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Uncooled Microbolometers for Low-Power Battlefield Sensors

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Abstract: Uncooled microbolometers have emerged as transformative infrared (IR) sensing technologies in modern military applications, offering thermal imaging capabilities without cryogenic cooling. This evolution marks a significant leap in reducing size, weight, and power (SWaP) requirements—critical metrics for battlefield and defence-based systems. Operating primarily in the long-wave infrared (LWIR) spectrum, microbolometers detect radiation-induced resistance changes in thermally sensitive materials. Their compactness and operational simplicity make them ideal for deployment in portable systems, unmanned aerial vehicles (UAVs), smart munitions, and remote sentry devices. Traditional cooled IR sensors, while highly sensitive, demand extensive cooling systems that limit their applicability in mobile, low-power settings. Uncooled microbolometers, in contrast, function effectively at ambient temperatures, providing high reliability, lower cost, and rapid deployment. Moreover, integrating advanced nanomaterials such as vanadium oxide (VOx), amorphous silicon (a-Si), and graphene has substantially improved responsivity, thermal conductivity, and pixel sensitivity. The report explores the working principles, recent advancements in design and nanomaterial integration, and diverse military applications. Detailed focus is given to the use of these sensors in smart munitions, remote sentry systems, and portable imaging devices, highlighting their strategic value in surveillance, targeting, and situational awareness. Challenges such as durability under harsh conditions, fabrication scalability, and performance under variable environmental factors are also discussed. Future directions include nanomaterial hybridisation, AI-based signal processing, and ultra-compact sensor architectures. With continued innovation, uncooled microbolometers are poised to redefine thermal imaging in asymmetric warfare and real-time battlefield intelligence.

Keywords: *Uncooled Microbolometers, Thermal Imaging, Battlefield Sensors, Smart Munitions, Nanomaterials, Vox, Graphene, Low-Power IR Detectors, Remote Sentry Systems, Swap.*

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I. INTRODUCTION

In the dynamic landscape of modern military engagements, the demand for lightweight, portable, and low-power sensing technologies has intensified. As adversaries become more agile and technologically equipped, the necessity for real-time situational awareness, surveillance, and target acquisition under varied environmental conditions becomes paramount. Infrared (IR) sensing systems, particularly thermal imagers, have long served this purpose, providing vision capabilities in low-light or obscured visibility environments. Historically, the most sensitive IR detectors relied on cooled technologies, which involved complex cryogenic systems to maintain functionality at low temperatures. While they delivered high sensitivity and fast response times, the associated logistics, power consumption, and size rendered them less ideal for distributed battlefield deployments. The emergence of uncooled microbolometers presents a paradigm shift. These detectors operate effectively without cryogenic cooling, using temperature-dependent resistance changes in materials to detect infrared radiation. The resultant devices are not only smaller and lighter but also consume significantly less power—attributes that are invaluable in soldier-borne devices, UAV payloads, and autonomous sentry systems. In recent years, the convergence of nanotechnology with microbolometer design has pushed the envelope further. The incorporation of nanomaterials such as graphene, black phosphorus, and carbon nanotubes (CNTs) has enhanced sensitivity, thermal conductivity, and pixel-level resolution. These advances enable the development of high-resolution thermal imagers that are energy-efficient and suitable for a wide range of military platforms. This report delves into the foundational concepts of uncooled microbolometers, their operating principles, integration with advanced materials, and their broadening role in military operations. From remote surveillance to guided munitions and wearable systems, uncooled microbolometers are setting the stage for next-generation battlefield sensor technologies.

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II. WORKING PRINCIPLE OF MICROBOLOMETERS

Uncooled microbolometers function based on thermal detection principles that leverage the thermosensitive properties of certain materials. These devices primarily detect infrared radiation in the long-wave infrared (LWIR) band, typically from 8 to 14 micrometers, which corresponds to the thermal emissions of most objects at or near room temperature. A microbolometer pixel consists of a thermally isolated membrane suspended over a silicon substrate. This membrane typically includes an infrared-absorbing layer, a thermally sensitive material (e.g., vanadium oxide or amorphous silicon), and a reflective cavity to enhance photon absorption. When infrared radiation from a scene impinges on the pixel, it heats the membrane, causing a change in temperature. This temperature rise leads to a measurable change in the electrical resistance of the thermos resistive material, which is converted into an electrical signal via a readout integrated circuit (ROIC) (**Ref Fig.1**)

