# CMOS Based Image Sensors

**Sushil Tirpude, Ashish Jaypurkar, Swapnil Chavhan**

*Sushil Tirpude Dept. of Electronics and Telecommunication , Jagdambha college of Engineering and Technology, Yavatmal , Maharastra , India*
*Swapnil chavhan, Dept. of Electronics and Telecommunication , Jagdambha college of Engineering and Technology, Yavatmal , Maharastra , India*
*Ashish Jaypurkar Dept. of Electronics and Telecommunication , Jagdambha college of Engineering and Technology, Yavatmal , Maharastra , India*

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**Abstract:** *CMOS image sensors are pivotal in modern imaging devices due to their compactness, energy efficiency, and cost-effectiveness. Operating on the principle of light-to-digital conversion, these sensors utilize pixel-level circuitry for noise reduction and faster data readout. Their advantages include low power consumption, integrated processing, and high-speed capabilities. As a result, CMOS image sensors are widely used in consumer electronics, automotive, medical imaging, industrial automation, and scientific applications, shaping the future of digital imaging technology*.

**Keyword: CMOS; optoelectronic imager; infrared imaging; focal plane array.**

## 1. Introduction:

The CMOS (Complementary Metal-Oxide-Semiconductor) image sensor has revolutionized visual technology, powering devices like smartphones, digital cameras, and medical imaging tools. Unlike traditional CCD sensors, CMOS sensors offer enhanced capabilities, making them pivotal in modern imaging.

Operating on the photoelectric effect, CMOS sensors feature an array of pixels, each a miniature light-capturing unit. These pixels convert light into proportional electric charges, forming the basis of image capture. Uniquely, CMOS sensors integrate readout circuits within each pixel, a design known as Active Pixel Sensor (APS). This enables parallel signal processing at the pixel level, resulting in faster readout speeds and reduced power consumption.

The APS architecture incorporates amplifiers and control circuits within each pixel, granting flexibility in signal processing. Additionally, CMOS sensors often embed on-chip processing functions such as noise reduction and colour correction. This streamlines image enhancement and optimizes overall quality, decreasing the need for extensive post-processing. Energy efficiency is a highlight of CMOS sensors. Their integrated structure and individual pixel addressing minimize power demands, especially beneficial for portable devices like smartphones. Rapid data readout is another asset, crucial for real-time video and capturing fast-moving subjects, enhancing video quality and responsiveness. Cost-effectiveness sets CMOS sensors apart. Their manufacturing aligns with standard semiconductor techniques, making them more affordable than CCD sensors. This accessibility fuels their broad adoption across industries and consumer markets.

CMOS sensors play diverse roles. In smartphones, they enable seamless photo and video capture. In science, they aid in astronomy and microscopy. Security cameras leverage their swift data readout and on-chip processing for effective surveillance. Automotive applications utilize CMOS sensors for advanced driver assistance and autonomous systems.

