CMOS Active Pixel Sensor (APS) Technology for Multimedia Image Capture

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Abstract

CMOS active pixel sensor (APS) technology has been developed as a potential replacement for charge-coupled devices (CCDs) for solid-state imaging. The CMOS APS has several advantages over CCDs for camera systems including much lower camera power, smaller camera size, lower camera cost, and on-chip functionality. This paper describes the CMOS APS technology.

History

Modern complementary metal-oxide-semiconductor (CMOS) device technology has its origins in the 1960's development of MOS for microelectronics. By the mid to late 1960's, the use of MOS technology was being explored for the realization of solid-state image sensors. This exploration centered around what is now called the *passive pixel* architecture[1,2]. A passive pixel is essentially a photodiode and a transistor switch. Charge integrated on the photodiode is readout by enabling the switch. The *active pixel* architecture was also proposed in the late 1960's.[3] The active pixel differs from the passive pixel by the use of an active amplifier within the pixel to buffer the signal. However, in the later 1960's, the state of the art of MOS was relatively poor, and these early attempts at MOS image sensors did not work well.

In 1970, AT&T Bell Labs announced the invention of the charge-coupled device (CCD).[4] The CCD had many advantages over the MOS image sensors of the time. These included relative freedom from fixed pattern noise (FPN), small pixel sizes, and insensitivity to MOS threshold mismatch and drift. The 1970's saw a large effort in the development of CCDs.

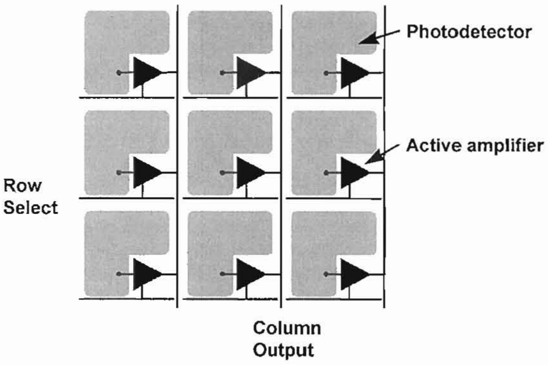

Fig. 1. Schematic illustration of an active pixel array.

Today, 27 years later, CCDs are a very mature technology. CCDs have good responsivity, low noise, and high dynamic range. Despite their widespread use they have several disadvantages compared to CMOS APS.[5] The main disadvantage of CCDs relates to the readout of the image occurs by shifting the signal charge hundreds or thousands of times. High charge transfer efficiency requires large clocking voltages and many different clock voltage levels. Furthermore, the CCD electrodes represent large capacitive loads to driving circuitry resulting in significant CCD drive power. Finally, it is difficult to integrate CCDs with CMOS VLSI circuits. The specialized CCD process was first integrated with a CMOS process over 20 years ago[6] and several times since[7,8] but the integration cost and CCD drive requirements make the combination practical in only very limited applications. Thus, CCD camera systems typically require a CCD and numerous peripheral ICs contributing to excess camera size and power.

CCDs did not totally eclipse MOS image sensors. From the 1970's to the present, Reticon has sold passive pixel MOS image sensors.

During the 1980's, passive pixel MOS image sensors were investigated by Hitachi[9] and Matsushita. However, these MOS sensors could not achieve the performance of CCDs and were not commercially successful. In the early 1990's, there was resurgence of work in passive pixel CMOS image sensors, especially by Denyer, now of VLSI Vision in Scotland.[10] In this case, poor image sensor performance was compensated by the large on-chip functionality afforded using CMOS VLSI circuitry.

Independently in 1992, the NASA Jet Propulsion Laboratory (JPL) as part of "smaller, faster, cheaper" drive to develop next-generation miniaturized instruments for space, began to investigate CMOS active pixel sensors. In 1993, JPL presented a CMOS-based active pixel sensor that achieved performance approaching the best scientific CCDs.[11] Over the next few years, rapid progress in the development of the CMOS APS was achieved at JPL.[12,13,14,15,16,17,18,19,20,21,22,23] The technology was also transferred to US industry such as AT&T Bell Laboratories[24] (now Lucent), Kodak[25], Intel and National Semiconductor. CMOS APS has now been pursued by many US companies such as Polaroid[26], IBM[27], Hewlett Packard and Rockwell. Foreign companies such as Toshiba[28], Hyundai[29] and VLSI Vision[30] are now also developing CMOS APS technology. Photobit, a JPL spin-off company, is developing custom CMOS APS chips for numerous clients.[31]

Technology

The block diagram for a CMOS APS sensor is shown below in Fig. 2. The sensor consists of an array of pixels, row and column select logic, and an analog- to-digital converter (ADC). In Fig.2, the ADC is implemented as a column-parallel architecture so that every column in the array has its own ADC[32,33,34]. There are certain benefits to this approach but a single ADC or 3-ADC (one for each color) architecture is also viable. The sensor is typically covered by a mosaic of color filters, one per pixel, such as red, green and blue, (RGB) that permit reconstruction of the original color image after readout and interpolation.

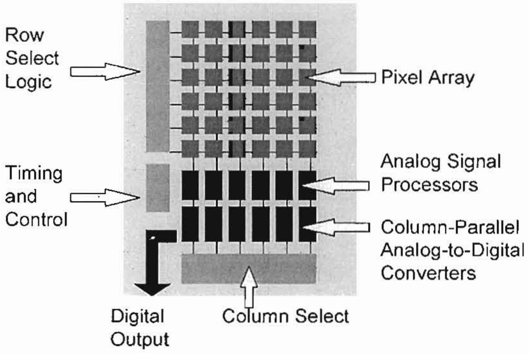

Fig. 2. CMOS APS integrates timing and control, ADC and other circuitry on to same chip.

