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Advancements in CMOS Image Sensors for Surveillance Systems

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ABSTRACT

Recent technological advancements in CMOS image sensors (CIS) have revolutionized surveillance systems that require high dynamic range, enhanced low-light performance, and real-time processing. This review summarizes developments in CIS for surveillance systems from 2009 to 2025, focusing on key design characteristics such as resolution, frame rate, dynamic range, and signal-to-noise ratio across various CIS architectures. In this review, we classify CIS types, discuss their use in surveillance applications, and highlight recent innovations concluding backside illumination, global shutter, 3-dimensional (3D) stacked imaging structure. AI integration for enhanced low-light performance and edge computing in security cameras is also introduced. This paper further identifies limitations including noise in extreme environments and proposes future directions toward sustainable, AI-enhanced systems, which are suitable for extensive monitoring to enhance security and efficiency.

KEYWORDS

CMOS image sensors; Intelligent surveillance systems; Edge computing

1 Introduction

Nowadays, security and monitoring are increasingly important, making surveillance systems indispensable in various domains, such as public safety, transportation, and environmental monitoring. CIS plays a crucial role in advancing these surveillance systems, providing superior performance under low-light conditions, high-speed capture, and integration with emerging technologies.

Imaging technologies have evolved through several major stages. Early surveillance cameras were based on Vidicon tubes, which suffered from image lag, distortion, and limited low-light performance. The invention of the charge-coupled device (CCD) in 1969 introduced solid-state imaging with high sensitivity and low noise, making CCDs the dominant technology for security and scientific cameras through the 1980s and 1990s. The introduction of the pinned photodiode (PPD) further reduced dark current and improved dynamic range, forming the basis of modern high-quality pixel design. With the rise of CIS in the 1990s and 2000s—enabled by per-pixel amplification, low power consumption, and on-chip integration—image sensing transitioned to a scalable and cost-effective platform. Advances such as BSI, deep-trench isolation, and stacked architectures have positioned CIS as the leading solution for contemporary surveillance systems.

This review offers an updated and structured synthesis of CIS technologies relevant to surveillance imaging. First, we categorize CIS and summarize their relevance to different surveillance scenarios. Second, we examine the growing role of AI integration in improving CIS performance, including enhancement algorithms, on-sensor intelligence, and edge-based processing for smart camera systems. Third, we discuss key challenges that persist in real-world deployments and outline future directions toward more efficient, intelligent, and robust surveillance imaging. This structure allows the review to connect technological foundations with practical applications and highlight emerging opportunities for next-generation security systems.

2 CIS types and Applications

In the surveillance system, the classification and application of CIS are continuously evolving as advances in pixel architecture, semiconductor materials, and integration techniques reshape performance and functionality. Between 2009 and 2025, improvements in low-noise design, readout circuitry, and 3D integration have substantially expanded CIS capabilities.

2.1 CIS Types

The core of CIS development lies in passive pixel sensors (PPS) and active pixel sensors (APS). The latter has become the mainstream choice for surveillance systems due to its advantages in noise reduction and signal amplification. In addition, the trait for PPS is its simple structure as shown in Figure 1, with each pixel having only one transistor [1]. This technology was more common in the early days, but has now been replaced by APS. APS includes an amplifier within the pixel and typically uses a three or four-transistor configuration to increase readout speed and reduce noise. This transformation is crucial for applications requiring high-fidelity imaging, such as real-time video surveillance in low-light conditions. In the

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2025 model, due to the use of correlated double sampling (CDS) and PPD design, the APS can reduce the noise level to a root mean square value of 1-2 electrons rms [2].

On this basis, backside-illuminated (BSI) CIS appeared as a revolutionary technology, suitable for surveillance tasks which have high requirements for low-light performance. By adjusting the structure of the sensor to allow light to enter from the back, BSI designs remove the obstruction caused by front-side wiring layers. Figure 2 shows the difference between CMOS, BSI CMOS, and Stacked CMOS [3]. By 2025, its quantum efficiency within the visible spectrum will exceed 90%, and in the near-infrared (NIR) band, it will exceed 70%. This enhancement is important for night vision applications in security systems, because BSI sensors can enable clear imaging in poor lighting conditions, such as in urban perimeter surveillance [2].