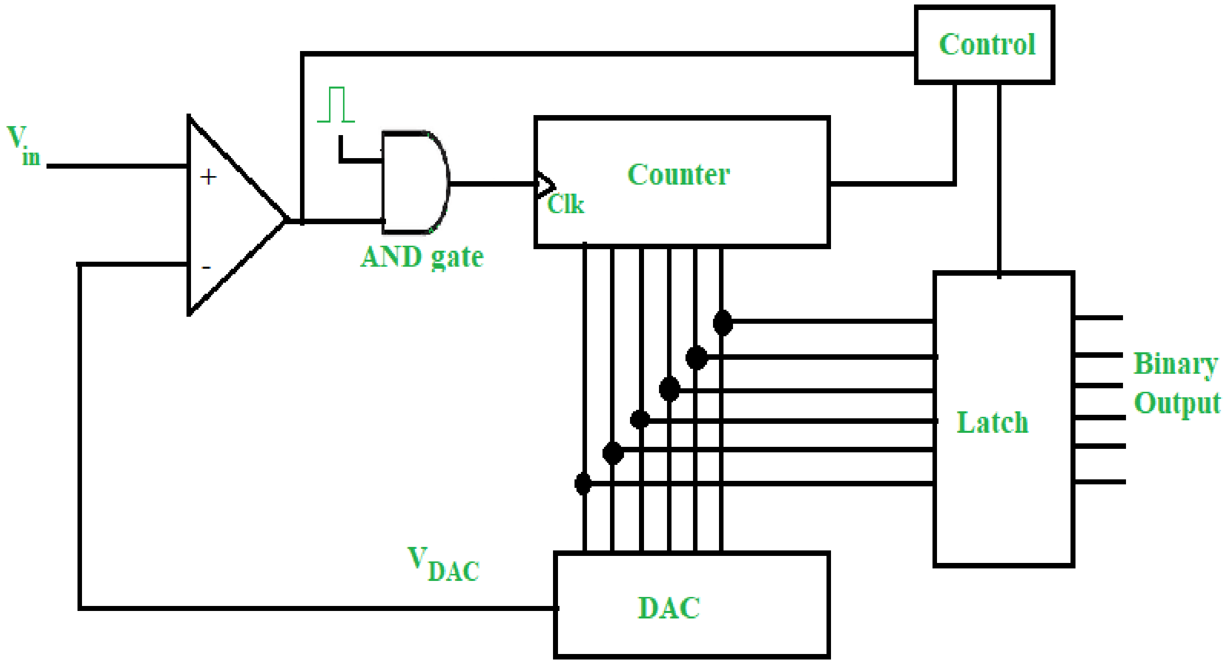
CMOS sensors have evolved, boasting improved sensitivity to light, resolution, and dynamic range. Their ongoing progress cements their dominance in the imaging landscape, promising continued advancements in fields like healthcare and entertainment.

### 1.1Section snippets :-

### Analog signal processors

An analog signal processor (ASP) integrated within a CMOS image sensor performs pivotal functions to enhance captured analog signals. This processor amplifies pixel-generated signals, applies gain adjustments, and utilizes techniques like correlated double sampling (CDS) to mitigate noise. Additionally, it corrects fixed pattern noise, optimizes black levels, and may include analog-to-digital conversion (ADC) capabilities. The ASP also contributes to color filter array (CFA) processing for accurate color reconstruction and implements noise reduction strategies. Overall, the ASP readies analog signals for subsequent digital processing, ensuring improved image quality and fidelity in the final output.

**Analog to digital convertor:**



Analog-to-digital converters (ADCs) are essential components within CMOS image sensors, converting continuous analog signals into discrete digital values for efficient processing and storage. Photodiodes within image sensors capture light and create analog signals proportional to the light intensity. ADCs quantize these analog voltages into binary digital codes, with higher bit depths enabling more precise representations.

Dynamic range, a critical factor, determines the ADC's ability to capture both bright and dark regions accurately. It ensures details in highlights and shadows are preserved without saturation or loss. Fast conversion speed is crucial for high-speed imaging, enabling rapid pixel readout for video and fast-moving scenes.

ADCs also influence power efficiency; lower power consumption extends device battery life, making them suitable for portable applications. Noise performance matters too. ADCs can introduce noise during conversion, affecting image quality. High-quality ADCs maintain accuracy while minimizing noise impact.

ADC architectures vary, such as successive approximation and delta-sigma, each balancing speed, accuracy, and power efficiency. Integration of ADCs onto the same CMOS chip as the sensor optimizes signal transfer, minimizes data degradation, and enhances overall efficiency.

In sum, ADCs are the linchpin for translating analog light signals into digital image data. Their role in maintaining dynamic range, speed, power efficiency, and noise performance greatly influences image quality and the capabilities of CMOS image sensors in various applications.

**CIS Circuit:-**

CIS are mainly of four types. They are Passive Pixel Sensor (PPS), Active Pixel Sensor (APS), Pinned Photodiode (PPD) and Digital Pixel Sensor (DPS). These types are discussed below.

### 1.2 Passive Pixel Sensor (PPS)

A Passive Pixel Sensor (PPS) is an imaging technology used in digital cameras and sensors. Unlike Active Pixel Sensors (APS), PPS eliminates the need for complex readout circuitry within each pixel. Each pixel directly connects to a single output line, simplifying the sensor's structure. PPS works by modulating the capacitance of each pixel in response to incident light, with the charge representing the light intensity. This modulation is achieved through variations in the pixel's capacitance, which changes as light falls on it. The capacitance changes are then converted into electrical signals and read out from the sensor. While PPS offers advantages like reduced fabrication complexity and potentially lower power consumption, it can also suffer from lower sensitivity and readout speed compared to APS technology. However, ongoing research aims to address these limitations and further enhance PPS performance.

