IJEAST

INTERNATIONAL JOURNAL OF ENGINEERING APPLIED SCIENCE AND TECHNOLOGY

VOLUME : 10 **ISSUE : 01** **Print / Issue Publication Date: 30-Jun-2025**

ISSN : 2455-2143

DOI : 10.33564/IJEAST.2025.v10i01.020

Indexed In

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International Journal of Engineering Applied Sciences and Technology, 2025
Vol. 10, Issue 01, ISSN No. 2455-2143, Pages 132-145

OPTICAL AND INFRARED PROPERTIES OF NANOMATERIALS FOR NIGHT VISION AND SURVEILLANCE SYSTEMS

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Abstract— **Nanomaterials are fundamentally transforming the capabilities of optical and infrared (IR) imaging technologies, offering unprecedented advancements for military night vision and surveillance systems. Their quantum-scale characteristics—marked by tunable bandgaps, enhanced surface-to-volume ratios, and tailored electronic interactions—enable fine control over photon absorption, emission spectra, and carrier dynamics across the entire infrared range. Among the most promising candidates in this domain are quantum dots (QDs), rare-earth doped nanocrystals, and black phosphorus (BP), each possessing unique optoelectronic signatures that facilitate high-performance imaging under extreme and low-visibility conditions. Quantum dots, with size- and composition-dependent energy levels, can be precisely engineered to operate across short-wave infrared (SWIR), mid-wave infrared (MWIR), and long-wave infrared (LWIR) bands. Their compatibility with CMOS architectures and solution-processability makes them ideal for lightweight, scalable, and multi-spectral imaging arrays in unmanned aerial vehicles (UAVs) and portable surveillance platforms. Rare-earth doped nanocrystals, leveraging stable intra-4f transitions of lanthanide ions, offer narrowband and persistent IR emission. Their luminescence properties and thermal and chemical robustness make them indispensable in passive night vision, covert signaling, and long-duration reconnaissance under harsh battlefield environments. Black phosphorus, a 2D layered semiconductor with a thickness-tunable direct bandgap and intrinsic anisotropic conductivity, exhibits strong potential in MWIR photodetection and polarization-sensitive imaging. Recent improvements in surface passivation have significantly enhanced its environmental stability, paving the way for its integration into flexible and miniaturized IR sensors. This paper explores the structure-property relationships, infrared performance, and system-level integration strategies of these nanomaterials, emphasizing their transformative role in advancing next-generation military imaging solutions for superior tactical awareness and threat detection.**

Keywords— **Quantum dots, black phosphorus, rare-earth nanocrystals, SWIR imaging, MWIR imaging, LWIR detection, hyperspectral imaging, night vision, nanomaterials.**

I. INTRODUCTION

Modern warfare and surveillance demand superior imaging capabilities under diverse environmental conditions, ranging from pitch darkness and dense fog to high-temperature combat zones. As threats become more concealed and battlefields more complex, the evolution of night vision and thermal surveillance systems has become a strategic imperative. From their origins as rudimentary, bulky apparatuses with limited spectral sensitivity, infrared imaging technologies have advanced into highly compact, intelligent systems capable of delivering high-resolution imagery in real time. This dramatic shift has been largely fueled by innovations in nanotechnology, particularly the integration of advanced nanomaterials into optical and infrared (IR) detection platforms. Nanomaterials offer several advantages over traditional bulk materials in optoelectronic applications. Their quantum-confined structures allow for precise control over absorption and emission properties, while their large surface-area-to-volume ratios facilitate enhanced interaction with incident light. These characteristics lead to improved sensitivity, faster response times, and greater spectral tunability—key requirements for infrared imaging across the short-wave infrared (SWIR), mid-wave infrared (MWIR), and long-wave infrared (LWIR) bands. Among the most promising nanomaterials are quantum dots (QDs), rare-earth doped nanocrystals, and black phosphorus (BP). Quantum dots can be engineered to detect specific IR wavelengths simply by altering their size or composition, making them ideal for multispectral and hyperspectral imaging. Rare-earth doped nanocrystals, known for their long-lived and narrowband infrared emissions, provide stable detection under low-light or no-light conditions. Black phosphorus, with its tunable bandgap and intrinsic anisotropy, offers a unique platform for developing broadband and polarization-sensitive IR sensors. Together, these nanomaterials are enabling the development of high-performance night vision and surveillance systems that are lightweight, energy-efficient, and adaptable to a wide range of platforms, including handheld devices, helmet-mounted systems, ground vehicles, and unmanned aerial vehicles (UAVs). This paper delves into the fundamental properties, fabrication methods, system integration, and military applications of these advanced materials, offering a roadmap for next-generation IR imaging in defence and security domains.

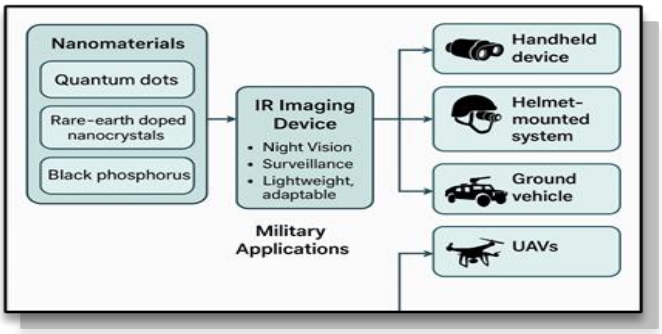


Fig 1. Schematic representation of Nanomaterials for Night Vision and Surveillance Applications.

II. QUANTUM DOTS (QDS): TUNABLE INFRARED SENSITIVITY

A. Structure and Optical Principles

Quantum dots (QDs) are nanoscale semiconductor particles, typically ranging between 2 to 10 nanometers in diameter, that exhibit quantum confinement effects in all three spatial dimensions. This confinement results in discrete, atom-like energy levels instead of the continuous bands seen in bulk semiconductors. The key optical property arising from this is the tunable bandgap, which varies inversely with particle size due to the spatial restriction of charge carriers—electrons and holes—within the dot. At the core of QD behavior lies the principle of quantum confinement: as the physical size of the QD decreases, the energy separation between its electronic states increases. This allows precise engineering of the absorption and emission wavelengths by simply adjusting the size or composition of the dot. For infrared imaging applications, this feature enables spectral tuning across short-wave infrared (SWIR), mid-wave infrared (MWIR), and even parts of the long-wave infrared (LWIR) spectrum. QDs are typically synthesized using colloidal methods, which provide excellent control over particle size, shape, and composition. Common infrared-active QD materials include lead sulfide (PbS), lead selenide (PbSe), mercury telluride (HgTe), and indium arsenide (InAs). These materials have narrow bandgaps suitable for detecting infrared photons. Surface passivation—through shelling with materials such as zinc sulfide (ZnS) or ZnSe—improves photostability, enhances quantum yield, and suppresses non-radiative recombination. The surface chemistry of QDs is another critical parameter that governs their optical performance. Ligands, which are organic molecules attached to the QD surface, stabilize the colloidal dispersion and influence carrier transport and environmental stability. Advances in ligand exchange strategies, including the use of short-chain or inorganic ligands, have significantly improved charge carrier mobility and enabled efficient device integration. Moreover, the core-shell structure, such as InAs/ZnSe or PbSe/CdSe, enhances the photoluminescent properties and provides better control over carrier confinement. These engineered nanostructures offer narrow full-width-at-half-maximum (FWHM) emission spectra, essential for wavelength-selective infrared imaging. The ability to synthesize these QDs with high reproducibility and spectral tunability has propelled them into the spotlight for cutting-edge night vision systems, hyperspectral surveillance, and advanced optical sensors. Their unique optical principles provide a versatile platform for building next-generation imaging systems tailored to diverse military scenarios.

