The Evolution of Digital Imaging: From CCD to CMOS

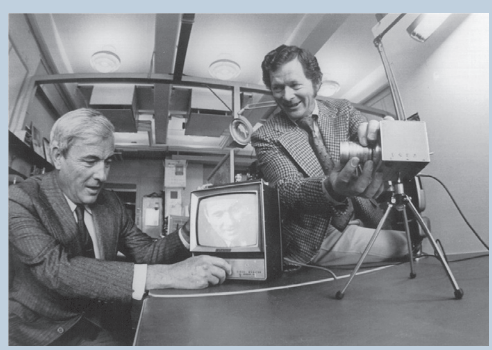
A Micron White Paper

Digital imaging began with the invention of the charge-coupled device (CCD) in 1969. Since then, the technologies used to convert light into electrical charges have become increasingly efficient. The processes for transforming optical to digital have evolved. Since its inception decades ago, digital imaging has progressed through improvements in CCDs and with the emergence of complementary metal-oxide semiconductor (CMOS) technology. And now CMOS is becoming a leading imaging technology.

In the Beginning...

On February 21, 2006 the National Academy of Engineering awarded Drs. Willard Boyle and George Smith the Charles Stark Draper Prize, one of engineering's highest honors, for developing the charge-coupled device (CCD) while they were both researchers in the Semiconductor Components Division at Bell Laboratories in 1969.

In a sense, Boyle and Smith were the grandfathers of the digital imaging revolution, which has all but converted cameras and video recorders from film to electrons. Their invention was first implemented commercially in television cameras in 1975. From there, CCD technology made possible a variety of new devices over the ensuing decades, like digital document scanners, bar code readers, digital copiers, and dozens of other business tools.



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Boyle and Smith's breakthrough CCD technology, demonstrated in an experimental video phone in 1974 at Bell Laboratories, which is now part of Lucent Technologies.

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Boyle and Smith's invention surpassed the technology of its day, improved commercial and consumer products for decades, and is perhaps one of the most important technological innovations of the past half-century. In fact, what some call the first golden age of digital imagery, 1983 to about 1989, was entirely CCD driven.

The Infancy of CMOS Imaging

Although CMOS image sensor development began in the late 1970s, it wasn't until the early-to-mid 1990s when CMOS was explored in earnest as a competitive digital imaging solution. While at the National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory in Pasadena, CA, Dr. Eric Fossum conducted the research that made CMOS image sensors practical "for space applications in which it has several advantages over CCDs, including a requirement for less power and less susceptibility to radiation damage in space."[1]

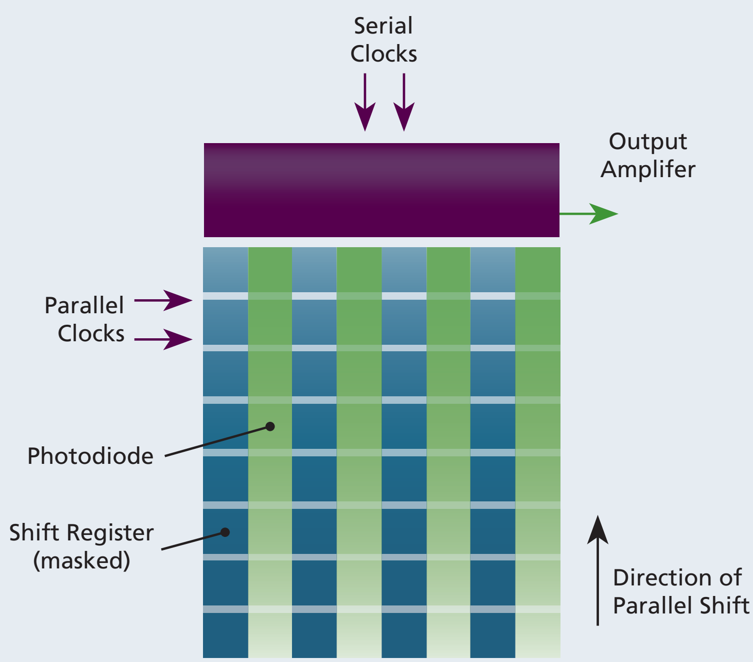
Dr. Fossum's research led to the development of CMOS active-pixel sensors that included many on-chip functions, allowing for more portability, lower power consumption, and complete miniature imaging systems.