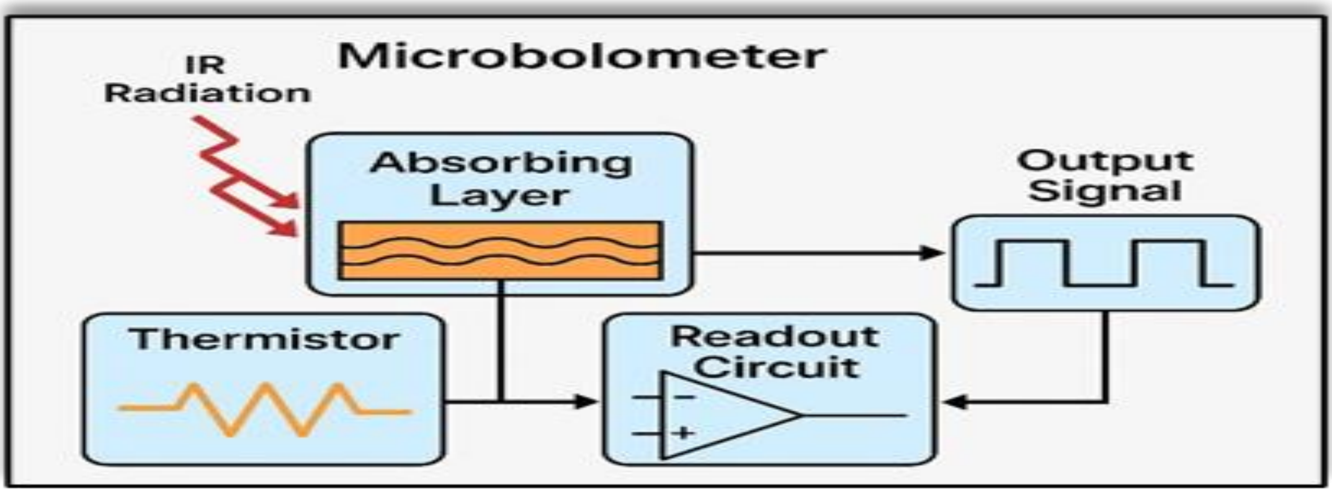

Fig 1 Schematic Diagram of an Uncooled Microbolometer.

Unlike photon-based detectors, which rely on quantum effects and require cryogenic cooling to minimise noise, thermal detectors such as microbolometers operate passively. Their performance is governed by parameters such as thermal time constant, noise equivalent temperature difference (NETD), thermal conductivity, and temperature coefficient of resistance (TCR). Lower NETD values and higher TCR values indicate better performance. The key innovation in microbolometer design is the use of micromachining techniques to create suspended microstructures with low thermal mass and high thermal isolation. These structures are fabricated using MEMS (Micro-Electro-Mechanical Systems) technology, enabling large pixel arrays to be manufactured at relatively low cost. Recent advancements focus on reducing pixel size to enhance resolution while maintaining or improving sensitivity. Nanostructured materials such as graphene and carbon nanotubes have been shown to offer high TCR, fast thermal response, and exceptional mechanical strength, making them suitable alternatives to conventional materials. Moreover, the elimination of the need for thermoelectric coolers allows for longer operational lifetimes, faster startup times, and increased reliability in harsh environments. This makes uncooled microbolometers particularly attractive for applications requiring stealth, durability, and mobility—traits essential for military deployment in the field.

III. NANOMATERIAL INTEGRATION

The integration of nanomaterials into microbolometer architectures marks a transformative shift in the development of thermal sensors, particularly in military and aerospace applications. Conventional microbolometers have primarily relied on vanadium oxide (VOx) and amorphous silicon (a-Si), which, while proven and cost-effective, present limitations in thermal response speed, sensitivity, and long-term stability. The advent of nanotechnology offers a new paradigm by introducing materials with superior physicochemical traits that directly enhance key performance parameters such as thermal sensitivity, electrical conductivity, and mechanical robustness.

A. Graphene, one of the most promising nanomaterials, is a single layer of carbon atoms arranged in a honeycomb lattice. Its exceptional thermal conductivity, reaching up to 5000 W/mK, and a high temperature coefficient of resistance (TCR) make it highly responsive to minute temperature variations—a critical requirement for accurate infrared (IR) detection. Additionally, graphene's mechanical flexibility and transparency pave the way for innovative detector architectures, such as flexible or transparent thermal imagers, which are ideal for next-generation wearable or embedded surveillance systems. Notably, graphene-based bolometers have demonstrated responsivity and noise-equivalent power (NEP) values that rival or exceed those of traditional VOx detectors.

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B. Carbon nanotubes (CNTs), which can be visualised as rolled-up sheets of graphene, possess tunable electrical properties depending on their chirality and diameter. Their hollow cylindrical structure offers a large surface-area-to-volume ratio, enhancing infrared absorption. Aligned CNT arrays act as efficient thermal transducers due to their rapid response time and high sensitivity to IR radiation. Their electrical conductivity and mechanical integrity also make them suitable for integration into flexible substrates, further diversifying potential applications.