B. Infrared Response

Quantum dots (QDs) offer remarkable flexibility in tailoring infrared (IR) response characteristics due to their size-dependent bandgap tunability. This property makes them highly suitable for applications in short-wave infrared (SWIR), mid-wave infrared (MWIR), and even portions of long-wave infrared (LWIR) imaging. Unlike bulk semiconductors, where the bandgap is fixed, QDs allow precise engineering of absorption and emission spectra simply by controlling the nanocrystal size and composition during synthesis. Lead-based QDs, such as lead sulfide (PbS) and lead selenide (PbSe), are among the most widely studied for their tunable absorption properties in the infrared region. PbS QDs, for instance, can be synthesized to absorb photons in the 1.0–2.5 µm range, which covers the entire SWIR window. This region is particularly important for night vision and low-light surveillance, as it provides high contrast and visibility through atmospheric haze and fog. On the other hand, PbSe QDs can extend sensitivity well into the MWIR region (~4.5 µm), offering enhanced thermal contrast for detecting warm targets such as vehicles, machinery, or human bodies in various environmental conditions. The quantum efficiency and responsivity of QD-based photodetectors have steadily improved due to advancements in material synthesis, surface passivation, and device architectures. For example, core-shell structures such as PbSe/CdSe or InAs/ZnSe improve carrier confinement and reduce surface trap states, resulting in higher responsivity and faster response times. Moreover, narrow emission bandwidths—typical of QD photoluminescence—enable multispectral and hyperspectral imaging, allowing for the discrimination of closely spaced spectral features. QD-based detectors also exhibit lower dark current and noise characteristics compared to traditional bulk semiconductors, especially when cooled. However, significant progress has been made toward developing uncooled QD detectors through the optimization of carrier mobility and recombination dynamics. This has critical implications for reducing system complexity and energy requirements in field-deployable military surveillance equipment. Furthermore, recent studies have demonstrated QDs with dynamic response properties under external stimuli, such as electric or magnetic fields, allowing for tunable and reconfigurable infrared sensors. These advances are enabling the development of multi-band sensors and smart detection systems that can adapt in real time to changing battlefield conditions. Collectively, the tunable and enhanced infrared response of QDs represents a major leap forward in the design of flexible, high-performance, and cost-effective imaging systems tailored for modern military and surveillance applications.

C. Integration into Imaging Systems

The integration of quantum dots (QDs) into imaging systems has become a cornerstone of next-generation infrared (IR) technologies, particularly for defence, surveillance, and autonomous aerial reconnaissance platforms. The unique optoelectronic properties of QDs—such as size-tunable bandgaps, high quantum efficiency, and compatibility with solution-based processing—make them highly versatile for incorporation into both conventional and emerging sensor architectures. One of the most transformative aspects of QD integration is its compatibility with complementary metal-oxide-semiconductor (CMOS) technology. Traditional IR detectors, especially those operating in the MWIR and LWIR bands, often require expensive and complex cooling mechanisms and are incompatible with silicon-based CMOS readout integrated circuits (ROICs). In contrast, QDs—particularly those based on materials like PbS, PbSe, or InAs—can be synthesized and deposited as thin films directly onto CMOS substrates. This enables the fabrication of low-cost, high-resolution imaging arrays using existing semiconductor infrastructure, drastically reducing the cost and size of IR imaging systems. Moreover, QDs support solution-processable fabrication techniques, such as spin coating, inkjet printing, and spray deposition. This opens pathways for scalable production of flexible and conformal sensors, ideal for lightweight UAVs and wearable military gear. In addition, the ability to fine-tune QD optical response through synthesis parameters allows the creation of multispectral or broadband focal plane arrays (FPAs). These FPAs can detect multiple infrared bands simultaneously, improving contrast, material discrimination, and target recognition capabilities in complex environments. Recent advancements have introduced QD-enhanced focal plane arrays with narrowband or wavelength-selective detection. By integrating filters or engineering pixel-specific QD layers, hyperspectral and multispectral cameras can now be miniaturized and deployed in tactical scenarios. These cameras provide real-time spectral data, essential for distinguishing between natural terrain and camouflaged threats, detecting chemical agents, or identifying equipment based on thermal emissions. Additionally, QDs exhibit favorable electrical properties for photoconductive and photodiode-based architectures. Through careful ligand engineering and surface passivation, carrier mobility and charge transfer efficiency have been optimized, enabling faster response times and higher sensitivity. Hybrid systems that combine QDs with graphene, black phosphorus, or 2D materials have further enhanced photodetection capabilities. In military applications, this level of integration translates to lightweight, portable, and intelligent infrared imaging systems that are not only high-performing but also field-deployable under harsh environmental conditions.

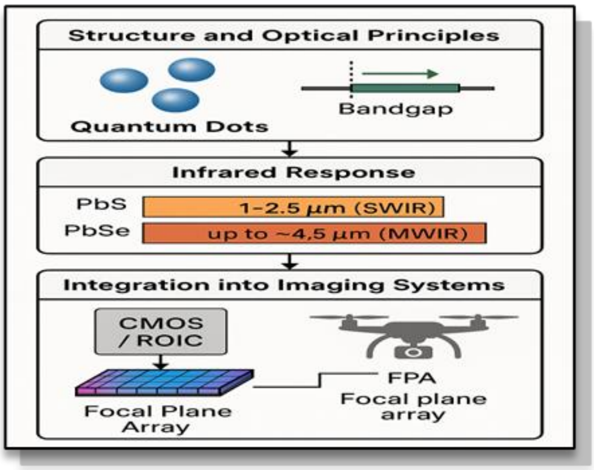


Fig 2. Schematic representation of Tunable Infrared Sensitivity of Quantum Dots (QD).

III. RARE-EARTH DOPED NANOCRYSTALS: PERSISTENT LUMINESCENCE AND DEEP IR EMISSION

A. Structural Features

Rare-earth doped nanocrystals are composed of an inorganic host lattice doped with trivalent lanthanide ions such as erbium (Er^{3+}), neodymium (Nd^{3+}), ytterbium (Yb^{3+}), holmium (Ho^{3+}), or thulium (Tm^{3+}). The host material, typically an oxide (e.g., Y_2O_3, Gd_2O_3), fluoride (e.g., $NaYF_4$, CaF_2), or phosphate (e.g., $LiYPO_4$), provides a crystalline matrix that facilitates the incorporation of these dopant ions into specific lattice sites. The lanthanide ions are responsible for the optical activity, while the host matrix significantly influences the luminescence efficiency, thermal stability, and spectral bandwidth. The defining feature of these doped nanocrystals is the nature of the 4f 4f electronic transitions in lanthanide ions. These transitions occur within the shielded 4f orbitals, which are effectively isolated from the crystal field due to the filled 5s and 5p outer electron shells. This shielding results in narrow emission lines that are relatively insensitive to the local lattice environment, ensuring highly stable and reproducible spectral characteristics. This intrinsic property is a major advantage over transition-metal-based systems, where electronic states are strongly affected by the host lattice and surrounding ligands. The choice of host lattice is critical to the efficiency of rare-earth doped nanocrystals. Low-phonon-energy hosts, such as fluorides, minimize non-radiative relaxation processes and thus support longer excited-state lifetimes and stronger emissions. Fluorides like $NaYF_4$ have emerged as one of the most efficient hosts for up conversion and infrared emission because they suppress multi-phonon relaxation, a common issue in oxides. The doping concentration of rare-earth ions must be carefully optimized. Excessive doping can lead to concentration quenching, where cross-relaxation between ions reduces overall emission efficiency. To overcome this, co-doping strategies are used, typically with sensitizer ions like Yb^{3+} to absorb pump photons and transfer energy efficiently to emitter ions such as Er^{3+} or Tm^{3+}. This sensitizer-activator configuration allows for better control over absorption and emission characteristics. Morphologically, these nanocrystals can be synthesized in various shapes—spheres, rods, or plates—using hydrothermal, solvothermal, or thermal decomposition methods. Core-shell structures, where the emitting core is coated with an inert or active shell, are often used to enhance luminescence by isolating the core from surface defects and quenching centers. The combination of precise structural control, robust spectral properties, and high thermal and chemical stability makes rare-earth doped nanocrystals highly attractive for infrared imaging and sensing applications in harsh or mission-critical environments.