Two types of pixels are used in CMOS APS. The first is the photodiode-type and the second is the photogate-type. These are illustrated below in Fig. 3.

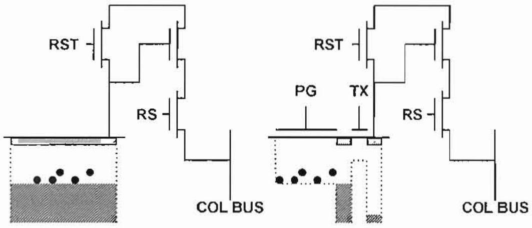

Fig. 3. Photodiode-type APS pixel (left) and photogate-type (right).

The differences in the two pixels are summarized in the table below:

Characteristic	PHOTODIODE	PHOTOGATE
Quantum Efficiency	better, esp. blue	Comparable to CCDs.
Noise	Higher (75 e- rms)	Low (<10 e- rms)
Low light SNR	Lower	Higher
Pixel size	Smaller	Larger
Conv. Gain	Lower	Higher

Table 1. Comparison of photodiode and photogate pixels

Typical quantum efficiency, measured as the ratio of total photons-in across the entire pixel, to total carriers collected by the pixel, is shown below in Fig. 4. Also shown is the QE of a commercial interline-transfer CCD.

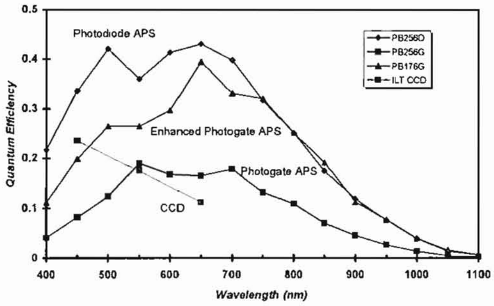

Fig. 4. Quantum efficiency of CMOS APS pixels.

The CMOS APS has achieved QE and responsivity comparable to the best CCDs. Other types of pixels such as logarithmic, floating-gate, and pinned-photodiode are also possible for specialized applications.

Analog signal processing at the bottom of the column includes correlated double sampling and FPN suppression. Sample and hold circuits with source-follower buffers are used to accomplish these functions.

Fig. 5. Unprocessed image taken from a Photobit 256x256 element sensor with on-chip ADC operating at 30 fps. Note no blooming from light and lack of other artifacts.

CMOS APS has achieved low noise (as low as 5 e- rms), ultra low offset FPN (<0.1% sat) and high dynamic range (80 dB) -- comparable to the best commercial CCD sensors. Gain variation is less than 1.5% - the same as for CCDs. Sensors as large as 1K x 1K and higher have been demonstrated. It is clear that yield in modern CMOS foundries will allow the realization of arrays sizes at least up to 2048x2048 or 4 Mpixels.

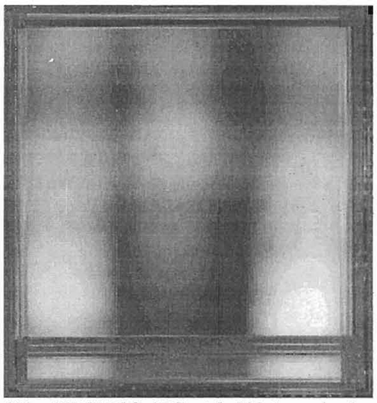

Fig. 6. 1K x 1K CMOS APS with 1024 single slope ADCs developed by JPL for low power scientific applications

Continued reduction in fabrication linewidths will allow for reduced pixel sizes and improved performance. Continued development of CMOS APS is required for use in ultra low power 3.3V and 1.8V environments to maintain dynamic range and low fixed pattern noise.

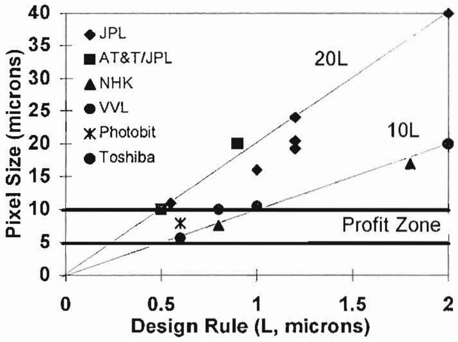

Fig. 7. Recent scaling trend for CMOS image sensors

Multimedia Applications

CMOS APS technology will play an important role in the development of cost-effective image capture devices for multimedia systems. Some examples include:

<u>PC teleconferencing camera:</u>
CMOS APS will allow the realization of small, low cost cameras such as PC peripherals. CMOS APS will offer functional advantages such an electronic pan, tilt and zoom with little additional increase in chip set cost.

Portable Applications:

The very low power dissipation of CMOS APS (10-50 mW) will permit the integration of CMOS APS into portable electronics such as laptops and personal digital assistants (PDAs).

Virtual Reality

The lightweight and low power of CMOS APS will allow the integration of real-world image capture functions on-board VR goggles. Real world imagery can be fused with virtual data to create real-time virtual assistant aides for manufacturing, repair, and entertainment.

Conclusion

CMOS APS technology will accelerate the use of multimedia by enabling low cost, high performance image capture devices.

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