C. Black phosphorus (BP), a lesser-known but rapidly emerging 2D material, exhibits strong infrared absorption and a unique anisotropic layered structure. This allows it to deliver direction-dependent thermal response, a feature that can be harnessed for creating directional infrared sensors. Such sensors can significantly improve spatial resolution and targeting precision in battlefield environments. Moreover, BP's tunable bandgap enables detection across a broad range of IR wavelengths, from near to mid-infrared, making it suitable for multi-spectral imaging.

To incorporate these materials into microbolometer designs, techniques like chemical vapor deposition (CVD), inkjet printing, and atomic layer deposition (ALD) offer scalability and uniformity. The creation of hybrid nanostructures, such as graphene-CNT or BP-CNT composites, further optimises device performance by merging the best attributes of each material. In sum, nanomaterials are not just enhancing microbolometer functionality; they are redefining what thermal imaging systems can achieve. By improving sensitivity, reducing power consumption, and enabling flexible form factors, these advanced materials are shaping a new generation of thermal sensors equipped for the complex demands of modern military operations.

IV. MILITARY APPLICATIONS

➢ *Smart Munitions*

Uncooled microbolometers are increasingly pivotal in the evolution of smart munitions, particularly in enhancing the precision and adaptability of guided weapon systems. Unlike traditional infrared sensors that require cryogenic cooling, uncooled microbolometers operate efficiently at ambient temperatures, offering a lightweight and energy-efficient solution ideal for compact and autonomous munitions. Their ability to detect infrared radiation emitted from heat sources—such as vehicle engines, human bodies, or equipment—enables thermal homing in diverse operational conditions, including darkness, fog, smoke, or cluttered urban environments. One of the standout advantages of microbolometers is their passive sensing capability. Since they do not emit signals, they maintain a stealth profile, avoiding detection by adversaries. This makes them especially suitable for covert and high-stakes operations, where exposure could compromise mission integrity. Smart munitions outfitted with these sensors can accurately engage targets even in GPS-denied zones or when visual cues are obscured, making them reliable tools in both conventional and asymmetric warfare. An exemplary case is the GBU-53/B StormBreaker, which employs a tri-mode seeker combining radar, infrared, and semi-active laser guidance. While specific sensor configurations are often classified, uncooled microbolometers offer a compelling option for thermal imaging due to their compactness and cost-efficiency. Moreover, recent advancements in nanomaterials such as graphene and carbon nanotubes significantly enhance the performance of microbolometers. These materials improve thermal sensitivity and reduce noise, which is crucial when distinguishing subtle heat signatures in complex combat scenarios. In urban warfare, where thermal contrast may be minimal and civilians are present, nanomaterial-enhanced sensors help reduce false positives and increase target discrimination accuracy. Overall, the integration of uncooled microbolometers, especially those leveraging nanotechnology, is redefining smart munitions, enabling precision, autonomy, and operational stealth in modern and future warfare.

➢ *Remote Sentry Systems*

Fixed surveillance systems and border monitoring stations rely heavily on thermal imaging to ensure comprehensive, all-weather security coverage. At the core of many modern installations are uncooled microbolometers, which enable passive, round-the-clock infrared monitoring without the logistical challenges and high energy demands of cooled alternatives. Their compact design, low power consumption, and durability make them particularly well-suited for remote and autonomous surveillance operations in challenging environments. These sensors are frequently deployed on gimbaled or pan-tilt platforms, enabling wide-area surveillance through continuous panoramic scanning and real-time target tracking. This flexibility allows for effective monitoring of expansive perimeters, border zones, or sensitive installations without constant human intervention. From arid deserts to icy polar frontiers, uncooled microbolometers perform reliably under extreme temperature fluctuations and low-visibility conditions, making them indispensable in defence and homeland security operations. The integration of AI-powered analytics significantly enhances the functionality of these thermal systems. By processing thermal data in real-time, AI algorithms can identify irregular movement patterns, differentiate between humans and animals, and detect unauthorised crossings. These intelligent systems can autonomously trigger alerts, activate lighting or drones, or even deploy non-lethal countermeasures, thereby extending response capabilities and minimising reaction time **(Ref Fig.2)**. Recent strides in nanomaterial-enhanced microbolometers—such as those utilising graphene or black phosphorus—have led to improved thermal sensitivity and image resolution. These advancements allow operators to detect and classify targets at greater distances with enhanced contrast, even under thermally ambiguous conditions where conventional sensors might fail. This capability is especially valuable in distinguishing real threats from environmental noise or deliberate decoys. In military bases and forward operating posts, these surveillance systems serve as force

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multipliers, reducing the need for manual patrols while ensuring continuous vigilance. As border security and strategic defence become increasingly automated, uncooled microbolometers remain central to safeguarding national interests through intelligent, resilient, and efficient surveillance infrastructure.