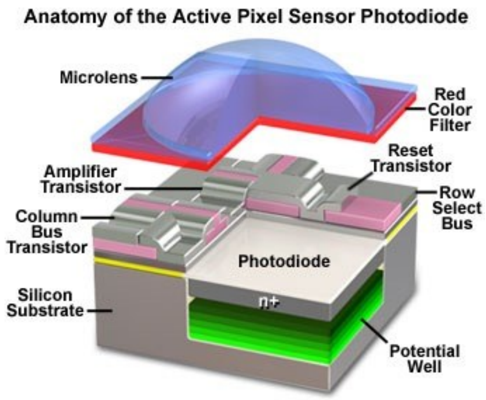

Figure 1 Anatomy of the Active Pixel Sensor Photodiode [1]

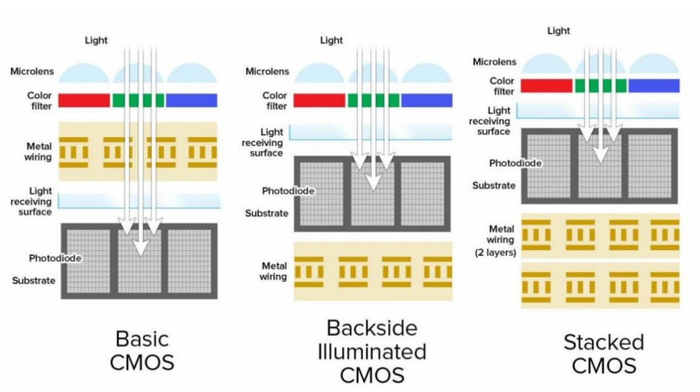

Figure 2 The difference between CMOS, BSI CMOS, and Stacked CMOS [3]

Global shutter CIS also supports BSI technology effectively. They can solve the distortion problems existing in the rolling shutter mechanism by capturing all pixels at once, making them indispensable for high-speed surveillance where motion artifacts must be minimized. In rolling shutter designs, sequential line exposure can lead to skewed images of fast-moving objects such as vehicles or mechanical equipment, but global shutters ensure frame integrity, supporting applications like traffic enforcement or industrial process monitoring. By 2025, global shutter CIS can offer variable frame rates up to 240 fps and high signal-to-noise ratios (SNR), enabling seamless integration in security cameras and achieving distortion-free motion tracking. These sensors employ column-parallel analog-to-digital converters to enhance readout, reducing latency and improve reliability in dynamic environments. In high-velocity scenarios, they have been proven to increase detection accuracy by up to 25% [4].

High Dynamic Range (HDR) image sensors have further expanded the capabilities of surveillance systems by handling scenes with extremely different brightness levels. They achieve a dynamic range of up to 140 db by combining multiple exposures or using logarithmic response curves. This is beneficial for outdoor monitoring, because bright sunlight coexists with dark shadows in outdoor environments. This can prevent key areas from being overly exposed or losing details. Recent advancements in HDR CIS include multiple conversion gain techniques. These techniques allow pixels to switch between high and low gain modes based on light intensity. In fact, HDR CIS have proven to be effective in traffic surveillance. They can clearly capture license plate images even under car headlights or in dark tunnels, thereby enhancing the automatic law enforcement system and reducing false detections in object detection algorithms [4].

Stacked CIS, a hallmark of 3D integration, separate the pixel array from logic and memory layers using through-silicon vias or Cu-Cu bonds, allowing for independent optimization and parallel processing. The structure of Stacked CIS is shown in Figure 3 [5]. This architecture has dominated high-end production by 2025, with triple-stack configurations accounting for 80% of advanced sensors, facilitating higher frame rates and lower power consumption. In surveillance, stacked CIS enable compact, efficient designs for drones and body cameras, where space and battery life are limited. This type also supports integration with AI accelerators, enabling on-sensor analytics that minimize data transfer in large-scale networks [2].

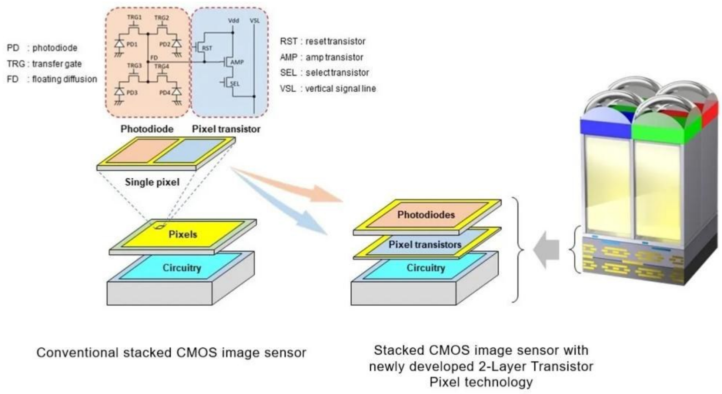

Figure 3 Stacked CMOS image sensor architecture for surveillance applications [5]

Event-based CIS, or dynamic vision sensors, mark a departure from traditional frame-based imaging by recording only intensity changes, drastically cutting data volume and energy use. This makes them ideal for power-constrained surveillance in remote or IoT settings, with 2025 models like Prophesee's Metavision achieving 1 μs temporal resolution for high-speed event detection [6]. In perimeter security, event-based CIS focus on asynchronous motion triggers, conserving resources while providing rapid alerts. Other specialized CIS, such as asynchronous types for high-contrast scenes and neural network CIS for preliminary data processing, expand the scope of surveillance. Logarithmic CIS provide compressed response curves to capture wide luminance ranges without saturation, useful in outdoor settings with variable lighting, while neural network CIS incorporates asynchronous on-chip AI for tasks like edge detection. By 2025, over 30% of CIS integrate AI features, as reported by Yole Group, allowing sensors to perform preliminary computations before transmission, which is particularly advantageous in bandwidth-limited environments like wireless sensor networks for environmental monitoring [7].