#### 1.2.1: Active Pixel Sensor (APS)

An Active Pixel Sensor (APS) is a type of image sensor used in digital cameras, smartphones, and other imaging devices. Unlike Passive Pixel Sensors, APS includes active components like amplifiers and digitization circuitry within each pixel. This integration enables each pixel to amplify and convert light signals into electrical voltages, enhancing sensitivity and allowing for faster readout speeds. When light strikes the photosensitive element of a pixel, it generates a charge that is then amplified by an adjacent transistor. This charge-to-voltage conversion allows for accurate representation of light intensity. APS technology offers benefits like improved signal-to-noise ratio, higher frame rates, and better performance in low-light conditions. However, the complexity of the readout circuitry can result in higher power consumption and potential manufacturing challenges. APS continues to be refined and developed to achieve higher resolutions and better overall image quality.

#### 1.2.2: Pinned Photodiode (PPD)

A Pinned Photodiode (PPD) is a specialized type of photodetector used in image sensors, particularly in digital cameras and other imaging devices. It's designed to enhance the performance of Active Pixel Sensors (APS) by reducing leakage current and improving charge capacity. A PPD consists of a photosensitive region and a pinned (or unpinned) layer, which helps prevent the flow of excess charge carriers (electrons or holes) during readout. This design reduces dark current, enhancing image quality, especially in low-light conditions. PPDs offer high quantum efficiency and lower noise, which contributes to improved signal-to-noise ratios and better dynamic range in images. The technology is widely used in modern CMOS image sensors, enabling them to capture more accurate and detailed images even in challenging lighting environments.

#### 1.2.3: Digital Pixel Sensor (DPS)

As of my last knowledge update in September 2021, there is no widely recognized or established technology referred to as "Digital Pixel Sensor" (DPS). It's possible that this term has emerged after my last update or may be a specific term used in a certain context or by a particular manufacturer.

However, if we speculate on the term, a "Digital Pixel Sensor" could imply an image sensor where each pixel directly generates digital output without the need for analog-to-digital conversion. This could potentially simplify the readout process and reduce noise introduced during conversion. Such a technology could have implications for faster data transfer and potentially improved dynamic range in certain scenarios.

### 1.3 The fabrication process of a CMOS (Complementary Metal-Oxide-Semiconductor)

Image sensor involves several key steps. Keep in mind that technology evolves, and the specifics of the process can vary based on the semiconductor manufacturing node and the design choices of the manufacturer. Here is a generalized overview of the CMOS image sensor fabrication process:

1. Substrate Preparation:

   - The process typically begins with a silicon wafer, which serves as the substrate.

   - The wafer undergoes cleaning and polishing to remove impurities.

2. Epitaxial Growth:

   - A thin, single-crystal layer of silicon (epitaxial layer) is grown on the wafer to improve the electrical properties.

3. Photolithography - Patterning:

- A layer of photoresist is applied to the wafer.

- The wafer is exposed to ultraviolet light through a mask, creating a pattern on the photoresist.

- The exposed or unexposed areas are selectively removed, leaving a pattern on the wafer.

4. Ion Implantation - Doping:

- Dopants (impurity atoms) are introduced into the silicon to alter its electrical properties.

- This step is crucial for creating n-type and p-type regions necessary for transistor formation.

5. Oxidation:

- A thin layer of silicon dioxide ($SiO_2$) is grown on the wafer's surface through thermal oxidation.

- This oxide layer provides insulation between different layers of the circuit.

6. Deposition:

- Thin films of various materials, such as polysilicon and metal, are deposited on the wafer's surface.

- These layers form the transistors, interconnects, and other components of the CMOS circuit.

7. Photolithography - Patterning (Again):

- Additional photolithography steps are performed to define the features of the transistors and interconnects.

8. Etching:

- Unwanted material is selectively removed through etching processes.

- This defines the shapes of the transistors and interconnects.