How the Light Sensors Work

Both CCD and CMOS technologies are based on arrays of light-sensitive pixels (or photosites), which gather photons of light and convert them to a visible image. How this process works influences the qualities and capabilities of the sensors.

CCD Pixel Arrays

CCD photosites, arranged in an array, collect electrons when exposed to light. They pass the electrons from one charge-collecting bucket to another charge-collecting bucket, traversing the entire array. This method allows for sequential readout and good output uniformity. Reading the values of each cell as they are transported across the chip uses significant amounts of power. It requires as much as 2.5-to-10 volt clocking signals and multiple supply and bias voltages. The high power consumption is necessary for the CCD to maintain its image quality and limit noise. Additionally, the process used to manufacture CCD chips keeps their fidelity and light sensitivity high, but it drives up production costs.

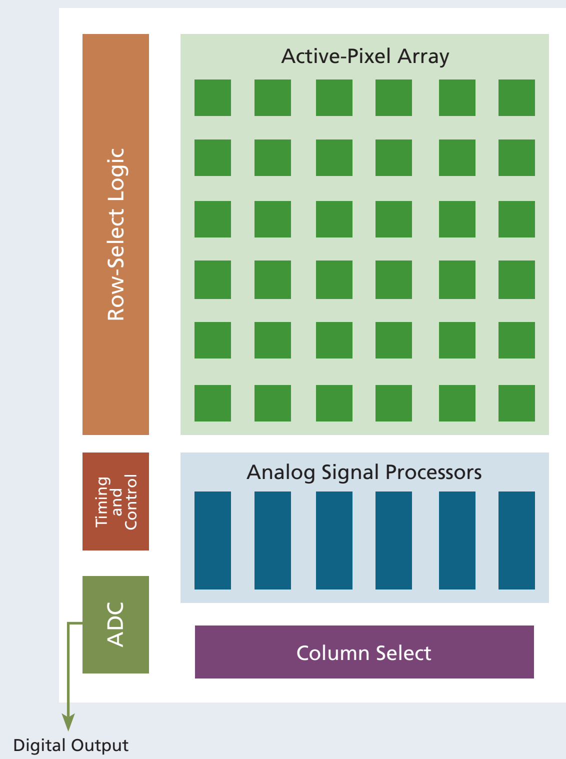


CCD pixel arrays are optimized to lower noise and improve image quality. Because of their architecture, they require additional clock signals, converters, and controls off of the chip.

[1]Announcement from the Jet Propulsion Laboratory, June 20, 1995, ***http://www.jpl.nasa.gov/releases/95/release_1995_9541.html***

CMOS Pixel Arrays

CMOS sensors often have three or four transistors in each photosite, which amplify and move the charge provided by incoming photons of light. They enable the pixels to be read individually. Some of the light entering a given pixel lands on a transistor, not on the sensor's light-detecting photodiode, which means that the CMOS pixel might not be as sensitive as a CCD pixel. CMOS image sensors operate at a very low gain and also produce more noise than a CCD imager. However, the CMOS manufacturing process uses standard microprocessor technology, which lowers the production cost significantly and can make integration simpler.



CMOS pixel arrays are fabricated with standard silicon processes, enabling peripheral electronics to be included on the chip.

Commercial CMOS Growth

The first commercial CMOS image sensors came from companies building imagers for applications that did not require crisp image quality—toy cameras or some machine-vision cameras. But Dr. Fossum's breakthrough at NASA, which promised all of the CMOS benefits, plus good picture taking, was soon of high interest to commercial semiconductor makers. In fact, the forward thinking Bell Laboratries—inventor of the CCD—was one of the first companies to contact NASA about its CMOS imager technology.

