

CMOS Image Capture for Digital Stills Cameras

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Introduction

The Digital Stills Camera community now universally embraces CMOS image sensors as the prime enabling image capture technology for product success. Even as the first CMOS based units find their way into the market, news of new models fills the trade press. Widespread adaptation of a different technology happens only for very good reasons. This paper discusses the reasons that CMOS imaging technology promises to be the cornerstone for filmless photography for years to come.

CMOS imaging technology first attracted the interest of the Digital Stills Camera community because of three very compelling reasons: low cost, low power and high integration. Anytime a technology promises to make a product can be made simpler, cheaper and last longer on battery power, that technology becomes of extreme interest to designers.

CMOS reduces cost because it is inherently simpler to produce. The number of masking steps that are required to manufacture a semiconductor device is a reliable indicator of the direct cost of manufacture. CMOS, in general, requires two-thirds of the masking steps of the CCD technology it replaces. In addition, CMOS reduces overall product cost by eliminating power conversion electronics, clock generation electronics, and other discreet functions such as analog to digital converters.

CMOS, because of the complimentary N-Channel and P-Channel transistors used in its fundamental operational structure (hence the C for complimentary in CMOS), consumes current only during the short time it switches from one state to another. This makes CMOS the lowest possible operating power technology available. Couple this with a single supply voltage, no power conditioning power drain, and no current draw during static stand-by periods, and battery life is maximized.

In today's world of electronics, nearly everything digital is produced using CMOS technology. In the Digital Stills Camera every function after the analog to digital converter is done digitally. It stands to reason, then, that one day the entire electronic content of a Digital Stills Camera will, like the calculator before it, be on a single Integrated Circuit. While this had not yet occurred, the precursor, the single chip television camera, Figure 1, has already been achieved. Attaining single chip status represents the ultimate in simplicity and contributes to significant cost reductions.

Given the promise of simpler, cheaper and longer lasting, it comes as no surprise that CMOS imaging has been a topic of interest in research labs for quite some time. CMOS imagers first reached the market in the mid-1970's from companies like Fairchild and EG&G's Reticon Division. These devices were performance limited, and at the time the process and analytic tools were not available to facilitate significant advances.

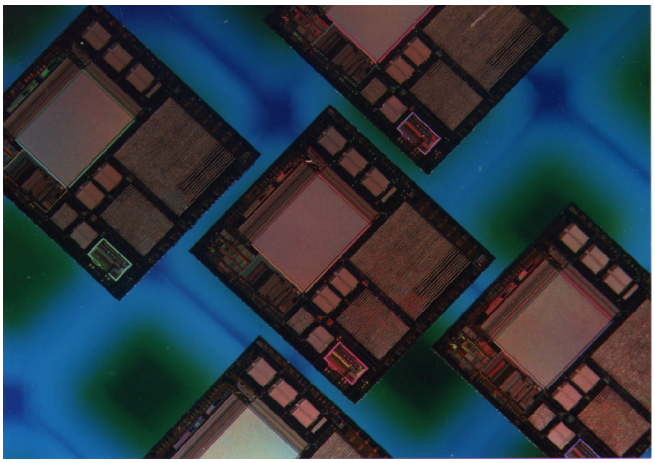

Figure 1. The VISION 6405 single chip color television camera

Serious interest was rekindled in the late 1980's at two different places. In the United States Cal Tech's JPL organization began serious efforts to utilize the advantages of CMOS for the cramped, power hungry environments of space exploration. This activity eventually led to the creation of Photobit Inc. and its subsequent licensing of the technology to such companies as Intel and Motorola.

Figure 2. The Fisher Price kids Creative Effects camera

At about the same time, work at the Scottish University of Edinburgh in biometric identification led to the application of CMOS imaging to low cost fingerprint readers. From this activity came VLSI VISION and its drive to produce affordable CMOS imagers for a variety of high volume applications. By Christmas of 1996 CMOS imagers were appearing in children's toys (Figure 2). Subsequent applications included Videoconferencing (Figure 3) and, of course Digital Stills Cameras (Figure 4).

Figure 3, the Creative Labs web blaster

Figure 4, the Vivitar 3000 Digital Stills camera

This progression of successful applications, from toys to videoconferencing to photography mirrors the continued rapid improvement of the CMOS imaging technology and leads to the primary reason that CMOS imaging is now universally considered the enabling technology for Digital Stills Cameras; CMOS outperforms every other alternative.