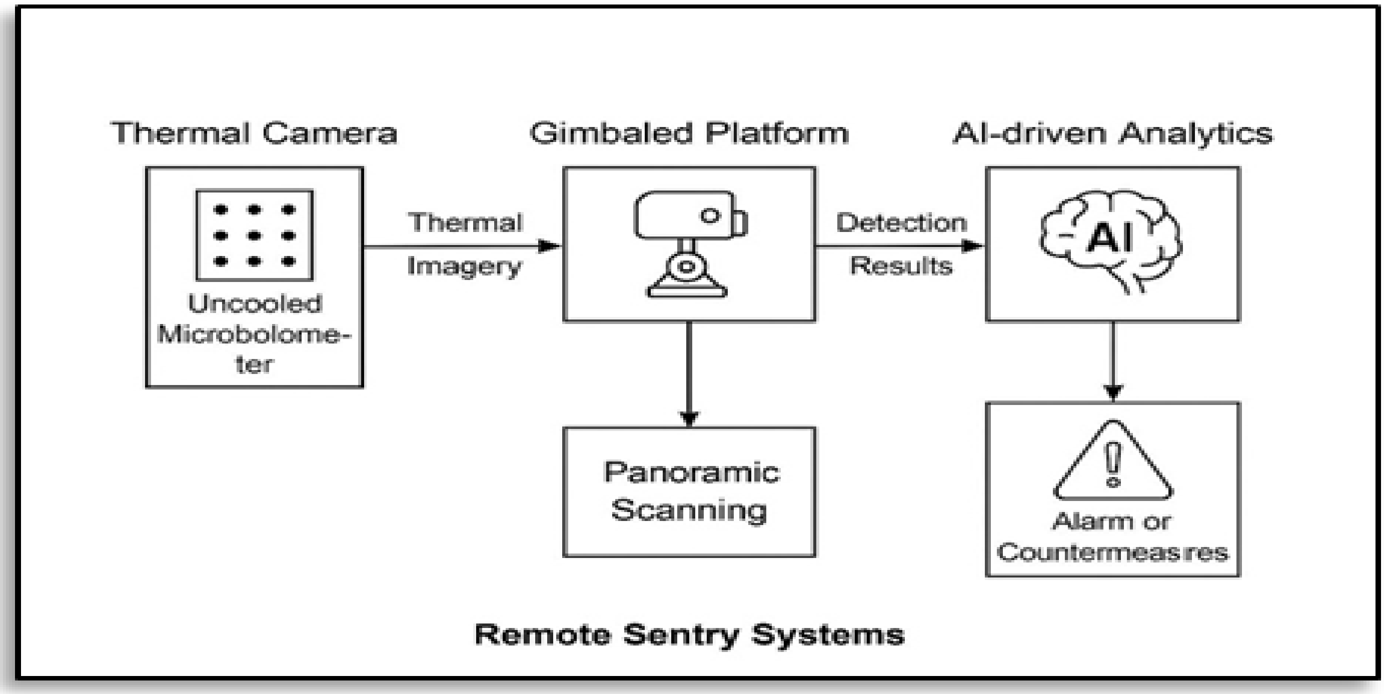

Fig 2 Schematic Diagram of a Remote Sentry System.

Examples include Israel’s border defence solutions and the U.S. Army’s Force Protection Suite, which rely heavily on thermal detection, increasingly favouring uncooled variants due to their cost-effectiveness and reduced maintenance.