B. Optical and Infrared Properties

Rare-earth doped nanocrystals exhibit distinctive optical and infrared (IR) properties that make them highly suitable for advanced imaging and sensing applications, particularly in night vision and surveillance technologies. These properties stem from intra-4f electron transitions of lanthanide ions, which are largely shielded from external perturbations by the outer filled orbitals. This shielding imparts sharp emission lines, high photostability, and long luminescence lifetimes—key features that distinguish rare-earth materials from conventional semiconductor emitters. Among the various dopant ions, erbium (Er^{3+}), neodymium (Nd^{3+}), and holmium (Ho^{3+}) are prominent for their strong IR emissions. Er^{3+} is especially valuable for its emission around 1.55 µm, which falls within the short-wave infrared (SWIR) spectral window. This wavelength not only coincides with the telecommunication band, allowing for dual-use in communication and sensing, but also provides excellent atmospheric transmission and low background noise, ideal for night vision imaging. Nd^{3+} exhibits strong emission near 1.06 µm and 1.3 µm, overlapping with both SWIR and MWIR ranges, while Ho^{3+} can extend the response deeper into the mid-wave IR, enabling thermal imaging applications. A notable advantage of these materials is their persistent luminescence, or afterglow, which allows them to emit IR light long after excitation has ceased. This phenomenon, often achieved by co-doping with trap-forming ions like Cr^{3+} or Dy^{3+}, enables stealthy imaging in no-light environments without active excitation, significantly reducing power consumption and sensor visibility. In military contexts, this feature is ideal for covert surveillance, decoy illumination, and low-signature optical tagging. The host lattice further influences the infrared performance. For instance, fluoride hosts (e.g., $NaYF_4$ or $BaYF_5$) are known for their low phonon energies, which help maintain radiative decay pathways, enhancing IR emission efficiency. Phosphate and oxide hosts, while more chemically stable, may exhibit slightly higher non-radiative losses but are advantageous in rugged environmental conditions. Furthermore, advances in up-conversion nanocrystals, where multiple lower-energy photons (e.g., NIR) are absorbed to emit higher-energy visible or IR photons, have opened new pathways for biological imaging and optical encryption in military devices. These upconverting systems are particularly valuable for developing IR-responsive nanomaterials with multiplexed emission and precise spatial resolution. In essence, rare-earth doped nanocrystals combine high spectral specificity with long-lived emission and robust physical properties, positioning them as a powerful class of materials for passive and active infrared imaging in defence applications.

C. Military Applications

Rare-earth doped nanocrystals have become increasingly vital to modern military technologies, particularly in night vision, battlefield imaging, secure communications, and covert surveillance. Their unique ability to emit stable, narrowband infrared (IR) light in the short-wave infrared (SWIR), mid-wave infrared (MWIR), and long-wave infrared (LWIR) regions makes them especially suitable for advanced defence systems operating in low-light or no-light environments. One of the most prominent applications lies in covert night vision systems. Rare-earth ions like Er^{3+} and Nd^{3+} offer strong emission in the 1.0–1.55 µm SWIR band, a spectral window with minimal solar interference and low scattering. When doped into nanocrystals embedded in optical sensors or goggles, these materials allow soldiers to detect, identify, and track targets under low-visibility conditions without exposing their position, thanks to their low radiative signature. Another key advantage is their persistent luminescence, which eliminates the need for continuous excitation. This enables long-duration, power-efficient operation of surveillance systems, particularly in unmanned platforms such as drones, unattended ground sensors, or long-range reconnaissance systems. Phosphors like $LiGa_5O_8:Cr^{3+}$ and $Y_2O_2S: Eu^{3+}$, co-doped with trap-filling ions, can store excitation energy and emit it gradually over time, making them suitable for optical tagging, stealth beacons, and signal encoding in secure communication systems. In laser designation and targeting, rare-earth doped crystals are employed in the development of solid-state lasers and optical amplifiers. For example, Nd^{3+}: YAG lasers are standard in rangefinders and laser target designators due to their high beam quality and reliability. These systems guide munitions with extreme precision and are widely used in NATO and allied defence forces. The narrow linewidths and stable emissions of these materials also make them ideal for optical filters and multispectral sensor arrays. Integrated into hyperspectral imaging systems on UAVs, rare-earth nanocrystals enable the detection of camouflaged objects, chemical signatures, and thermal anomalies over large areas. Furthermore, their robust performance in extreme conditions, such as high-altitude cold, desert heat, or electromagnetic interference, makes them highly suitable for aerospace, satellite, and border monitoring applications. These nanocrystals maintain luminescence efficiency even at cryogenic or elevated temperatures, ensuring mission reliability across varied operational theaters. Overall, rare-earth doped nanocrystals serve as a cornerstone for next-generation military optoelectronics, combining spectral precision, energy efficiency, and ruggedness for enhanced tactical superiority and battlefield awareness.

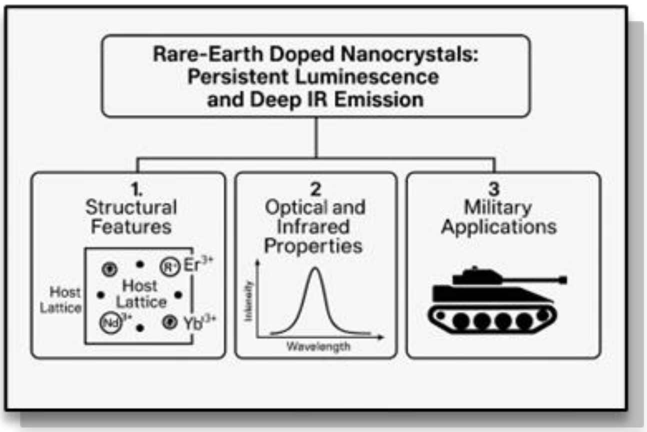


Fig 3. Schematic representation of Rare-Earth doped Nanocrystals.

IV. BLACK PHOSPHORUS (BP): ANISOTROPIC AND TUNABLE INFRARED PERFORMANCE

A. Crystal Structure and Bandgap

Black phosphorus (BP) has emerged as a promising two-dimensional (2D) semiconductor with exceptional optical and electronic characteristics suitable for infrared imaging technologies. Structurally, BP belongs to the family of layered van der Waals materials. Each layer consists of phosphorus atoms arranged in a puckered honeycomb structure, forming a unique anisotropic orthorhombic lattice. These layers are held together by weak van der Waals forces, allowing for facile exfoliation into thin films or monolayers. One of the most attractive features of BP is its direct and layer-dependent bandgap, which spans a broad energy range—from approximately 0.3 eV in bulk form to nearly 2.0 eV in monolayer configurations. This tunability enables optical absorption and emission across the entire infrared spectrum, from long-wave infrared (LWIR) in bulk form to the visible and near-infrared (NIR) ranges in few-layer structures. This continuous bandgap adjustability makes BP an ideal material for multispectral and hyperspectral imaging, particularly in applications where covering a wide spectral range with a single material is advantageous. Additionally, BP's puckered crystal lattice introduces strong in-plane anisotropy, meaning its electronic and optical responses vary significantly depending on the polarization direction of incident light. This anisotropic behavior is highly beneficial for developing polarization-sensitive detectors and directional photonic components, which are critical in advanced surveillance technologies for distinguishing between materials and textures under varying light conditions. From a quantum confinement perspective, the ability to mechanically or chemically exfoliate BP into few-layer or monolayer films allows for precise control of the electronic structure. As the thickness decreases, quantum confinement effects become pronounced, and the bandgap increases, shifting the absorption edge toward shorter wavelengths. This property enables the design of tunable photodetectors and emitters tailored to specific infrared windows, such as short-wave infrared (SWIR) and mid-wave infrared (MWIR). Moreover, because of its direct bandgap at all thicknesses, BP efficiently absorbs and emits photons, leading to high quantum efficiency in optoelectronic applications. Unlike indirect bandgap materials, BP does not require phonon assistance for radiative transitions, which reduces energy losses and enhances sensitivity. Overall, the versatile crystal structure and tunable bandgap of black phosphorus offer unparalleled opportunities for infrared optoelectronics, establishing it as a key material in next-generation night vision systems, SWIR/MWIR photodetectors, and polarization-resolved imaging.

