TO DISGUISE MILITARY EQUIPMENT FROM DETECTION. APPLICATIONS IN STEALTH TECHNOLOGIES

The application of perovskites for military camouflage covers several key areas. As shown in [29], hybrid Sn–Pb photodetectors integrated into an IR-emission frequency boosting system can convert near-infrared light into visible light, masking the thermal signatures of tanks or aircraft. The stability of these devices (over 240 hours) and low noise (5.36×10^{-13} A $Hz^{-1/2}$) make them suitable for long-term use in combat conditions.

[30] describes $CsPbCl_3$ sensor arrays for ultraviolet detection with a resolution exceeding previous developments. These arrays can be used to create protective screens that reflect or scatter UV signals, protecting equipment from drones and satellites. Stability up to 80% humidity and temperatures of 450°C ensures their reliability [30].

0D perovskites, due to their optical properties [27, 28], offer broadband emission (100–350 nm Stokes shift) and PL QY up to 100%, which allows to simulate natural background light. For example, Cs_4PbBr_6 with tunable emission can be integrated into stealth coatings for IR scattering [28, 60] and the synthesis methods provide stability and photostability, which is critical for camouflage of mobile equipment.

THE USE OF PEROVSKITES FOR WATER PURIFICATION FROM ORGANIC AND BIOORGANIC POLLUTANTS FOR MILITARY PURPOSES MECHANISMS OF CATALYTIC WATER PURIFICATION USING PEROVSKITES

Catalytic water purification using perovskites is based on complex physicochemical processes that depend on the electronic structure of the materials, environmental conditions, and

the nature of the contaminants. The main mechanism is photocatalysis, which is initiated by the absorption of photons of solar or artificial light with an energy exceeding the band gap (Eg) of perovskites, which usually varies within 1.2–3.0 eV [61]. When a photon with the appropriate energy (hv > Eg) is absorbed, an electron moves from the valence band (VB) to the conduction band (CB), forming an electron-hole pair (e^-/h^+). For perovskites such as $LaFeO_3$ or $SrTiO_3$, this process can be described by the equation: $LaFeO_3 + hv \rightarrow e^- + h^+$ [62]. The holes in the valence band (h^+) have a strong oxidation potential (up to 2.7 V vs. NHE) and react with water molecules or hydroxyl ions to form hydroxyl radicals (•OH) according to the reaction: $h^+ + H_2O \rightarrow •OH + H^+$. The electrons in the conduction band, on the other hand, participate in reduction reactions, reducing dissolved oxygen to superoxide radicals ($•O_2^-$) according to the reaction: $e^- + O_2 \rightarrow •O_2^-$ [4]. Ts and reactive oxygen species (ROS) are key degradation agents, attacking organic molecules such as methylene blue or tetracycline, breaking their chemical bonds (e.g., CC, CN) and converting them to simpler products such as CO_2, H_2O, and NO_3^-. It has been experimentally confirmed that the concentration of NO_3^- reaches 5.2 ppm at an initial pollutant concentration of 40 ppm, which indicates complete mineralization [4].

Photoelectrocatalytic mechanism (PEC) extends the possibilities of photocatalysis by integrating electrochemical oxidation, which significantly reduces the recombination of electron-hole pairs due to an external electric field. In heterostructures such as $BiFeO_3/TiO_2$, electrons are directed to the cathode, while holes remain at the anode, where they participate in oxidation reactions [2]. For example, the $BiFeO_3/TiO_2$ system achieves 100% degradation of rhodamine B in 150 minutes at a voltage of 0.6 V due to the increased charge separation [2]. In more complex systems such as flexible POF-ITO/ABI optoelectrodes, light with a wavelength of 395 nm (2.18 W) excites electrons from the valence band (VB, ~5.5 eV) to the conduction band (CB, ~4.0 eV), generating holes (hVB^+) [63]. The ROS generation reactions include: $hVB^+ + H_2O \rightarrow •OH + H^+$ and $eCB^- + O_2 \rightarrow •O_2^-$, where the addition of a potential of 1.2 V (relative to Ag/AgCl) favors electron migration, reducing recombination. This increases the index quantum efficiency (IPCE) to 21% in the range of 340–550 nm and provides >90% removal of benzoate ion in 60 min due to a 6000% increase in electrode surface area [63].