➢ *Portable Imaging Gear*

Portable infrared imaging devices have become essential tools for modern soldiers engaged in reconnaissance, target acquisition, and threat detection. Leveraging uncooled microbolometers, these compact systems—ranging from handheld thermal monoculars and binoculars to helmet-mounted imagers—provide real-time thermal visualisation, empowering troops with enhanced situational awareness in complex and unpredictable environments **(Ref Fig.3**). Unlike traditional night vision that relies on ambient light, thermal imagers detect heat signatures emitted by objects, enabling operators to spot hidden or camouflaged adversaries, detect recently fired weapons, or monitor movement through smoke, fog, or complete darkness. This thermal advantage is especially crucial in asymmetric warfare scenarios, where identifying threats swiftly and accurately can determine mission success or failure. One of the defining benefits of uncooled microbolometers in portable gear is their lightweight and low-power design, which allows extended operation without imposing additional physical strain on soldiers. These systems are user-friendly, often requiring minimal training, and can be deployed rapidly in field conditions. Advancements in nanomaterials, particularly graphene and carbon nanotube (CNT)-based sensors, have further enhanced these devices by reducing the size of pixel elements while improving sensitivity and resolution. This miniaturisation has led to more compact and efficient thermal cameras that deliver high-definition imagery with lower power consumption—a crucial factor for battery-operated, wearable systems. A notable example is the Enhanced Night Vision Goggle-Binocular (ENVG-B), which integrates uncooled thermal imaging with image intensification, providing dual-mode vision for superior navigation, targeting, and threat detection. The inclusion of thermal sensing ensures operability in all weather and lighting conditions, making it an invaluable tool for both urban and wilderness operations. As battlefield dynamics continue to evolve, portable thermal imaging gear built on uncooled microbolometer technology is playing a critical role in giving soldiers the upper hand through improved visibility, faster decision-making, and increased survivability in high-stakes environments.

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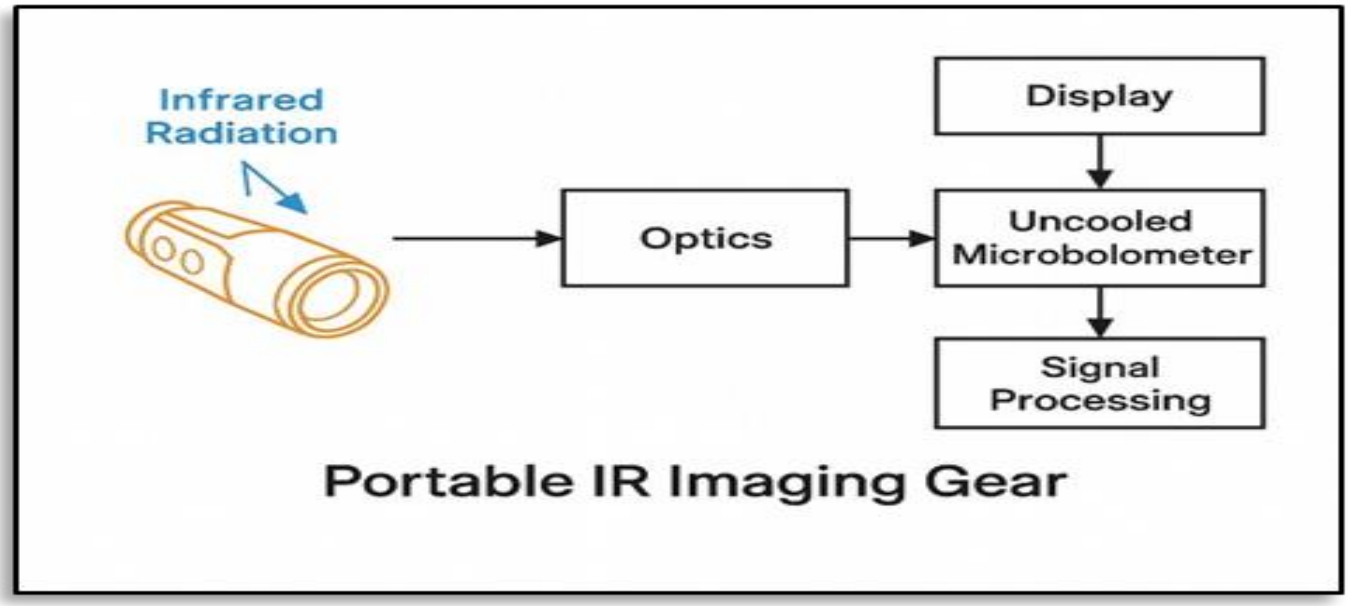

Fig 3 Schematic Diagram of a Remote Sentry System.

Future developments aim to integrate real-time data transmission and augmented reality overlays, further transforming portable imagers into command-and-control interfaces on the battlefield.

