

Development Research Summary of CMOS High-Speed Image Sensors

Haichuan Kang

College of Mechanical Engineering, Xihua University, Chengdu, China

* Corresponding author: Jixue Xiao

Abstract: The CMOS high-speed image sensor is a new type of image sensor that has the advantages of high speed, low power consumption, and low noise, and has received widespread attention and research. The CMOS high-speed image sensor has a wide range of applications in medical imaging, industrial inspection, and security monitoring both domestically and internationally. However, this sensor still has some problems in image noise, such as dark current and dark noise. This article proposes strategies such as using new materials and optimizing device structures for optimization. With the continuous advancement of technology, the performance of this sensor in resolution, frame rate, dynamic range, and other aspects will be further improved.

Keywords: CMOS image sensor, image noise, high-speed image sensor, CMOS process.

1. Introduction

With the continuous advancement of technology, image sensors have become an indispensable part of modern society. Among the many types of image sensors, CMOS image sensors (CIS) have attracted attention and research in the fields of digital cameras, mobile phones, security surveillance, etc., due to their low power consumption and high integration. CMOS sensors are solid-state image sensors based on complementary metal-oxide-semiconductor technology, which are camera chips with built-in pixels. The term "built-in pixels" refers to the fact that each pixel of the sensor can perform charge conversion. This type of image sensor with built-in pixel points reduces the energy consumed in image generation and simplifies the circuitry, thereby expanding the methods of reading and converting visual information. It provides intuitive, true, multi-level, and multi-content visual image information, and has the advantages of low power consumption, high integration, and ease of manufacturing [1].

This article aims to provide a review of the development history, technical features, and application fields of CMOS image sensors, analyze the development and application of this sensor domestically and internationally, summarize the main issues currently existing with the sensor, and the solutions provided by experts at home and abroad for different aspects of the problem. Finally, it discusses the future development direction of this technology. Through the study of this sensor, it can provide strong support and impetus for the development of related fields.

2. Domestic and International Development Status

With the rapid development of the semiconductor industry, the manufacturing technology of CMOS image sensors is also continuously advancing. CMOS image sensors integrate digital and analog circuits within their internal structures, with resolutions and sensitivities greatly improved from the initial million pixels to today's tens of millions and even hundreds of millions of pixels. Prominent companies in the domestic and international CMOS image sensor market, such

as GCM (GalaxyCore Microelectronics), SmartSens, and BYD, have a multitude of mature products and application solutions in this field.

2.1. Development and Application of CMOS Image Sensors in Asia

Compared to traditional CCD image sensors, CMOS image sensors have the advantages of low power consumption, ease of manufacturing, high integration, and low cost. Moreover, CMOS image sensors can achieve high-speed readout, high frame rates, and high resolution, making them widely applicable in high-speed photography, motion capture, virtual reality, and other fields [2].

In Asia, the research on CMOS image sensors started relatively late, but in recent years, with the rapid development of China's semiconductor industry, the research and application of CMOS image sensors have also been rapidly advanced. Currently, universities and research institutions are actively conducting research on CMOS image sensors, involving fields such as design, manufacturing, and testing. Companies like GCM (GalaxyCore Microelectronics), SmartSens, and BYD have conducted extensive research and application on CMOS image sensors. These companies have achieved certain results in the design, packaging, and application of CMOS image sensors and are also exploring the application of CMOS image sensors in emerging fields, such as virtual reality, augmented reality, and autonomous driving.

Japan has also achieved outstanding results in this area. For example, in 2000, the Ishikawa laboratory [3] introduced the "1ms Column Parallel Vision System (CPV)" system, which can significantly shorten the visual feedback time of the sensor. However, the system sacrifices image resolution while increasing the rate and can only be used for certain specific scenarios. In 2006, ShiMiZu et al. [4] designed a CMOS+FPGA vision system solution using the high readout speed of CMOS and the parallel data processing capability of FPGA. The system uses a CMOS sensor capable of capturing images at a frequency as high as 1000Hz. Sony Corporation in Japan is one of the leading manufacturers in this field, and its CMOS image sensor products have been widely used in

smartphones, digital cameras, and other fields.