B. Optical Absorption and Carrier Dynamics

Black phosphorus (BP) exhibits exceptional optical absorption characteristics and ultrafast carrier dynamics, making it a highly attractive material for advanced infrared imaging and optoelectronic systems. Its anisotropic structure leads to highly direction-dependent light-matter interactions, which, when combined with its direct and tunable bandgap, result in efficient absorption across the short-wave infrared (SWIR) and mid-wave infrared (MWIR) spectra. BP demonstrates strong and broadband optical absorption, especially in the SWIR (~1–2.5 µm) and MWIR (~3–5 µm) regions. This stems from its layered architecture and high density of states near the band edges. Importantly, the absorption coefficient of BP is significantly higher than that of traditional materials like silicon in these spectral ranges, allowing for efficient photodetection even in thin-film configurations. This high absorption efficiency is critical in designing compact and lightweight imaging sensors, especially for applications in small UAVs and handheld surveillance devices. Another standout feature is BP's high carrier mobility, which exceeds 1000 cm²/V·s in few-layer samples under optimized conditions. This enables fast response times and high-frequency operation, vital for real-time night vision and surveillance where rapid image acquisition is crucial. In comparison to other 2D materials such as MoS_2 or graphene, BP offers a favorable balance between mobility and bandgap tunability for infrared applications. The carrier dynamics in

BP are governed by ultrafast photoexcitation and recombination processes. Studies using pump-probe spectroscopy have revealed sub-picosecond carrier relaxation times, allowing for high-speed modulation and detection in infrared photonic circuits. This ultrafast behavior supports the development of GHz-range photodetectors and dynamic imaging systems that require rapid data processing and minimal latency. BP also supports photoconductive and photovoltaic effects, enabling the design of both passive and active imaging devices. Its photoresponsivity can be further enhanced through gating effects, plasmonic enhancement, or integration with optical cavities. Moreover, its thin-film nature enables direct integration onto silicon substrates or flexible polymers, providing opportunities for flexible, wearable night vision gear or conformal UAV-mounted sensors. The combination of strong infrared absorption, high carrier mobility, and ultrafast carrier dynamics makes BP a versatile material for high-performance, broadband infrared detection systems. These attributes are particularly valuable in military imaging applications requiring compact size, rapid response, and high sensitivity across variable spectral bands.

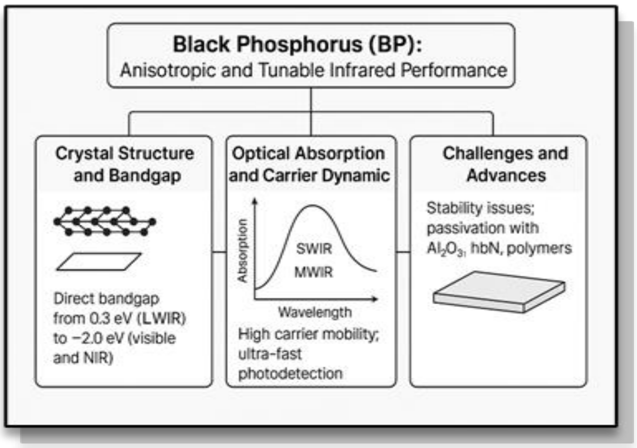


Fig 4. Schematic representation of Anisotropic and Tunable Infrared Performance of Black Phosphorus

C. Challenges and Advances

While black phosphorus (BP) holds great promise for infrared imaging and night vision systems due to its tunable bandgap and high carrier mobility, its practical deployment faces several critical challenges, chief among them being environmental instability. BP is highly reactive with oxygen and moisture, undergoing rapid degradation when exposed to ambient conditions. This leads to oxidation and the formation of phosphorus oxides that deteriorate its electrical and optical performance, thereby limiting its shelf-life and usability in real-world applications, particularly for military and field-deployable systems. To address these concerns, encapsulation and passivation strategies have emerged as primary research areas. Encapsulation with materials like aluminum oxide (Al_2O_3) using atomic layer deposition (ALD) has shown substantial success in improving environmental stability by forming a conformal barrier that prevents moisture ingress. Similarly, hexagonal boron nitride (hBN), a chemically inert 2D material, offers atomically smooth interfaces and excellent protection for BP, preserving its electronic and optical properties over extended periods. Polymer coatings, such as PMMA and Parylene-C, have also been explored for flexible encapsulation solutions compatible with wearable and UAV-mounted imaging systems. In terms of device integration, another major challenge lies in the controlled synthesis and scalability of BP films. Mechanical exfoliation, while widely used in research, is not viable for large-scale production. Alternatives like liquid-phase exfoliation and chemical vapor deposition (CVD) are under active development to produce high-quality, uniform BP films suitable for industrial fabrication of infrared detectors and sensors. Recent advances have also focused on integrating BP with complementary metal-oxide-semiconductor (CMOS) technologies, allowing for the development of BP-based photodetectors that are compatible with existing imaging infrastructure. Researchers are also exploring heterostructure engineering, combining BP with materials like MoS_2 or graphene to tailor interlayer charge transfer and improve device efficiency, thermal stability, and spectral selectivity. In military contexts, prototypes of BP-based polarization-sensitive imagers are being evaluated for UAV reconnaissance, where weight, sensitivity, and directional contrast are critical. These imagers leverage BP's intrinsic in-plane anisotropy for enhanced material classification and object detection. In summary, while black phosphorus presents integration and stability challenges, ongoing material science breakthroughs in encapsulation, synthesis, and hybridization are paving the way for its inclusion in robust, field-ready infrared imaging platforms. These developments suggest a strong trajectory toward BP becoming a cornerstone material in next-generation surveillance and night.

V. APPLICATIONS IN SWIR, MWIR, AND LWIR IMAGING SYSTEMS

A. SWIR Systems

Short-Wave Infrared (SWIR) imaging, covering wavelengths from 0.9 to 1.7 μm, plays a pivotal role in modern surveillance and reconnaissance operations. This spectral range offers unique advantages, such as reduced atmospheric scattering and the ability to capture clear images under low-light conditions, including starlight or passive illumination. The integration of advanced nanomaterials, notably quantum dots (QDs) and rare-earth doped materials, has significantly enhanced the capabilities of SWIR imaging systems.

Quantum Dots in SWIR Imaging

Quantum dots are semiconductor nanocrystals with size-tunable optical properties. By adjusting their size and composition, QDs can be engineered to absorb and emit light in specific spectral regions, including the SWIR band. Materials like lead sulfide (PbS) and indium arsenide (InAs) QDs have demonstrated strong absorption in the SWIR range, making them suitable for photodetector applications. One of the key advantages of QDs is their compatibility with existing silicon-based technologies. They can be integrated onto silicon Complementary Metal-Oxide-Semiconductor (CMOS) readout integrated circuits (ROICs) through solution-based processes like spin-coating or printing. This integration facilitates the development of high-resolution, low-cost SWIR sensors, enabling widespread adoption in various applications. Moreover, QDs exhibit high quantum efficiency and low dark current, essential parameters for sensitive imaging. Their broad absorption spectra and narrow emission peaks contribute to enhanced image contrast and clarity, crucial for identifying human targets, vehicles, and terrain features during night-time missions.

Rare-Earth Doped Materials in SWIR Imaging

Rare-earth doped materials, such as those incorporating erbium (Er^{3+}) or neodymium (Nd^{3+}) ions, offer narrowband emission in the SWIR region. These materials are characterized by their sharp emission lines and long luminescence lifetimes, resulting from intra-4f electron transitions that are shielded from the surrounding matrix. In SWIR imaging systems, rare-earth doped materials serve as efficient light sources or gain media. For instance, Er^3-doped fibers are commonly used in SWIR lasers and amplifiers, providing stable and coherent light sources for active illumination or communication systems. Additionally, rare-earth doped nanocrystals can be incorporated into imaging sensors to enhance sensitivity and spectral selectivity. Their persistent luminescence properties enable imaging without continuous excitation, reducing power consumption and thermal load, beneficial for portable or remote surveillance equipment.