V. DESIGN AND MANUFACTURING ADVANCES

The design and manufacturing of uncooled microbolometers have undergone a significant transformation over the last decade. Originally limited by low resolution, high noise, and relatively large pixel sizes, modern microbolometers are now more compact, sensitive, and reliable—largely due to advancements in MEMS fabrication, nanomaterial science, and digital design methodologies. One of the primary focuses in design evolution has been the reduction of pixel pitch—the distance between the centers of adjacent pixels—from the early standard of 35 µm to today's sub-10 µm pixels. This reduction enables higher spatial resolution within the same sensor footprint, making microbolometers more viable for compact, high-performance imaging systems. Achieving smaller pixels while preserving thermal isolation, mechanical stability, and signal-to-noise ratios requires meticulous MEMS engineering and advanced materials. In battlefield environments, where sensors must distinguish subtle heat variations amidst clutter, maintaining high thermal sensitivity with reduced pixel size is critical. The shift from conventional sensing materials like vanadium oxide (VOx) and amorphous silicon (a-Si) to nanomaterials such as graphene, black phosphorus (BP), and hybrid composites marks a turning point in detector design. These materials possess superior electrical and thermal conductivity, allowing for faster response times and better thermal resolution. For instance, graphene-based absorbers can convert infrared radiation into electrical signals with higher efficiency due to their high carrier mobility and tunable bandgap. Additionally, 3D nanostructured absorber layers increase the effective surface area, improving thermal capture without increasing mass or size. To ensure mechanical robustness and performance reliability, modern microbolometer arrays incorporate thermally isolated support bridges, made using high-aspect-ratio structures via deep reactive ion etching (DRIE). DRIE facilitates the fabrication of precisely shaped suspensions that thermally decouple the active layer from the substrate, minimising heat loss and enhancing detector sensitivity. These isolated platforms are crucial for operation without active cooling systems, enabling truly uncooled sensor arrays. From a manufacturing perspective, wafer-level packaging (WLP) has significantly reduced both the size and complexity of microbolometer modules. WLP techniques allow for vacuum sealing, optical window integration, and mechanical protection to be performed directly on the wafer before dicing. This not only decreases the production cost but also increases yield and reliability, a vital factor for mass deployment in military systems. Another noteworthy trend is the monolithic integration of the readout integrated circuit (ROIC) with the detector array. This allows for reduced parasitic losses, increased signal integrity, and lower power consumption. With direct connectivity between the sensor pixels and readout electronics, system latency is minimised—a crucial benefit for applications involving fast-moving targets or autonomous threat detection. To further streamline development, AI and machine learning are now used in the design phase. Simulation-driven design optimisation, guided by neural networks or genetic algorithms, allows engineers to predict the thermal and electrical performance of a microbolometer before fabrication. These predictive models can quickly evaluate thousands of design permutations, ensuring the most effective structure is selected for prototyping.

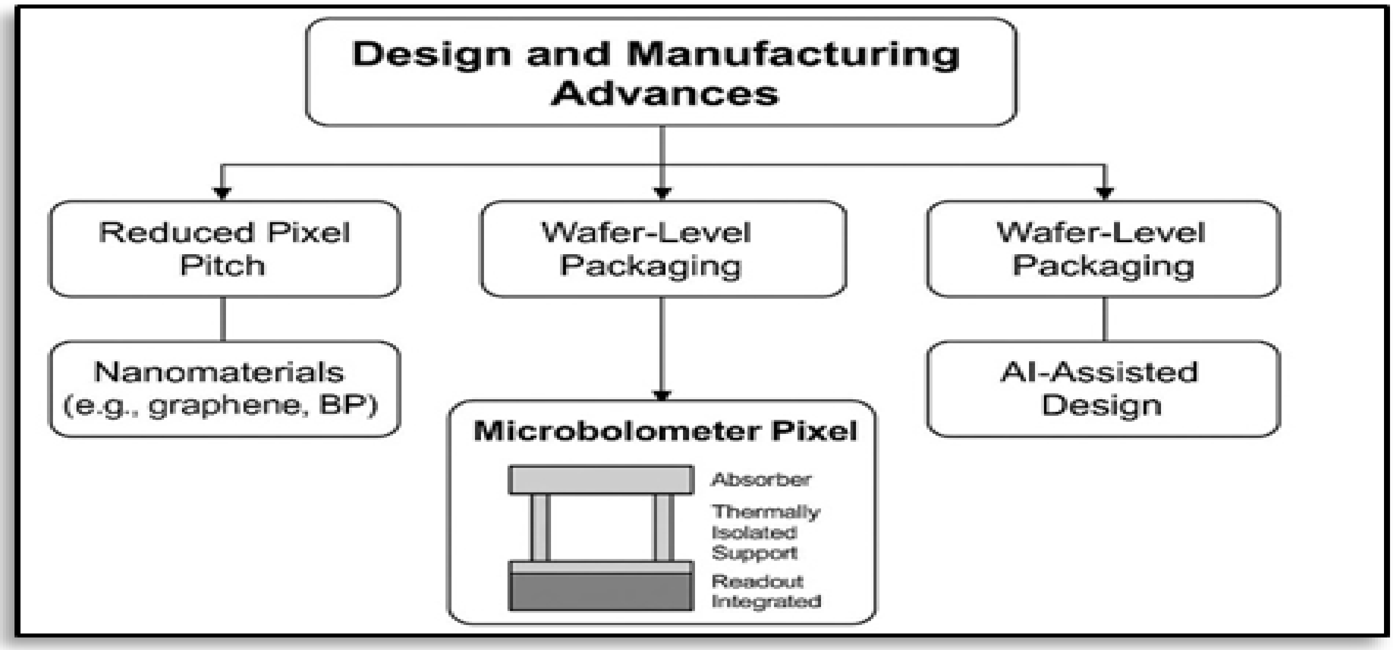

Fig 4 Advances in the Design and Manufacturing Techniques.