Persulfate activation (PMS or PDS) is another important mechanism based on the generation of sulfate radicals ($SO_4•^-$) with an oxidation potential of 2.5–3.1 V, which is higher than that of •OH (1.8–2.7 V) [64]. Perovskites such as La_2CuO_4 catalyze the decomposition of PMS according to the reaction: $S_2O_8^{2-} + e^- \rightarrow SO_4•^- + SO_4^{2-}$, achieving 97% removal of M. aeruginosa in 20 min at doses and 300 mg/L catalyst and 0.24 mM PMS with a rate constant of 0.1304 min^{-1} [64]. Oxygen vacancies (OVs) in perovskites, such as $LaFeO_3$, play a critical role, acting as electron capture centers and increasing the quantum efficiency to 0.85 [65]. In the presence of light, the reaction $S_2O_8^{2-} + hv \rightarrow 2SO_4•^-$ is enhanced, and OVs stabilize the intermediates, which increases the efficiency of bisphenol A degradation by 35% in microwave systems [65]. The synergistic effect of the Fe^{3+}/Fe^{2+} cycle in $LaFeO_3$ further enhances the generation of radicals, reaching a rate constant of 0.0218 min^{-1} for tetracycline [62].

Electrochemical advanced oxidation processes (AOPs) use perovskites such as $CaCu_3Ti_4O_{12}$ (CCTO) as anode materials with high dielectric constant [65]. Direct oxidation occurs through electron transfer from the pollutant (e.g. paracetamol) to the anode surface at pH3 and a current density of 9.5 mA/cm^2, achieving 90% removal in 240 min in 0.1 M Na_2SO_4 [65]. Indirect oxidation is based on activation of PMS by heat (>60°C), UV or metals (Co^{2+}), where CCTO enhances the decomposition to form $SO_4•^-$ according to the reaction: $S_2O_8^{2-} + e^- \rightarrow SO_4•^- + SO_4^{2-}$. The Jahn–Teller distortion of Cu^{2+} in CCTO optimizes charge transfer, reducing the oxidation overvoltage.

The kinetics of these processes are determined by external factors. Optimal pH values (7–11) favor the formation of •OH, reaching 90% degradation of tetracycline at pH 10 [2]. High concentration of impurities (>20 mg/L) reduces light penetration, reducing the efficiency to 47%,

requiring pre-filtration [2]. Optimal catalyst dosage (0.05–0.15 g) provides maximum performance, while excessive loading (>0.15 g) leads to particle aggregation and a drop in degradation to 50% [2]. Temperature range from -20°C to 60°C maintains the stability of perovskites, which is important for extreme conditions [2, 65].

Regarding the spectrum of action, perovskites effectively decompose organic compounds such as dyes (methyl orange, Congo red), pesticides, petroleum products, pharmaceutical residues (paracetamol, tetracycline) and bioorganic toxins (microcystin-LR, azofloxin) [2, 4, 62–65]. The mechanism is based on the oxidation of functional groups (C=C, CN, -OH), which is characteristic of organic molecules. Bioorganic contaminants, such as M. aeruginosa cells, are destroyed by membrane damage and degradation of internal organic components by ROS [64].

As for inorganic compounds such as heavy metals (Pb^{2+}, Cd^{2+}) or nitrates (NO_3^-), perovskites are not effective for their purification. This is explained by the lack of reactive centers capable of oxidizing or reducing stable inorganic ions that do not contain organic functional groups. Although some perovskites, such as $BiFeO_3$, have magnetic properties that facilitate their extraction from water together with adsorbed metals [2], direct degradation, for example, of Pb^{2+} to elemental lead Pb0, does not occur due to the thermal and kinetic stability of these ions. However, heterostructures such as $LaFeO_3$-$SrTiO_3$ can indirectly affect inorganic compounds, reducing them to less toxic forms (for example, Cr(VI) to Cr(III)) in the presence of appropriate electronic states CB, if Eg and the position of the band edges allow the reaction [2]. The effectiveness of this approach is limited by the low electron transfer rate and requires additional research.

Perovskite materials are opening up new horizons for military applications due to their ability to effectively purify water in the field. Portable systems with film catalysts such as $MnTiO_3$ provide 100% degradation of contaminants such as methylene blue in 60 minutes at a rate of 5 mL/min and are easily recovered without loss of mass [4]. Flexible POF-ITO/ABI optoelectrodes, weighing less than 0.10 USD/m, withstand 1000 bending cycles and effectively neutralize chemical agents such as organic poisons, achieving 100% removal in 60 minutes [63]. Integration with drones or solar panels allows for real-time water purification, which is critical in war zones with limited access to infrastructure. Compact reactors with a packing density of 2670 m^2/m^3 can be integrated into mobile units, providing clean water for personnel and equipment [63].