In the future, the development of CMOS image sensors will be even more rapid, bringing more innovation and development opportunities to the field of digital image processing and applications.

2.2. Application of CMOS Image Sensors in Western Countries

Research on CMOS image sensors began in the 1980s, and with continuous technological advancements, the performance of CMOS image sensors has been improving. However, there are still some key technical challenges that are difficult to overcome. In recent years, Western countries have been deepening their research on the critical technologies of CMOS image sensors. The main technological advancements include the following aspects.

Firstly, the issue of resolution. With the popularity of devices such as digital cameras and smartphones, the demand for high resolution has also increased. Although some CMOS image sensors can achieve resolutions exceeding 100 million pixels, they still struggle to meet market demands.

Secondly, low-noise technology. Noise is an important factor affecting image quality, determining the integrity and authenticity of the image. In this regard, CMOS image sensors far exceed other types of sensors.

Thirdly, high dynamic range. Dynamic range refers to the difference in brightness between the brightest and darkest areas of an image. To capture high-quality images, CMOS image sensors must achieve a dynamic range exceeding 100dB.

Fourthly, increased readout speed. High-speed readout means that CMOS image sensors can read image data in an extremely short time. To achieve high-speed photography and motion capture applications, CMOS image sensors can achieve readout speeds of millions of pixels per second.

In Europe and America, many well-known technology companies such as Apple, Google, and Intel have conducted extensive research and development in this field. Apple's iPhone series uses CMOS image sensor technology, while Google's Pixel series phones use CMOS image sensors from Sony. Additionally, Intel has conducted extensive research and development in this area and has launched several high-performance CMOS image sensor products. Germany's Bosch company has adopted CMOS image sensor technology in the automotive field for autonomous driving and intelligent driving assistance systems.

The global market for CMOS image sensors is very large. In 2017, the growth rate of this sensor reached 20%, marking an important turning point in market growth. By 2018, the global market size for CMOS image sensors had reached 15.5 billion US dollars, and in 2019, it grew by 10% year-on-year, increasing to 17 billion US dollars. With the continuous progress in research and application of CMOS image sensors, their application fields are also expanding and deepening, and it is expected that the market size will exceed 20 billion US dollars by 2025.

2.3. Development History

The evolution of image sensors can be traced back to 1873 when scientists Joseph May and Bruno Schweitzer first proposed the concept. Entering the 1950s, the photomultiplier tube (PMT) was introduced. Subsequently, between 1965 and 1970, companies such as IBM and Fairchild developed photoelectric and bipolar diode arrays. In 1970, the Bell

Laboratories invented the CCD image sensor, which quickly became the market mainstream due to its high quantum efficiency, sensitivity, low dark current, consistency, and low noise. It was not until the late 1990s that CMOS sensors were first put into use, initially applied to computer memory chips. With continuous technological advancements, the design and manufacturing technology of CMOS sensors became stable and reliable, and CMOS sensors began to be applied in digital cameras, mobile phone cameras, security surveillance, and other fields.

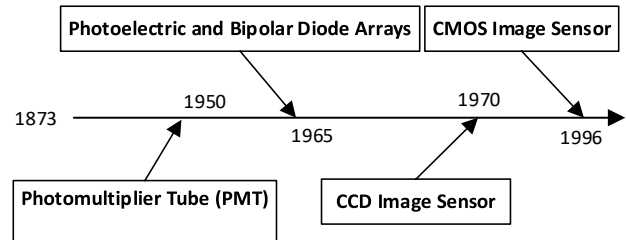


Figure 1. The Evolution of Image Sensors

The birth of CMOS image sensors has gradually turned the concept of "chip cameras" from imagination into reality, with the size of cameras becoming increasingly smaller. In the field of digital cameras, the application of CMOS sensors began in 1999 when Sony introduced the world's first digital camera with a CMOS sensor. Subsequently, CMOS sensors gradually replaced CCD sensors to become the mainstream in digital cameras. The launch of the Siimpel AF camera in 2007 represented a significant advancement in camera miniaturization. The rise of chip cameras has opened up new possibilities for technological innovation in multiple industries.