AI-assisted design not only reduces the time-to-market but also supports the creation of custom solutions for niche military applications. In addition, additive manufacturing and nanoimprint lithography are emerging as promising methods for low-cost and scalable production **(Ref Fig.4)**. These technologies enable direct printing of complex nanostructures on flexible substrates, opening the door to bendable or wearable thermal sensors that conform to various surfaces, including soldier uniforms, vehicle exteriors, or drone airframes. Finally, supply chain diversification and defence-backed manufacturing initiatives have improved access to critical fabrication resources, ensuring that microbolometer production can meet the rising demands of modern military forces. The fusion of nanomaterials, MEMS miniaturisation, AI-driven optimization, and scalable fabrication methods is revolutionizing the design and manufacture of uncooled microbolometers. These advances not only push the boundaries of sensor performance but also align with the evolving needs of lightweight, low-power, and high-resolution thermal imaging systems on the modern battlefield.

VI. OPERATIONAL CHALLENGES

➢ *Environmental Resilience*

Military environments present some of the harshest conditions for sensor technology, requiring robust and resilient systems capable of withstanding a wide range of physical and electromagnetic stressors. Uncooled microbolometers, which are widely used in infrared imaging, must operate effectively despite extreme temperature swings, intense vibrations, mechanical shocks, and continuous electromagnetic interference. One of the primary challenges lies in preserving the sensitivity and accuracy of these devices without sacrificing durability. While nanomaterials have demonstrated remarkable performance under controlled laboratory conditions, translating this performance to real-world military applications remains complex. These advanced materials often suffer from instability when exposed to environmental variables such as humidity, radiation, and prolonged mechanical stress. In aerospace and defence scenarios, exposure to high-energy radiation and atmospheric moisture can significantly degrade sensor performance or lead to functional failure. To mitigate these risks, innovative encapsulation and shielding techniques are required. These may include multi-layered coatings, hermetic sealing, or the integration of radiation-hardened nanostructures, all tailored to protect delicate nano-engineered components and ensure reliable, long-term operation in hostile environments.

➢ *Signal, Noise, and Drift*

Uncooled microbolometers, while advantageous due to their compactness and low power requirements, face persistent challenges related to signal noise and thermal drift. As passive thermal detectors, they rely on ambient infrared radiation without active cooling mechanisms, making them inherently susceptible to fluctuations in temperature and environmental conditions. This sensitivity often results in image noise, degraded thermal contrast, or even false thermal signatures—problems that are exacerbated in high-humidity or rapidly changing environments. Thermal drift, in particular, causes gradual shifts in baseline readings, which can distort thermal images and reduce reliability during extended operation. To address these limitations, researchers are leveraging a combination of hardware and software innovations. Pixel-level compensation techniques are being developed to correct for localised irregularities, while real-time calibration algorithms dynamically adjust output based on environmental feedback. Additionally, artificial intelligence and machine learning models are now being trained to recognise and suppress noise patterns, enhancing overall image clarity. These advancements aim to maintain image consistency, reduce false detections, and support critical decision-making in defence and surveillance applications where accuracy is paramount.

VII. FUTURE PROSPECTS

The future of uncooled microbolometers lies in hybrid technologies, AI integration, and material science innovations. Hybrid systems combining multiple nanomaterials—such as graphene-CNT composites—could offer enhanced thermal sensitivity and mechanical strength while maintaining fast response times. Researchers are exploring active pixel architectures that integrate pre-processing at the pixel level, reducing latency and enhancing contrast. Artificial intelligence and machine learning will play an increasing role in thermal image interpretation. AI can distinguish targets from clutter, correct for drift, and provide real-time threat classification—especially important in automated sentry systems and autonomous drones. Edge AI processors embedded in thermal systems will reduce the need for backhaul communication, allowing rapid decision-making on the battlefield. Miniaturisation efforts will continue, aiming for flexible or even textile-based microbolometer arrays for integration into uniforms and helmets. This will empower soldiers with persistent thermal vision without carrying additional gear. Similarly, conformal sensors for UAV fuselages or missile skins will offer 360-degree thermal awareness, significantly enhancing mission outcomes.