Environmental safety is also an important aspect. The development of lead-free perovskites, such as $Cs_2BiAgBr_6$, reduces toxicity and meets modern environmental standards [2]. The stability of catalysts, such as $LaFeO_3$, has been confirmed by five cycles of use with minimal ion leaching (0.02 mg/L Fe, 0.03 mg/L La), making them suitable for long-term use [62]. Scaling up the technology involves integration with tubular reactors and testing on real water samples containing various impurities for industrial and military implementation [63, 65]. In addition, the potential for hydrogen generation in the PEC process can provide an additional energy source for autonomous systems.

DISCUSSION

The prospects for the use of perovskites in military applications look promising, but are accompanied by technical and practical challenges. In night vision devices, high sensitivity (56.35 A /W [1]) and a wide spectral range (400–1100 nm [1, 35]) provide an advantage over silicon sensors, allowing them to see through camouflage or smoke. However, instability in humidity [1, 32] and the need for energy-efficient solutions [33, 34] pose challenges that can be overcome by applying protective coatings such as PMMA or SiO_2, which increase moisture resistance by more than 50% [48]. Lasers with a threshold of 1.37 μJ/cm² [39] and tunable wavelengths (420–530 nm [3]) promise high targeting accuracy, but lead toxicity [40] and Joule heating [46] make commercialization difficult, prompting a shift to lead-free counterparts, such

as Cs_2SnBr_6 or $Cs_2BiAgBr_6$ [42]. Optimization of thermal management through the integration of compact cooling systems will stabilize operation at high currents (>100 mA/cm² [46]), reducing heating effects.

Sensors with a limit of detection (LOD) of 0.017 ppm [48] and a resolution of 12.6 lp/mm [59] are effective for detecting chemical and radiation threats, but limited selectivity [52] and aggregation of nanocrystals [50, 51] pose challenges in the field. To improve accuracy, doping (e.g., Y in $LaFeO_3$ [48]) or nanocomposites (graphene with $Cs_3Cu_2Br_5$ [50]) can be used to improve the recognition of targets among interferences. Masking systems with photoluminescence (PL) quantum yields QY) 100% [6] provide stealth effects, but low thermal conductivity [30] and photodegradation [65] limit the service life. Integration with adaptive technologies [60] and protective coatings [52–55] can protect the material from external influences, extending the service life. Water purification with a degradation constant of 0.1304 min^{-1} [64] and an index quantum efficiency (IPCE) of 21% [63] solves logistical problems, but instability in water [48] and high processing temperature [65] pose challenges for mass deployment, which can be overcome by protective coatings and process optimization.

Integration with drones [59, 65] and autonomous systems [60] could revolutionize reconnaissance and monitoring, but scaling up production [63] and environmental concerns related to lead waste disposal [65] require significant investment and innovative solutions. The introduction of automated synthesis systems with controlled cooling (1.5 K/day [64]) to produce materials in excess of 10 grams per cycle [36] would enable industrial applications. Modules for drones and solar panels [55, 63] would increase mobility and energy efficiency. Improving stability through protective coatings [52–55] and selective groups [65] could overcome these challenges by protecting the material from degradation and enhancing its specificity. Prospects for use include adaptation to extreme climates (from -20°C to 60°C [53, 55]) and cost-effective optimization [57, 59], which could determine their role in the future, providing an advantage in night operations, attack detection, and logistics.

CONCLUSIONS

Research into perovskite materials opens up new opportunities for improving military technologies, demonstrating their potential in creating innovative systems for night vision, target designation, detection of chemical and biological threats, camouflage of equipment and water purification. These materials are characterized by flexibility, compactness and high efficiency, which makes them promising for integration into portable and autonomous devices adapted to extreme combat conditions. Despite significant advantages, such as low production cost and wide spectral coverage, key challenges remain instability in wet conditions, toxicity of lead compounds and the need for scaling up technologies. Future development should focus on the development of lead-free alternatives, improvement of protective coatings and optimization of manufacturing processes, which will contribute to their widespread implementation in the defense sector over the next decade.