Applications in Night-Time Missions

The integration of QDs and rare-earth doped materials into SWIR imaging systems has led to significant advancements in night-time operational capabilities. These systems can capture high-contrast images under minimal ambient light, enabling the detection and identification of objects that are otherwise invisible to the naked eye or traditional visible-light cameras. In military operations, SWIR imaging facilitates target recognition, navigation, and threat assessment in darkness or obscured environments. It also supports covert surveillance, as SWIR sensors can detect reflected light from passive sources without emitting detectable signals. Beyond defence, SWIR imaging finds applications in search and rescue missions, border security, and infrastructure monitoring. The ability to see through smoke, fog, or camouflage enhances situational awareness and decision-making in critical scenarios. In summary, the deployment of quantum dots and rare-earth doped materials in SWIR imaging systems has revolutionized night-time surveillance, offering compact, efficient, and high-performance solutions for a range of applications.

B. MWIR Systems

Mid-Wave Infrared (MWIR) systems, operating in the 3–5 μm wavelength band, serve as a critical component in military surveillance, reconnaissance, and target acquisition. This spectral region is particularly advantageous for thermal imaging, as it corresponds to the peak emission of objects at human body temperature (~300 K). Nanomaterials such as quantum dots (QDs) and black phosphorus (BP) have demonstrated exceptional promise in enhancing MWIR sensor performance through tunable absorption, fast response times, and miniaturization potential.

Quantum Dots for MWIR Detection

Quantum dots tailored for MWIR imaging—such as lead selenide (PbSe), mercury telluride (HgTe), and InAs-based systems—enable photodetection in the 3–5 μm band with high responsivity. By controlling particle size and shell composition, researchers have engineered QDs with band gaps that precisely match the MWIR range. These materials are solution-processable, which supports cost-effective fabrication and integration into existing detector platforms. Unlike traditional cooled InSb or HgCdTe (MCT) detectors that require cryogenic cooling, QD-based detectors can operate at higher temperatures or with thermoelectric cooling, significantly reducing power consumption and system complexity. Recent advances in ligand exchange chemistry have also improved carrier mobility and passivation in QD films, increasing sensitivity and long-term stability. QD-enhanced focal plane arrays (FPAs) are being explored for dynamic MWIR imaging, enabling real-time threat detection and tracking. These FPAs can be integrated with CMOS readouts, allowing for lightweight, portable systems suitable for manned and unmanned platforms alike.

Black Phosphorus in MWIR Optoelectronics

Black phosphorus (BP), a layered two-dimensional (2D) material, is gaining traction for MWIR applications due to its tunable direct bandgap (~0.3–2.0 eV) and high carrier mobility. BP’s anisotropic electronic properties allow for polarization-sensitive imaging, adding a new dimension of spectral analysis to MWIR surveillance. BP photodetectors can operate over a broad IR range, but their strong response in the MWIR band makes them ideal for thermal imaging under adverse conditions such as smoke, fog, or low visibility. Moreover, their atomically thin structure facilitates the design of compact, lightweight sensors for use on drones and handheld reconnaissance devices. Efforts to overcome BP’s environmental sensitivity—primarily its reactivity to oxygen and moisture—have yielded promising encapsulation techniques. Al_2O_3 coatings, hBN layering, and polymer composites have significantly improved BP stability, paving the way for its deployment in field-ready MWIR sensors.

Applications in Defence and Emergency Services

MWIR imaging systems equipped with QDs and BP have transformative applications in both defence and civil sectors. These include:

- Missile Guidance and Targeting: MWIR sensors enable heat-seeking missiles to track engine exhaust plumes with high precision.
- Forward-Looking Infrared (FLIR): Used in vehicles, aircraft, and UAVs for real-time thermal mapping of terrain and potential threats.
- Firefighting UAVs: MWIR-equipped drones can penetrate smoke to identify hotspots and trapped individuals during fire emergencies.

Furthermore, the reduced weight, power, and cost profiles of nanomaterial-based MWIR systems align well with next-generation tactical demands for mobile, autonomous, and resilient imaging solutions.

C. LWIR Systems

Long-Wave Infrared (LWIR) systems, operating in the 8–14 µm spectral range, play a pivotal role in military and security applications where long-distance, low-visibility, and all-weather imaging capabilities are essential. This spectral band corresponds to thermal emissions from ambient temperature objects, making it ideal for passive thermal imaging during both day and night. Although traditional detectors like mercury cadmium telluride (MCT) and microbolometers dominate the LWIR landscape, emerging nanomaterials—especially black phosphorus (BP), rare-earth doped nanocrystals, and hybrid systems—are beginning to reshape the performance boundaries of LWIR technologies.

Limitations and Potentials of Quantum Dots in LWIR

Quantum dots (QDs) have demonstrated extensive tunability across visible to mid-wave IR bands; however, their application in LWIR systems has historically been constrained due to intrinsic material limitations. Most II–VI QDs (e.g., PbSe, PbS) exhibit band gaps insufficient to support detection beyond 5 µm. While HgTe QDs and other heavy-metal QDs can reach into the LWIR range, their stability, toxicity, and fabrication challenges limit large-scale deployment. Recent research, however, has shown that QDs can be incorporated into hybrid architectures—combining QDs with 2D materials or photonic structures—to extend spectral responsivity. Colloidal QD-in-matrix composites and type-II superlattice structures offer potential breakthroughs in achieving LWIR detection with improved quantum efficiency and noise characteristics.

Black Phosphorus and Rare-Earth Nanocrystals in LWIR

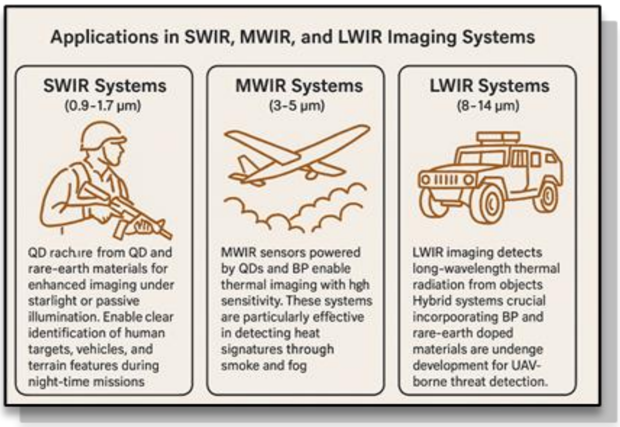
Black phosphorus (BP), with a bulk bandgap of ~0.3 eV, is well-suited for LWIR optoelectronic applications. It supports strong light absorption and photodetection across the 8–14 µm band. BP's anisotropic crystal structure also enables directional thermal imaging, which can be advantageous in battlefield scenarios for identifying motion, camouflage penetration, and target orientation. In parallel, rare-earth doped nanocrystals—particularly those containing holmium (Ho^{3+}), thulium (Tm^{3+}), and erbium (Er^{3+})—can emit and absorb radiation in the far infrared due to their intra-4f transitions. Although these transitions are inherently narrowband, they are remarkably stable and resistant to temperature fluctuations, making them suitable for specialized military uses such as coded thermal signaling, covert target illumination, and long-duration beaconing.

Military and Surveillance Applications

LWIR imaging systems offer a suite of mission-critical capabilities:

- All-weather Reconnaissance: LWIR sensors can penetrate smoke, dust, haze, and fog, ensuring situational awareness in degraded visual environments.
- Thermal Camouflage Detection: Subtle variations in thermal emissions from hidden or camouflaged threats (e.g., IEDs, vehicles) can be detected using high-resolution LWIR systems.
- Perimeter and Border Security: Ground-based and airborne LWIR platforms are extensively used for border monitoring, particularly in extreme conditions or during nighttime operations.
- Uncooled Soldier Gear: Nanomaterial-enhanced microbolometers using BP or rare-earth composites are making headway into portable thermal monoculars and helmet-mounted displays, reducing size, weight, and power (SWaP) requirements.