In the field of mobile phone cameras, the application of CMOS sensors has also been widely promoted. As mobile phone cameras continue to upgrade, the pixel count and image quality of CMOS sensors have seen significant improvements. In the security surveillance field, the application of CMOS sensors is becoming more widespread. Compared to CCD sensors, CMOS sensors have lower power consumption and higher integration, enabling higher image quality and lower costs [5].

The development history of CMOS sensors can be summarized as a transition from computer memory chips to widespread applications in digital cameras, mobile phone cameras, security surveillance, and other fields.

3. Current Issues with CMOS Image Sensors

3.1. Noise Issues in CMOS Image Sensors

Due to factors such as manufacturing processes and circuit design in CMOS image sensors, various types of noise are generated, such as dark current noise, readout circuit noise, and quantization noise, which affect image quality [6, 7].

The impact of noise on CMOS image sensor imaging is mainly manifested in two aspects: (1) The magnitude of noise limits the ability of CMOS image sensors to handle weak light signals. When CMOS image sensors are imaging under low-light conditions, the signal amplitude is small, and noise severely affects the quality of the image. The main parameter for measuring this standard is the signal-to-noise ratio (SNR). (2) The magnitude of noise limits the dynamic range characteristics of the image sensor. Since the dynamic range of the image sensor is equal to the ratio of the maximum non-

saturated signal to the noise, and the magnitude of noise is generally low, the dynamic range is very sensitive to changes in noise [8].

Figure 2 lists the main factors causing noise in CMOS image sensors and the current suppression techniques for noise in CMOS image sensors. Understanding these noise sources and their suppression methods is crucial for optimizing image processing and enhancing sensor performance.

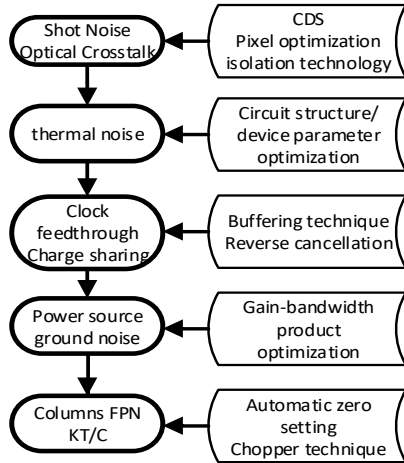


Figure 2. Sources of Image Sensor Noise and Traditional Solutions

3.2. Imaging Error Issues of Image Sensors

During the data acquisition process of image sensors, various factors can interfere, such as deviations from the ideal position of the principal point, lens distortion, atmospheric turbulence, etc. At the same time, due to the inherent characteristics of the sensor itself, the captured image differs from the actual scene to some extent [9, 10].

The error factors caused by the sensor's own characteristics include: dark current leading to uneven background brightness in the image, dark current noise affecting the signal-to-noise ratio of the image, and dark field non-uniformity causing uneven background brightness in the image.

3.3. Image Acquisition Noise Issues

To reduce the noise generated during the acquisition process of CMOS image sensors, experts and scholars at home and abroad have conducted extensive research. Researchers such as Zheng Ran and Zhao Ruiguang [11] have explored the impact of spatial radiation on the random telegraph noise characteristics of CMOS image sensors and their generation mechanisms, achieving significant progress in related testing methods. Wang Bo and Li Yudong [12] focused on the radiation mechanism of CMOS APS image sensors, established a testing system for radiation effect parameters, and conducted research on testing methods for radiation-sensitive parameters. Wang Yan and Li Binqiao [13] optimized line noise, successfully eliminating random horizontal stripes in the image, thereby expanding the application range of sensors in low-light environments. Zhao Yuanfu [14] proposed some hardening schemes from the perspective of circuit implementation, but found that with increased radiation, the dark current rose significantly, increasing by an order of magnitude, and it was difficult to maintain low-noise characteristics at the same time. Reference [15] achieved a high radiation index, but key indicators fluctuated greatly under radiation changes, making

it difficult to meet the needs of practical applications. Guo Zhongjie and Wu Longsheng et al. [16] proposed a timing improvement based on the sampling circuit, achieving multi-level optimization of system noise, making the resistance to total dose radiation higher than 100k rad (Si). This improvement based on the timing of the sampling circuit significantly enhanced the growth rate of dark current and noise with radiation.