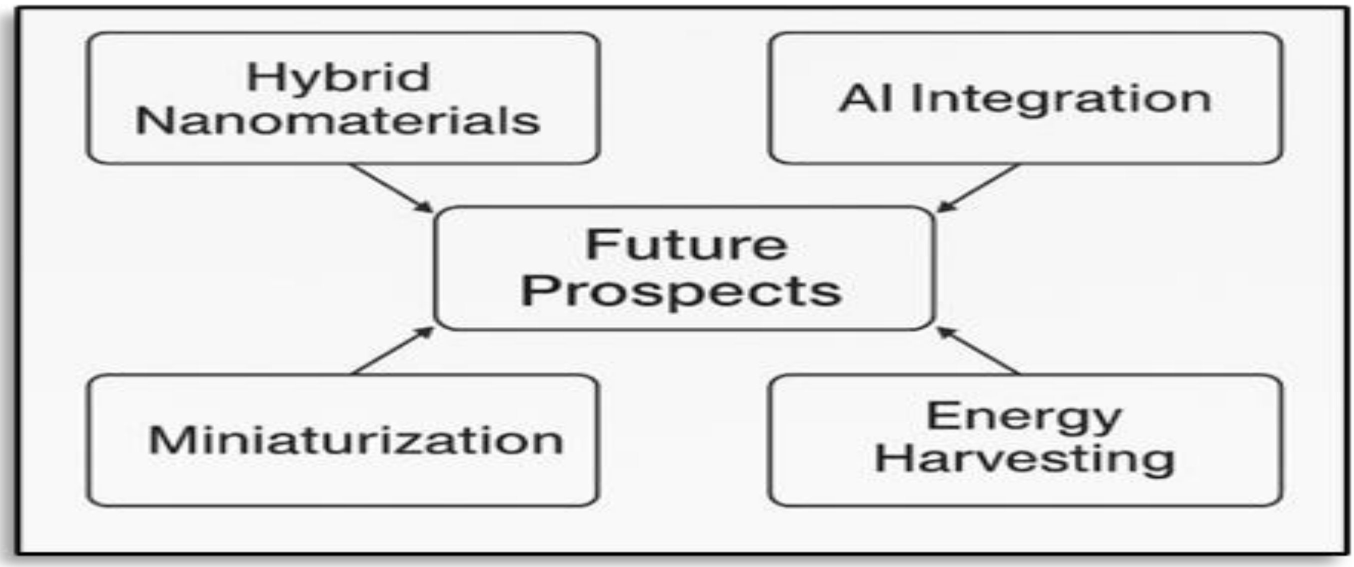

Fig 5 Future of Uncooled Microbolometers in Hybrid Technologies.

Energy harvesting techniques, such as thermoelectric generators and triboelectric materials, may power future uncooled microbolometers autonomously, reducing battery dependence and enabling continuous operation **(Ref Fig.5)**. Lastly, international defence collaborations and public-private partnerships are expected to drive funding and rapid technology transfer. With the rise of near-peer adversaries and increasingly complex theatres of war, the importance of uncooled microbolometer systems will only grow.

VIII. CONCLUSION

Uncooled microbolometers have revolutionised thermal imaging within military domains by offering a compact, energy-efficient alternative to traditional cryogenically cooled sensors. Operating passively, these devices detect infrared radiation without the need for cooling systems, significantly reducing power consumption and mechanical complexity. Their low weight and reduced thermal signature make them ideal for integration into mobile platforms, enhancing the agility and stealth of military operations. These attributes are crucial in dynamic combat zones, where real-time situational awareness can determine mission success. The infusion of advanced nanomaterials such as graphene, carbon nanotubes (CNTs), and black phosphorus has driven a new wave of innovation. These materials provide exceptional thermal conductivity, electron mobility, and mechanical flexibility, allowing microbolometers to achieve heightened sensitivity, faster response times, and improved image resolution. Their adaptability in harsh environments also makes them suitable for deployments in extreme temperature zones, high-radiation areas, and moisture-prone regions. Applications for these enhanced sensors have expanded rapidly, now encompassing smart munitions with real-time target tracking, autonomous perimeter defence systems, next-generation soldier-wearable optics, and lightweight payloads for UAVs and drones. However, the technology still faces challenges, including long-term durability, signal drift, and scalable nanomaterial integration for mass production. Ongoing advancements in artificial intelligence are enabling smart calibration, adaptive noise reduction, and predictive analytics to further refine sensor output. Looking ahead, uncooled microbolometers are poised to become multifunctional platforms, integrating with other sensor modalities to deliver enriched battlefield intelligence. Their evolution marks a pivotal shift toward smarter, more autonomous, and networked military sensing systems.

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