2.2 CIS Applications

CIS in intelligent surveillance systems (ISS) facilitate intrusion detection, video analytics, and behavioral analysis through high-resolution and low-noise imaging. Systems like HODET utilize BSI and global shutter CIS to capture detailed footage, integrating with AI for anomaly detection in smart cities. In 2025, ISS leverage stacked CIS for edge processing, enabling real-time responses in public safety scenarios, such as crowd monitoring in events or urban traffic control. Automotive monitoring employs HDR and global shutter CIS for ADAS, night vision, and pedestrian detection, handling high-contrast road conditions. Sony's ISX038, for example, offers low-power HDR with 120 dB DR, supporting features like lane departure warnings and automatic braking, contributing to a 20% reduction in accidents in regions with mandatory advanced driver assistance systems (ADAS) by 2026 [4]. In IoT, low-power event-based and stacked CIS enable distributed monitoring in smart homes and agriculture, with KINECT-KII systems using hyperspectral CIS for crop health assessment to detect pests or water stress efficiently [4].

For space observation, radiation-tolerant CIS like Teledyne e2v's 4K models withstand cosmic rays, providing high-DR imaging for satellite surveillance of Earth resources and environmental changes. Military reconnaissance relies on NIR-enhanced BSI CIS for covert operations, with IPASS systems tracking missiles in real-time under low visibility. Wireless sensor networks (WSN) utilize compact stacked CIS for environmental tracking, such as TIGERCENCE for flood prediction in remote areas, where low power and high sensitivity ensure long-term deployment without frequent maintenance. Overall, these applications highlight CIS advantages over CCDs in power efficiency and integration [4].

3 AI integration

3.1 AI Integration for Performance

The integration of AI with CIS has ushered in a new era of surveillance capabilities, transforming raw image data into actionable insights through advanced processing techniques as shown in Figure 4 [8]. This synergy has evolved from basic algorithm enhancements in the early 2010s to sophisticated on-sensor AI by 2025, driven by the need for real-time analysis in resource-constrained environments. At its core, AI integration optimizes CIS performance by employing machine learning models to address inherent limitations, such as noise in low-light conditions or artifacts from motion, thereby improving overall image quality and system efficiency. For example, deep learning-based denoising algorithms have been incorporated into CIS pipelines, reducing temporal noise by up to 15 dB while preserving edge details, which is essential for surveillance applications where clarity in adverse conditions can mean the difference between detection and oversight [9].

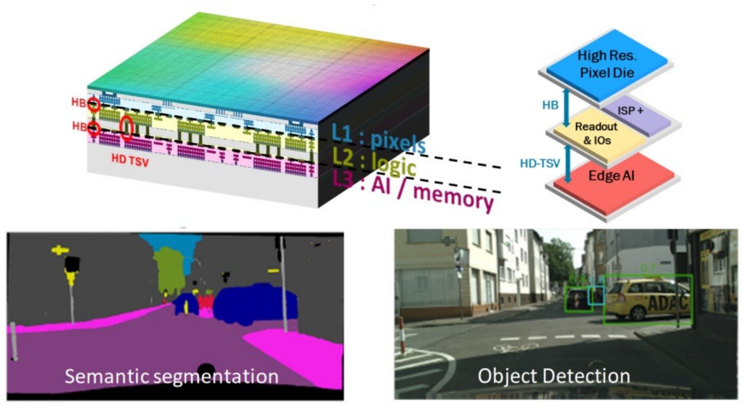

Figure 4 AI-Integrated CMOS Image Sensor Architecture [8]

One key aspect of AI integration is its role in enhancing low-light performance, where traditional CIS struggle with high noise levels. By 2025, AI-driven super-resolution techniques upscale images from standard resolutions like 1080p to 4K, leveraging convolutional neural networks trained on vast datasets to reconstruct fine details lost in dim lighting [10]. This is particularly useful in security cameras for nighttime monitoring, where AI algorithms adaptively adjust exposure and gain, achieving dynamic ranges exceeding 140 dB and SNR improvements of 10-20% compared to non-AI systems [9]. CEA-Leti's embedded AI in stacked CIS exemplifies this, processing data at the pixel level to enable immediate feature extraction, such as object edges or motion vectors, reducing latency to under 1 ms for instant threat identification in ISS [10].