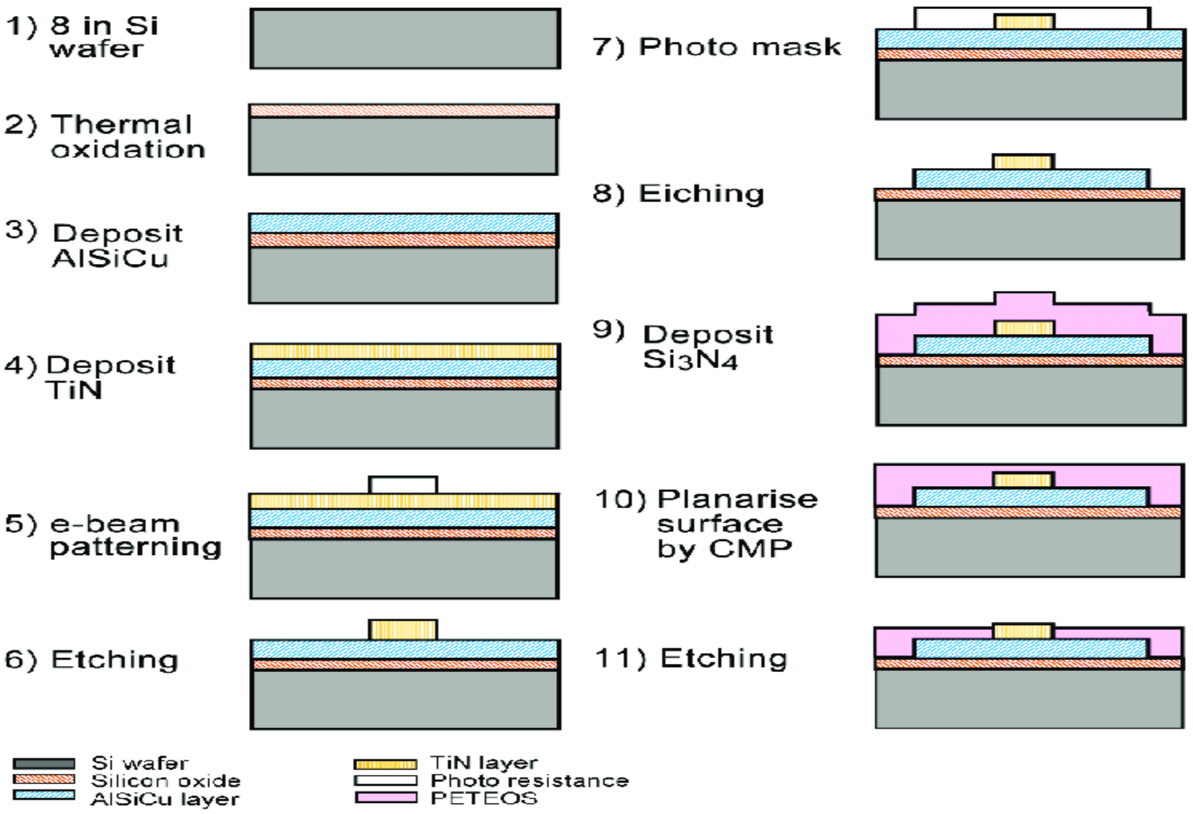
9. Back-End-of-Line (BEOL) Process:

- Further layers of metal and dielectrics are added to complete the interconnect structure.

10. Testing and Packaging:

- The fabricated wafer undergoes testing to ensure the functionality of individual sensors and the entire chip.

- The wafer is then cut into individual dies, and each die is packaged for integration into camera modules or other devices.



### 1.3 Noises In Image Sensors:

Noise in image sensors" refers to unwanted variations in captured images caused by factors like photon fluctuations (shot noise), electronic processes (readout noise), and manufacturing variations (fixed pattern noise). Temporal noise and quantization noise also contribute. These disturbances degrade image quality, affecting clarity and accuracy.

Photons arriving randomly create photon shot noise, noticeable in low light. Readout noise stems from electronics reading pixel charges. Fixed pattern noise results from pixel sensitivity differences. Temporal noise varies pixel output over time. Quantization noise arises during analog-to-digital conversion due to discrete levels.

Strategies to combat noise encompass sensor design, calibration, and post-processing techniques. Noise reduction algorithms like filtering and denoising mitigate noise while preserving image detail. Larger sensors, improved signal-to-noise ratio, and exposure adjustments help minimize noise impact.

Understanding and managing these noise sources are vital for achieving high-quality images in various applications, ensuring accurate representation and visual fidelity.