The main purpose of the traditional correlated double sampling method is to eliminate fixed pattern noise caused by process differences, power supply fluctuations, and threshold inconsistencies during the pixel output process. The principle of this method is to sample the reset signal and the integration signal in segments, then perform differential processing on these two, and finally obtain the true image signal. According to the principle model of the correlated double sampling technique, it actually samples the same signal at different time points. In the correlated double sampling circuit, after the input signal is sampled and processed, two sampling values are generated, which correspond to different time moments. These two sampling values are sent into the correlator for correlation operation, thereby obtaining the output signal. In the time domain, there is a certain relationship between the input signal and the output signal, which can be described by a mathematical model:

$$V_0(t) = V_i(t)[\delta(t) - \delta(t - t_d)] \quad (1)$$

Taking the Fourier transform of equation (1) yields equations (2) to (4):

$$v_0(s) = v_i(s)(1 - e^{-st_d}) \quad (2)$$

$$\frac{v_0(s)}{v_i(s)} = 1 - e^{-st_d} \quad (3)$$

$$\left| \frac{v_0(s)}{v_i(s)} \right| = |1 - e^{-st_d}| = 2 - 2 \cos(2\pi f t_d) \quad (4)$$

According to the aforementioned mathematical model, the correlated double sampling circuit can effectively suppress low-frequency noise while allowing high-frequency noise to pass through, thereby eliminating the fixed pattern noise caused by process variations and the 1/f noise within the pixels. By employing two stages of correlated double sampling, the second stage of correlated double sampling can eliminate the low-frequency 1/f noise and power supply noise from the high-speed column readout circuit.

3.4. CMOS Image Sensor Error Correction Issues

In response to the issues of image sensor errors, researchers have conducted studies on automatic correction methods and have achieved certain results. For instance, some scholars have used the Monte Carlo method to analyze the imaging errors of image sensors, established simulation models based on the analysis results, and thus realized error correction [17]. Additionally, researchers have proposed correction methods based on Extreme Learning Machines (ELM), primarily compensating for temperature and environmental factors of the sensor, and using the ELM algorithm to correct errors [18]. At the same time, scholars have designed correction methods based on pattern recognition, classifying image data, and utilizing the relationship between the generated image's field of view and distortion, employing fitting techniques to correct errors [19]. These methods have significantly reduced the errors of image sensors.

In recent years, with continuous breakthroughs in the field of artificial intelligence, there have been new approaches to error correction for image sensors—automatically correcting errors based on deep learning algorithms. Huang Meiyi [20] proposed an automatic method for correcting image sensor errors, which is based on deep learning algorithms. Specifically, he used Support Vector Machines (SVM) to compensate for the offset angle of the image sensor and constructed an automatic error correction model through deep learning algorithms, considering various influencing factors. Ultimately, a coarse calibration mechanism was used to fit the sensor's response parameters, thereby achieving automatic error correction for image sensors.

4. Future Development Trends

CMOS technology has clear advantages in cost and performance, giving it greater market development potential. With the continuous advancement of manufacturing processes in the future, there is still a lot of room for cost reduction. Reducing image noise is one of the main challenges faced by CMOS image sensors [21]. Additionally, the development direction of CMOS image sensors will focus on increasing integration, striving to integrate functions such as pixel acquisition, clock and control units, A/D conversion, and signal processing together, in order to achieve smaller size and better performance, becoming true single-chip cameras [21]. It is not hard to predict that the future development trend of CMOS image sensors will be towards higher pixel counts, better low-light performance, and higher integration.

With the continuous progress of technology, the pixel count of CMOS image sensors will continue to increase, thereby improving the resolution and clarity of images. At the same time, the performance of CMOS image sensors in low-light environments is also a challenge, and future development trends will focus on improving their low-light performance to achieve better night shooting effects.

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