In 1995, Dr. Fossum co-founded Photobit Corporation to commercialize CMOS image sensors. His company, an industry leader in scientific, military, and industrial applications, was acquired in 2001 by Micron Technology, Inc., a semiconductor company that had caught the vision of CMOS imaging's enormous potential. They merged Photobit's cutting-edge imagers with their own extensive CMOS manufacturing expertise.

At the time, CMOS imagers had the reputation of producing lower-quality images with high noise and low fill factors. These issues related to how CMOS imagers collected and processed light and the newness of the technology.

A Maturing Technology

Nothing is perfect, and so it was with CMOS imagers. Despite the immaturity of the technology, it had too many advantages to be deterred. Enterprising engineers began gradually improving CMOS image sensor sensitivity and reducing noise to the point that many CMOS sensors now have quantum efficiencies that meet or exceed the sensitivity of their technological forerunner, the CCD. With this newfound sensitivity, the image quality from CMOS imagers has increased dramatically.

Micron Technology and other CMOS makers have added their own innovations to the basic CMOS active-pixel sensor design. To improve image quality on their CMOS chips, Micron has developed the TrueSNAP™ global electronic shutter. It enables simultaneous exposure of the entire pixel array, accurately photographing fast-moving subjects, and delivering clear images. Some TrueSNAP-enabled imagers can capture 10,000 frames per second.

Micron's engineers developed a series of innovations referred to as DigitalClarity® technology. With it they increased the chip's dynamic range and improved its signal-to-noise ratio. The sensors were able to output a low dark current of 20 electrons per second (which reduced background noise at nearly all light levels), to eliminate variations that caused the high noise levels often found in a 4-transistor pixel design, to minimize crosstalk, and to heighten light sensitivity.

Many CMOS image sensors, like several of those Micron manufactures, can pixel bin to automatically reduce an image's size so it can be easily previewed on a digital still camera's LCD or on a relatively low-resolution mobile handset display. These sensors are capable of scaling images to an arbitrary size for preview, display, and image storage. These sensors can also aid in image stabilization, image compression, color encoding, and multi-resolution imaging.

An on-chip phase-lock loop (PLL) makes possible a flexible clock-in scheme, easing design and shortening time to market. A global reset function enables the CMOS imager to work in conjunction with a mechanical shutter and external photographic flashes to illuminate low-light scenes. CMOS chips with on-chip JPEG compression can output compressed and formatted JPEG images without additional processing. Plus many CMOS image sensors have parallel and high-speed serial I/O.

The New Standard—CMOS Comes of Age

The optical resolutions available with CMOS sensors have improved by leaps and megapixels over the last few years. Resolutions are now high enough and run at fast enough frame rates to enable electronic pan, tilt, and zoom in cameras. Because of how they capture light, CMOS imagers offer lower dark (junction) current and enable applications like high-density television (HDTV) where CMOS image sensors capture considerably better pictures (in terms of signal-to-noise ratio and dynamic range) at HDTV rates. CMOS architecture allows for random pixel access and window-of-interest readout for applications requiring image compression, motion detection, or target tracking.

The advantages of CMOS and the efforts to overcome its shortcomings have dramatically expanded what it can be used for compared to the CMOS of the previous decade. CMOS imagers are now designed in to generations of digital still cameras, IP security cameras, even intelligent vehicle systems. Their portability and low power consump-

tion have driven these sensors to dominance in markets like mobile handset camera systems, digital SLRs, high-speed, machine-vision cameras, and medical devices like the Given Pill.

These CMOS image sensors offer several advantages in manufacturing costs, power consumption, ease of system design, and on-chip feature sets—all of which boost time-to-market success and enhance competitiveness.

CMOS image sensors generally represent the most advanced imaging technology and are likely to dominate the image sensor market for years to come, or at least until the next great invention from another innovator like Drs. Boyle, Smith, or Fossum.

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