While challenges such as environmental stability and integration costs remain, the incorporation of black phosphorus and rare-earth materials into LWIR systems holds great promise. As encapsulation techniques and hybrid detector architectures evolve, nanomaterial-driven LWIR imaging is set to become a cornerstone of advanced military surveillance and targeting technologies.



QD rachıre from QD and rare-earth materials for enhanced imaging under starlight or passive illumination. Enable clear identification of human targets, vehicles, and terrain features during night-time missions

MWIR sensors powered by QDs and BP enable thermal imaging with hgh sensitivity. These systems are particularly effective in detecting heat signatures through smoke and fog

LWIR imaging detects long-wavelength thermal radiation from objects Hybrid systems crucial incorpoorating BP and rare-earth doped materials are undenge development for UAV-borne threat detection.

Fig 5. Application of Nanomaterials Imaging Systems in various Spectral Ranges (i.e., SWIR, MWIR, LWIR)

VI. HYPERSPECTRAL IMAGING FOR UAVS

Hyperspectral imaging (HSI) represents a transformative capability in modern surveillance and reconnaissance operations, particularly when integrated with unmanned aerial vehicles (UAVs). Unlike conventional imaging systems, HSI captures data across hundreds of narrowly spaced, contiguous spectral bands, often spanning from the visible through the near-infrared (VNIR), short-wave infrared (SWIR), and into the mid- and long-wave infrared (MWIR and LWIR) domains. This rich spectral information enables precise identification of materials, detection of concealed threats, and highly detailed environmental monitoring, making it invaluable for defence and intelligence applications. The integration of nanomaterials into HSI sensors has significantly enhanced their performance, miniaturization, and spectral resolution—critical attributes for UAV-mounted platforms. Quantum dots (QDs), rare-earth doped nanocrystals, and black phosphorus (BP) are among the most promising materials in enabling compact, high-efficiency hyperspectral systems. Quantum dots are especially suited for designing narrowband, tunable filters in hyperspectral detectors. Their size-dependent optical properties allow for precise spectral selectivity, enabling sensors to isolate specific wavelengths with high fidelity. This tunability is ideal for constructing multispectral filter arrays that are lightweight and power-efficient—key advantages for UAV deployment. Colloidal QDs can also be integrated into photodetector architectures to enhance responsivity in specific infrared bands, particularly SWIR and MWIR, which are vital for night vision and thermal contrast imaging.

Rare-earth doped nanocrystals bring added functionality by amplifying specific spectral regions through their characteristic narrowband emission and absorption features. Materials doped with ions such as erbium (Er^{3+}), neodymium (Nd^{3+}), or thulium (Tm^{3+}) offer high signal-to-noise ratios and can be engineered to boost weak signals in crowded or noisy environments. Their inherent stability under varying thermal and atmospheric conditions makes them suitable for extended UAV missions in harsh operational settings.

Black phosphorus offers a unique advantage due to its anisotropic carrier mobility and broad infrared absorption, especially in the MWIR region. Its ultrathin nature allows the development of flexible, lightweight photodetectors capable of real-time, high-speed image acquisition. Furthermore, BP's polarization sensitivity introduces the potential for advanced imaging modalities, including the detection of surface textures and target orientation, features highly valuable in identifying camouflaged or buried objects.

Military UAVs equipped with nanomaterial-enabled HSI systems are capable of autonomous surveillance with unprecedented spectral and spatial precision. Applications range from tracking enemy movements and mapping chemical spills to identifying improvised explosive devices (IEDs) and analysing terrain features under varied lighting or weather conditions. As materials science advances, the synergy between UAV platforms and hyperspectral sensors will further revolutionize battlefield awareness, reducing the cognitive load on human operators while expanding strategic decision-making capabilities.

VII. FUTURE PROSPECTS AND CHALLENGES

A. Performance Optimization

Quantum dots (QDs), rare-earth-doped nanocrystals, and black phosphorus (BP) have demonstrated significant potential in enhancing the sensitivity and spectral range of infrared (IR) detectors. However, their performance metrics—such as responsivity, noise-equivalent power (NEP), and detectivity—require systematic optimization to meet the stringent demands of military night vision and surveillance systems. One promising strategy in QD engineering is the development of advanced heterostructures, including core/shell and core/crown configurations. These structures improve carrier confinement and reduce non-radiative recombination, significantly enhancing quantum efficiency across the SWIR and MWIR bands. Ligand chemistry plays a pivotal role in surface passivation, charge transport, and device integration. Traditional long-chain organic ligands tend to impede charge mobility. The replacement of these with shorter, more conductive inorganic ligands—such as halides, chalcogenides, or metal thiolates—has been shown to improve photoconductivity and environmental robustness. Moreover, ligand exchange processes tailored to specific substrates (e.g., ZnO, TiO_2, or graphene) further enhance integration into focal plane arrays (FPAs) and CMOS-compatible systems. In rare-earth nanocrystals, efforts are directed toward improving quantum yield and reducing cross-relaxation losses by optimizing host matrices and dopant concentrations. Host materials such as $NaYF_4$, $LaPO_4$, and $LiYF_4$ have demonstrated high efficiency in up-conversion and down-conversion processes. Moreover, co-doping strategies using sensitizers like Yb^{3+} with activators such as Er^{3+} or Tm^{3+} enable tunable emission across NIR and SWIR ranges, aligning well with the spectral windows used in low-light military imaging. Black phosphorus, on the other hand, benefits from strain engineering and layer number control to tailor its direct bandgap. Strain can be externally applied or induced through substrate selection, modifying BP's electronic structure to achieve optimal absorption in the MWIR to LWIR range. Additionally, combining BP with transition metal dichalcogenides (TMDs) or perovskites in van der Waals heterostructures opens new pathways for hybrid infrared detectors with enhanced sensitivity and speed. Emerging technologies such as machine-learning-based material design and predictive modeling are now being integrated into the performance optimization pipeline. These techniques enable the simulation of energy band alignment, phonon interactions, and defect states to accelerate the design of more efficient nanomaterials. Furthermore, 3D nano-structuring—such as nanopatterned meta-surfaces or photonic crystals—offers additional control over absorption, reflectance, and emissivity, enhancing the spectral selectivity and resolution of the detectors. Overall, while considerable progress has been made, the future lies in multi-disciplinary innovations that integrate materials science, computational physics, and advanced fabrication methods. The continuous refinement of these techniques is expected to push the boundaries of IR imaging systems, offering unparalleled sensitivity and adaptability in increasingly complex and demanding battlefield environments.

B. Stability and Integration

The operational reliability of nanomaterials under diverse and extreme field conditions is a fundamental requirement for their successful deployment in military night vision and surveillance systems. While materials like quantum dots (QDs) and rare-earth doped nanocrystals have exhibited promising levels of chemical and photostability, challenges remain in achieving long-term operational stability, especially when these materials are exposed to fluctuating temperatures, humidity, radiation, and mechanical stress. The integration of these nanomaterials into robust and scalable device architectures also continues to demand innovative engineering approaches. Quantum dots, particularly those based on II–VI semiconductors such as CdSe and PbS, are known for their susceptibility to oxidation and photobleaching when exposed to air or ultraviolet light. To counteract this, surface passivation through inorganic shells (e.g., ZnS or ZnSe) has been widely adopted. These core/shell structures not only enhance photostability but also improve quantum efficiency. Furthermore, encapsulating QDs within protective polymer matrices or embedding them in hybrid glass structures has shown significant improvements in environmental resistance. However, such protective measures must be finely tuned to avoid compromising the material’s optoelectronic performance.