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НОВІ МОЖЛИВОСТІ ВИКОРИСТАННЯ ПЕРОВСКІТІВ ДЛЯ ОБОРОННИХ ТЕХНОЛОГІЙ

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У міні-огляді обговорюється інноваційний потенціал перовскітних матеріалів у військовій сфері. Мета огляду – проаналізувати можливості цих матеріалів для створення передових технологій, таких як системи нічного бачення, цілевказівки, виявлення хімічних, біологічних і радіаційних загроз, маскування техніки та очищення води, а також визначити ключові виклики та перспективи їхнього впровадження. Розглянуто унікальні оптоелектронні властивості перовскітів, такі як висока чутливість до слабкого світла, широкий спектральний діапазон і гнучкість інтеграції, що робить їх придатними для портативних пристроїв для експлуатації у екстремальних умовах. Огляд охоплює аналіз структурних особливостей перовскітів і їхнє застосування: сенсори забезпечують ефективне виявлення загроз із високою точністю, лазери пропонують точне наведення, а маскувальні покриття імітують фонове світло для захисту техніки. Фотокаталітичні системи вирішують проблему очищення води в польових умовах. Водночас зазначаються обмеження, такі як нестабільність у вологості, токсичність свинцю, короткий час життя заряду та нагрівання, які потребують розробки захисних покриттів, безсвинцевих аналогів і систем охолодження для стабільної роботи пристроїв. Інтеграція з дронами підвищує мобільність, але масштабування виробництва й екологічні аспекти вимагають подальших покращень.

У міні-огляді розглядаються перовскітні матеріали (що містять квантові точки), які наразі є ключовою галуззю розробки для військового застосування завдяки своїм унікальним оптоелектронним властивостям. Ці оптоелектронні властивості забезпечують ефективну роботу в умовах слабкого освітлення, дозволяючи розпізнавати об'єкти в темряві, а також демонструють високу чутливість до зовнішніх впливів, таких як гази або радіація, та здатність функціонувати в екстремальних умовах.

Перовскітні матеріали в даний час стають ключовим напрямком у розвитку технологій військового призначення, вирізняючись унікальними оптоелектронними властивостями, що забезпечують ефективну роботу в умовах низької освітленості,

дозволяючи розпізнавати об'єкти в темряві, а також демонструючи високу чутливість до зовнішніх впливів, таких як гази або радіація, та здатність функціонувати в екстремальних умовах. Ці матеріали привертають увагу завдяки своїй здатності контролювати випромінювання, високій стабільності та гнучкості в інтеграції з різними системами, що робить їх перспективними для маскувальних засобів, цілевказівки, моніторингу хімічних, біологічних та радіаційних загроз, а також забезпечення чистою водою в польових умовах. Такі сполуки, як $CsPbX_3$ (де X = Cl, Br, I) та аналоги метиламонію ($MAPbX_3$), демонструють винятковий потенціал для оптоелектронних пристроїв, таких як лазери та сенсори, а також для фотокаталітичних та фотоелектрокаталітичних наносистем.

Однією з основних проблем теоретичних досліджень наносистем, що містять квантові точки, є коректний опис взаємодій наночастинок (кулонівської, поляризаційної, обмінної, спін-орбітальної, спін-спінової) з межами розділу наносистем (напівпровідник-діелектрик-метал). Теоретичне моделювання гібридних наносистем на основі перовскітних та напівпровідникових квантових точок, яке враховує квантово-розмірні ефекти, дозволяє передбачити вплив розміру, форми та складу квантових точок на ефективну ширину забороненої зони, спектри випромінювання та поглинання, що є ключовим для оптимізації оптоелектронних властивостей матеріалів. Дослідження показують, що взаємодія між наночастинками, локалізованими над поверхнями квантових точок у перовскітній матриці, може призвести до ефективного переносу енергії, змін спектрів випромінювання та поглинання і навіть до виникнення квантових ефектів, таких як когерентність, що відкриває перспективи для квантових технологій. Гібридні структури типу квантова точка в перовскіті забезпечують високу якість межі розділу, що сприяє ефективному переносу заряду та збільшує стабільність та довжину дифузії носіїв заряду.

Ключові слова: *перовскітні матеріали, оптоелектронні властивості, технології для військових цілей, фотокаталітичні і фотоелектрокаталітичні властивості.*