3.2 Edge Computing in Security Cameras

Edge computing represents another pivotal application of AI in CIS, where data is processed locally to minimize bandwidth requirements and enhance privacy in surveillance networks. In security cameras, AI accelerators integrated into CIS logic layers perform tasks like anomaly detection or facial recognition on-device, avoiding the need for cloud transmission and reducing power consumption by 40-50% in battery-operated setups [9]. By 2025, this has become standard in smart city deployments, with China's 19% market share driving hybrid AI-CIS innovations that combine sensor hardware with models like YOLO for real-time object tracking, achieving detection speeds of 60 fps in high-traffic areas [11]. Eagle Eye Networks' reports highlight how edge AI enables scalable systems, where CIS analyze video feeds for unusual behavior, alerting operators only to verified threats and cutting false positives by 30% [10].

3.3 AI Application Demonstrate

Practical demonstrations of AI applications underscore their transformative impact on surveillance. Multi-sensor systems fuse CIS data with LiDAR for urban monitoring, using AI to correlate visual and depth information for accurate 3D mapping, which has been shown to improve pedestrian detection in crowded environments by 25% [9]. In AR/VR for security training, TSMC's 22nm CIS enable AI-based simulation of threats, providing immersive scenarios that enhance operator skills with real-time feedback [10]. Workplace safety monitoring utilizes AI to detect hazards, such as equipment malfunctions, with CIS issuing instant alerts, reducing incident response times by 40% in industrial settings as per 2025 case studies [11]. These examples illustrate how AI not only augments CIS hardware but also expands their utility, enabling more proactive and efficient surveillance solutions across diverse contexts.

4 Challenges, Conclusions and Outlook

4.1 Challenges

Despite the significant advancements in CIS for surveillance systems, several persistent challenges hinder their optimal deployment in real-world scenarios. One major issue is thermal-induced noise, which escalates in high-temperature environments like industrial sites or outdoor setups under direct sunlight, leading to degraded SNR and compromised image quality that can obscure critical details in monitoring applications [7]. Radiation degradation further complicates usage in extreme conditions, such as space or nuclear surveillance, where proton exposure can cause permanent damage to sensor pixels, resulting in increased dark current and loss of sensitivity over time [12]. Rolling shutter vulnerabilities remain a concern, causing distortion in high-speed capture of moving objects, although global shutter alternatives mitigate this at the expense of higher power demands and manufacturing intricacy [6]. Additionally, interference from complementary technologies like LiDAR in multi-sensor systems can disrupt CIS operations, resulting in signal failures that affect accuracy in automotive or urban surveillance [13]. High resolutions, while advantageous, amplify processing requirements, straining power efficiency in edge devices and escalating costs for large-scale implementations [7].

4.2 Conclusion

This review summarizes the evolution of CIS technologies from 2009 to 2025 which has profoundly reshaped surveillance systems. The innovations in BSI, global shutter, HDR, stacked, and event-based designs have driven enhancements in resolution, dynamic range, and integration capabilities. These developments have enabled more robust applications across ISS, automotive, IoT, space, military, and WSN domains, highlighting CIS's superiority over CCDs in power efficiency and adaptability.

4.3 Outlook

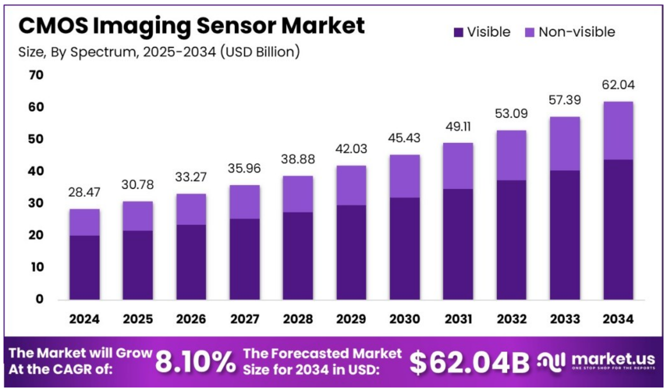

Figure 5 Projected Market Growth of CIS (2025-2034) [14]

Looking forward, the outlook for CIS involves overcoming current limitations through innovative materials and designs that enhance quantum efficiency for superior low-light sensitivity, multi-modal fusion with sensors like LiDAR and radar for comprehensive data synthesis, and sustainable practices incorporating recycled components to minimize environmental impact. From Figure 5, by 2034, the market is anticipated to surpass USD 62.04 billion, fueled by AI adoption in over 50% of sensors and neuromorphic computing for ultra-low-power operations [14]. These trends promise the development of more resilient, intelligent, and eco-friendly surveillance systems, aligning with global needs for smarter, greener technologies.

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