In the case of rare-earth doped nanocrystals, their inherent stability makes them particularly attractive for field applications. Their resistance to photobleaching and thermal degradation enables continuous operation under intense optical excitation, as required in up-conversion-based imaging and illumination systems. Nevertheless, the challenge lies in achieving uniform doping and preventing clustering of dopant ions, which can introduce luminescence quenching. Advances in sol-gel synthesis and controlled co-precipitation methods have helped to address this issue, producing highly stable phosphor nanoparticles with consistent emission properties.

Black phosphorus (BP), although highly promising due to its direct and tunable bandgap, remains chemically unstable under ambient conditions. Exposure to oxygen and moisture leads to rapid degradation, resulting in compromised electrical and optical properties. To overcome this, recent research has focused on developing encapsulation techniques using materials such as hexagonal boron nitride (h-BN), aluminum oxide (Al_2O_3), or graphene oxide layers. These barrier layers can effectively isolate BP from environmental contaminants, preserving its structural integrity and performance. Moreover, inert gas or vacuum packaging methods have been employed in experimental systems, although scalability remains a hurdle. From an integration standpoint, one major goal is the compatibility of these nanomaterials with standard silicon-based CMOS platforms. Ligand engineering, surface functionalization, and low-temperature deposition processes have been developed to facilitate this compatibility. In particular, hybrid architectures combining QDs with 2D materials like graphene or MoS_2 have enabled the creation of broadband photodetectors with improved flexibility and durability. For rare-earth nanocrystals, embedding within polymer waveguides or optoelectronic films offers seamless integration into existing sensor systems. Mechanical robustness is another key consideration. For deployment on UAVs or in soldier-worn gear, IR sensors must withstand vibrations, shocks, and harsh weather conditions. Nanomaterials are being incorporated into flexible, rugged substrates such as polyimide, PET, and PDMS to enhance resilience without sacrificing performance. In summary, while notable strides have been made in enhancing the stability and integration of nanomaterials, continued research is needed to transition lab-scale solutions into real-world, mission-ready technologies. Multilayer encapsulation, advanced packaging, and hybrid system designs are among the strategies poised to enable durable, next-generation IR imaging systems.

C. Environmental and Ethical Considerations

The deployment of nanomaterials in military infrared imaging systems introduces not only technological opportunities but also significant environmental and ethical challenges. As the defence sector increasingly turns to quantum dots (QDs), rare-earth doped nanocrystals, and black phosphorus (BP) to enhance night vision and surveillance capabilities, there is a growing need to evaluate the sustainability, safety, and societal impact of these advanced materials. This evaluation spans their entire lifecycle—from raw material extraction and synthesis to usage and end-of-life disposal.

One of the foremost concerns centers around the toxicity of conventional QDs, particularly those composed of heavy metals such as lead (Pb), cadmium (Cd), and selenium (Se). These elements, while essential for achieving desirable optoelectronic properties, are highly toxic and pose risks to both environmental ecosystems and human health. Accidental release during manufacturing, handling, or disposal could result in soil and water contamination, bioaccumulation in food chains, and occupational health hazards. In response, researchers are increasingly focused on developing environmentally benign alternatives such as indium phosphide (InP), copper indium sulfide ($CuInS_2$), and silicon-based QDs. These “greener” QDs provide competitive performance while significantly reducing ecological impact, although scalability and cost remain under investigation.

Rare-earth elements (REEs), though less toxic in their final forms, present another challenge due to their extraction and processing. The mining of REEs often results in large-scale land degradation, water pollution, and radioactive waste generation. Moreover, the global supply of these materials is geopolitically concentrated, raising ethical issues around resource exploitation, labor conditions, and supply chain monopolies. Sustainable sourcing, recycling of rare-earth elements from electronic waste, and synthetic substitutes are currently being explored to mitigate these impacts.

Black phosphorus, although free from heavy metals, poses its own set of environmental concerns. Its degradation products—phosphoric acids—are less toxic than heavy metals but can still alter soil and water chemistry if not properly contained. Moreover, the large-scale synthesis of BP via top-down exfoliation of bulk phosphorus remains energy-intensive and hazardous due to strong oxidizers and inert environments. Green synthesis routes, such as electrochemical exfoliation and plasma-assisted methods, are being developed to make BP production more sustainable and safer.

From a military ethics perspective, nanomaterial-enhanced night vision technologies' increasing miniaturization and efficiency raise questions about surveillance overreach, autonomous targeting, and privacy violations. While these technologies enhance national security, they may also be used in ways that conflict with international human rights norms or escalate conflicts through disproportionate surveillance or weaponization. Ensuring ethical governance over the development and deployment of such technologies is vital. This includes implementing robust export control frameworks, compliance with environmental and occupational safety standards, and fostering transparency in dual-use research. Lifecycle analysis (LCA) frameworks are being adopted to assess the full environmental impact of nanomaterials from cradle to grave. Military organizations are collaborating with environmental agencies, academic institutions, and industry partners to establish safe handling, recycling, and disposal protocols. Technologies such as encapsulation, solid-state matrices, and solvent-free fabrication are also being considered to reduce the environmental footprint during application. As nanomaterials become central to next-generation IR systems, balancing performance with sustainability and ethical responsibility will be critical. Future strategies must integrate eco-design principles, global regulatory alignment, and transparent ethical oversight to ensure that innovation in defence technologies does not come at the expense of planetary health and societal values.

VIII. RECENT ADVANCES AND INDUSTRY APPLICATIONS

A. Quantum Dots (QDs) in Infrared Imaging

Quantum dots (QDs) have emerged as leading candidates for next-generation infrared (IR) photodetectors and imaging platforms due to their size-tunable bandgaps, high photoluminescence efficiency, and compatibility with low-cost, solution-based processing techniques. Recent advancements in QD synthesis have focused on optimizing surface passivation, structural stability, and emission intensity within the short-wave infrared (SWIR) range. One of the most significant breakthroughs has been the development of InAs/ZnSe core/shell colloidal nanorod QDs. These nanorods demonstrate enhanced quantum yield and photostability under ambient conditions, making them highly attractive for integration into real-world IR imaging systems. The ZnSe shell in these heterostructures effectively passivates surface traps on the InAs core, thereby reducing non-radiative recombination pathways. This surface engineering not only stabilizes the QDs against oxidation and photodegradation but also enhances the photoluminescence intensity in the SWIR band (1000–1700 nm). As a result, detectors incorporating these QDs exhibit improved responsivity and detectivity when compared to their unpassivated counterparts. Furthermore, the anisotropic nanorod shape contributes to directional light absorption and enhanced charge separation, both of which are beneficial for photoconductive and photovoltaic IR devices. In terms of integration, QDs are compatible with silicon-based complementary metal-oxide-semiconductor (CMOS) technologies, allowing for the fabrication of hybrid IR focal plane arrays (FPAs) with high spatial resolution and spectral tunability. Techniques such as spin-coating, inkjet printing, and layer-by-layer self-assembly have been employed to deposit QD films on photodetector substrates, maintaining uniformity and strong coupling to electronic readout circuits. Their low-temperature processing requirements further support their use in flexible and lightweight imaging modules, suitable for drones, portable scopes, and helmet-mounted systems. Emerging research is now exploring the combination of QDs with two-dimensional materials like graphene and black phosphorus to enhance carrier mobility and broaden spectral sensitivity. Such hybrid architectures represent a major step forward in the development of compact, high-performance IR imaging systems for tactical military and surveillance applications.

B. Rare-Earth Doped Nanocrystals for Night Vision

Rare-earth doped nanocrystals have emerged as critical components for night vision technologies, particularly for their unique capability to emit in the near-infrared (NIR) and short-wave infrared (SWIR) spectral regions. These nanocrystals exhibit sharp and stable luminescence peaks due to the shielded 4f electronic transitions of rare-earth ions, which are largely unaffected by the surrounding host lattice. This property ensures consistent emission characteristics, even under high-temperature or high-radiation environments, making them exceptionally well-suited for military-grade imaging and surveillance systems. Among recent developments, $LiGa_5O_8:Cr^{3+}$ phosphors have demonstrated significant potential. These materials exhibit persistent luminescence in the NIR region (650–900 nm), allowing for afterglow imaging without the need for continuous external excitation. This property is especially advantageous in low-light conditions where stealth is critical, such as in covert military operations and long-range reconnaissance missions. The ability of Cr^{3+}-doped phosphors to be recharged by visible or NIR light further enhances their operational flexibility, making them ideal for passive night vision systems.