### 1.4 Application of CMOS :

Complementary Metal-Oxide-Semiconductor (CMOS) technology finds diverse applications due to its low power consumption, scalability, and integration capabilities. In electronics, CMOS is fundamental for integrated circuits (ICs), microprocessors, and microcontrollers, powering devices like computers, smartphones, and IOT devices.

CMOS image sensors are prevalent in digital cameras, smartphones, and medical imaging equipment. They offer low power consumption, enabling longer battery life, while providing high-quality images and videos.

In analog circuits, CMOS is used for amplifiers, voltage converters, and data converters due to its low noise and power efficiency. CMOS-based analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) enable accurate signal processing in communication systems and sensors.

CMOS also plays a role in radio frequency (RF) applications. CMOS RF circuits are used in wireless communication devices, such as Wi-Fi routers and cellular transceivers.

In recent years, CMOS technology has extended to the field of biosensors, enabling the development of lab-on-a-chip devices for medical diagnostics, DNA analysis, and environmental monitoring.

Moreover, CMOS has made its way into emerging technologies like quantum computing, where it is used to control qubits and read out their states.

Overall, CMOS technology's versatility and low power consumption have led to its integration into numerous applications, shaping the modern technological landscape.

### 1.5 Discussion:

Complementary Metal-Oxide-Semiconductor (CMOS) technology has significantly transformed numerous industries due to its low power consumption, scalability, and integration capabilities. Its impact spans diverse sectors, from digital electronics and processors to imaging sensors. CMOS technology is the backbone of modern digital devices like microprocessors and microcontrollers, ensuring efficient energy usage and enabling high-speed processing. It has revolutionized imaging through CMOS image sensors, powering digital cameras and smartphones with high-quality photo and video capabilities. In the realm of analog circuits, CMOS has led to precision amplifiers and data converters, crucial for communication systems and sensors. The emergence of CMOS radio frequency (RF) circuits has transformed wireless communication, while CMOS sensors find applications in various domains including automotive electronics, biomedical devices, and the Internet of Things (IoT). Its integration even extends to quantum computing and space exploration. Overall, CMOS technology's versatility and energy efficiency have positioned it as a driving force behind technological progress across an array of applications.

### 1.6 Conclusion:

The CMOS image sensor is a transformative technology that integrates photodetectors, processing circuitry, and conversion capabilities into a single chip. Despite challenges like noise, these sensors have revolutionized imaging across various domains. Ongoing evolution promises enhanced resolution, dynamic range, and innovative AI integration, pushing the boundaries of visual experiences. The CMOS image sensor's trajectory shapes a future where imaging surpasses current limits, underscoring its vital role in reshaping the landscape of digital visual capture.

In summary, CMOS-based image sensors stand as essential components in electronic imaging, marked by continuous evolution and heightened versatility. The intricate fabrication process, encompassing substrate preparation to packaging, underscores the complexity of semiconductor manufacturing, pivotal in creating efficient imaging solutions. Current research emphasizes performance enhancement, addressing challenges, and extending applications, portraying a field ripe for interdisciplinary collaboration. Celebrating the accomplishments of CMOS image sensors is synonymous with acknowledging a dynamic technological landscape that promises continued innovation. As we recognize their pivotal role in diverse applications from digital cameras to medical imaging, the ongoing pursuit of knowledge and collaborative efforts within the scientific community becomes paramount. This technology's future holds exciting prospects, with researchers and engineers at the forefront, driving advancements that will shape the next phase of CMOS image sensor evolution. In essence, the celebration of past achievements serves as a catalyst for the collective commitment to exploration, ensuring that CMOS-based image sensors will remain at the forefront of transformative technological progress.

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6. Books:
"CMOS: Circuit Design, Layout, and Simulation" by R. Jacob Baker: This book covers CMOS technology, including design principles and layout considerations.
"CMOS Image Sensors: Theory and Practice" by R. M. Guidash: Provides a comprehensive overview of CMOS image sensor theory and practical considerations.

7. Online Resources:
"Image Sensors World" (https://image-sensors-world.blogspot.com/): A blog that regularly updates with news and developments in the image sensor industry.

8. Research Papers:
Explore databases like IEEE Xplore, PubMed, or Google Scholar for specific research papers related to your topic of interest. Look for papers from reputable conferences and journals.