The synthesis of rare-earth doped nanocrystals typically involves solid-state reactions, sol-gel processes, or hydrothermal techniques to achieve high crystallinity and uniform dopant distribution. Host matrices such as Y_2O_3, $NaYF_4$, and $LaPO_4$ are frequently used due to their chemical stability and efficient energy transfer mechanisms. Recent efforts have focused on tailoring the doping concentration, co-doping strategies (e.g., Yb^{3+}/Er^{3+} or Yb^{3+}/Tm^{3+}), and nanocrystal morphology to optimize luminescence efficiency and photostability. From an application standpoint, these nanocrystals are being integrated into IR-emitting coatings, wearable imaging sensors, and optoelectronic components embedded in goggles, scopes, and unmanned systems. Their long luminescence lifetime also allows for time-gated imaging, which helps suppress background noise and improves target contrast in cluttered environments. Furthermore, rare-earth-based materials are inherently less toxic than heavy-metal QDs, offering a more environmentally sustainable alternative for night vision applications.

As research continues to optimize host-dopant combinations and improve nanocrystal processing, rare-earth doped systems are poised to become foundational in advanced night vision technologies across land, air, and sea-based military platforms.

C. Black Phosphorus (BP) in Mid-Wave Infrared Applications

Black phosphorus (BP), a two-dimensional layered material with a direct and thickness-dependent bandgap (ranging from ~0.3 eV in bulk to ~2.0 eV in monolayer form), has emerged as a promising candidate for mid-wave infrared (MWIR) applications. Its unique combination of high carrier mobility, broadband light absorption, and tunable electronic properties makes it ideal for optoelectronic devices operating in the MWIR spectrum (3–5 μm), which is particularly significant for thermal imaging, target acquisition, and missile guidance systems. One of BP's standout features is its in-plane anisotropy, which allows for directionally selective optical and electronic responses. This property can be harnessed in polarization-sensitive MWIR detectors, offering a novel imaging modality with enhanced contrast and information content. Additionally, BP exhibits high responsivity and fast photo response times, essential for real-time surveillance and tactical infrared applications where rapid signal processing is critical.

Recent studies have demonstrated BP-based photodetectors with responsivities exceeding 300 mA/W in the MWIR region, achieved through optimization of electrode contacts and dielectric encapsulation. These detectors are often fabricated using mechanical or liquid-phase exfoliation techniques to obtain few-layer BP, followed by integration on dielectric substrates like SiO_2/Si or sapphire. Incorporation of BP with plasmonic or dielectric meta-surfaces further boosts light absorption and sensitivity, paving the way for ultra-thin, miniaturized MWIR cameras.

However, BP's practical deployment has been challenged by its inherent instability in ambient conditions. Exposure to oxygen and moisture results in rapid degradation due to surface oxidation. To counter this, advanced encapsulation methods using materials such as hexagonal boron nitride (h-BN), aluminum oxide (Al_2O_3), and parylene films have been developed. These coatings preserve the optoelectronic properties of BP and extend device lifetimes under operational environments. Moreover, BP's compatibility with flexible substrates and low-temperature processing techniques makes it suitable for wearable MWIR sensors and UAV-mounted surveillance systems. Ongoing research is exploring the hybridization of BP with other 2D materials, such as graphene and MoS_2, to create broadband and multiband detectors with enhanced functionality. With continued progress in material stabilization and scalable synthesis, BP is set to play a pivotal role in the future of mid-infrared defence technologies.

D. Hyperspectral Imaging Systems in UAVs

Hyperspectral imaging (HSI) is revolutionizing remote sensing by enabling the capture of detailed spectral information across hundreds of contiguous bands. When integrated into unmanned aerial vehicles (UAVs), HSI systems significantly enhance situational awareness, reconnaissance, and target identification, particularly in defence and surveillance applications. Unlike conventional imaging, which captures data in a few spectral bands (such as RGB or thermal), HSI enables the detection of materials based on their unique spectral signatures, even under camouflage or poor visibility conditions. Recent advancements in miniaturization and sensor integration have made it feasible to deploy high-resolution HSI systems on compact UAV platforms. Companies like Specim, Headwall Photonics, and IMEC have developed lightweight hyperspectral payloads capable of operating across visible to short-wave infrared (SWIR) ranges (400 nm to 2500 nm). These systems are engineered to optimize weight, power consumption, and onboard processing—key requirements for UAV-based surveillance missions in constrained environments. In military operations, HSI-equipped UAVs are used for real-time battlefield mapping, monitoring enemy movement, detecting improvised explosive devices (IEDs), and identifying chemical or biological threats. For instance, camouflage materials that visually blend with surroundings can still be distinguished through their unique spectral reflectance patterns in SWIR or MWIR bands. This enables the detection of hidden equipment or personnel, even under foliage or netting. Modern hyperspectral systems employ either push-broom (line scanning), snapshot, or tunable filter technologies. Push-broom scanners are preferred for UAVs due to their high spatial and spectral resolution, although snapshot systems are gaining popularity for dynamic scenes where movement is critical. Integration with onboard AI and machine learning algorithms further enables real-time object classification, anomaly detection, and automatic decision-making. Data handling remains a key challenge due to the massive volumes of spectral information generated during flights. To mitigate this, edge computing modules and compression algorithms are increasingly used onboard to pre-process data before transmission. Coupled with GPS and inertial navigation systems, hyperspectral UAVs can generate geo-tagged spectral maps with high accuracy. With rapid progress in sensor technology, optics, and AI-assisted analytics, hyperspectral imaging on UAVs is poised to become a core capability in next-generation defence surveillance architectures.

IX. CONCLUSION

The convergence of nanotechnology and infrared imaging has ushered in a new era in military surveillance and night vision capabilities. Quantum dots (QDs), rare-earth doped nanocrystals, and black phosphorus (BP) are at the forefront of this transformation, offering unmatched control over optical and electronic properties that surpass the limitations of traditional infrared sensors. These materials bring flexibility in design, tunability across spectral regions, and compatibility with modern fabrication techniques, making them indispensable to the development of next-generation SWIR, MWIR, and LWIR imaging systems. Quantum dots, with their size-dependent bandgap and high quantum efficiency, offer precise control over infrared emission and absorption properties. Innovations such as InAs/ZnSe core/shell nanorods have significantly improved the photostability and efficiency of QDs, enabling their integration into compact, high-performance IR focal plane arrays. Similarly, rare-earth doped nanocrystals like $LiGa_5O_8:Cr^{3+}$ and Yb^{3+}/Er^{3+} co-doped systems provide persistent, stable NIR luminescence and offer environmentally safer alternatives for long-duration night vision operations. Black phosphorus, on the other hand, has introduced new capabilities in mid-wave infrared imaging due to its unique anisotropic behavior, high carrier mobility, and thickness-tunable bandgap. Despite challenges in ambient stability, advances in encapsulation and hybrid device architectures are making BP increasingly viable for field deployment in harsh environments. In parallel, the integration of these nanomaterials into hyperspectral imaging systems mounted on UAVs has opened up new avenues for covert surveillance, target identification, and environmental sensing. The ability to extract spectral fingerprints from complex scenes greatly enhances tactical decision-making and operational effectiveness in real time. The deployment of such lightweight, intelligent, and highly sensitive systems allows military forces to monitor larger areas with unprecedented spectral precision and spatial resolution. As research continues to address challenges related to material durability, environmental impact, and large-scale production, the path forward lies in the seamless fusion of advanced materials with AI-driven data analytics and system integration. These innovations will play a pivotal role in enhancing national security infrastructures, establishing technological superiority, and redefining the future landscape of military surveillance and night vision systems.

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