Performance

The performance comparison between CMOS and CCD imaging has been one of ongoing debate for some time. For most of that time CCD was the unquestioned performance leader. With the Tyco kids camera being held as the best possible example of CMOS imaging, no one would argue that CCD was superior. This ultimately lead to some to take the position that CMOS would never approach, let alone surpass, CCD quality. In less than three years, this position has proven completely untenable. In that time the mature CCD technology has progressed somewhat, but the still evolving CMOS technology has leapt forward with still no end of improvements in sight.

What had been overlooked in the early days was the inherent performance advantages that the CMOS imaging technology could deliver. The following paragraphs discuss these advantages.

With the focus on the relative simplicity of CMOS processing and the cost advantage gained there, the fact that CMOS is made better than CCD was largely ignored by camera designers. The semiconductor industries drive to ever-bigger memories, ever faster and more capable micro-processors, and ever-larger ASICs has lead to CMOS wafer processing with ever-smaller feature sizes on ever-larger wafers. The process accuracy and process control needed to achieve high yielding ICs using sub-.2 micron features on eight inch and larger wafers demands billions of dollars in investment in equipment and facility. Such advanced and advancing process quality is available to the CMOS image sensor manufacturer from a variety of sources. It is not available to the CCD maker without them first making huge investments.

Better processing and smaller feature sizes result in higher yields, smaller die sizes, and therefore lower costs. They also result in increased performance in such factors as better photo-response non-uniformity, lower tolerance analog-circuits, reduced parasitic effects, reduced bad pixel count and better temperature tolerance. Better manufacturing processes results in better performing sensors.

With the focus on the functional integration of CMOS and the drive toward Digital Stills Camera simplification, the use of integration to increase performance was also largely ignored. Techniques to reduce noise in image sensors apply to both CMOS and CCD. The ability to integrate those noise reduction techniques at the source of the noise increases their effectiveness. For example, CMOS allows double correlated sampling to take place on every column at the base of every column, integrated analog-to-digital conversion eliminates noise from analog interconnects on the printed circuit board, and single clock operation minimizes switching noise. Higher functionality results in better performing sensors.

CCD technology uses electric fields to capture, hold, transfer and control charge packets. As effective as this technique is, it does put a practical limit on the maximum number of photon generated electrons that can be handled per pixel and therefore imposes an upper bound on dynamic range. Field size, strength or uniformity does not limit Photodiode type CMOS technology. It is limited only by the size of the pn junction that is selected for use. Photodiode type CMOS has no inherent upper bound on dynamic range.

Upper bounds on dynamic range concerns itself with bright light conditions. Perhaps the most significant of bright light performance is how extremely bright point, or near point, sources of light are handled. This phenomena of blooming, or more accurately anti-blooming, represents a major difference between CCD performance and photodiode

type CMOS performance. CCDs handle excess electrons by building in an anti-blooming drain in each pixel. The size of this drain can be large or small, but the larger it gets the lower the percentage of pixel area that is used for photon conversion and the less efficient the pixel becomes. Since pixel efficiency determines low light performance, CCDs normally sacrifice blooming performance for sensitivity.

Photodiode CMOS, on the other hand, works by handling photocurrent. Since the current carrying capacity is determined by the total number of pixels, an excess in a few only represents a small change in the total current that need be handled. The net result is that CMOS delivers extra-ordinary anti-blooming performance. Extremely bright point light sources do not destroy large sections of images as is common in CCDs.

The combination of wider dynamic range and superior anti-blooming translate into superior performance for CMOS in bright light and excess light conditions.

Sensitivity is the measure of how well an image sensor performs in low light conditions. The specialty CCD process was conceived and enhanced with the single-minded goal of delivering excellent low light performance. To this day no other technique matches the performance of the especially selected and processed, cryogenically cooled, low speed CCDs used in serious astronomy. These devices have sub-one electron noise figures in multi-hour-long exposure times. While such CCD cameras represent the ultimate in Digital Stills Cameras they are far too expensive for wide spread usage.

Sensitivity is a result of two factors; light collecting ability and noise reduction. Since both CMOS and CCD are silicon based, the charge conversion ability for both is, at least theoretically, equal. Assuming good pixel design, knowing that microlensing is available for both, light collecting ability reduces to a direct function of pixel size, the larger the better. Either technology can produce pixels as small a 4µ by 4µ. On the other hand, CCDs have a practical maximum pixel size limit dictated by field strength and uniformity considerations while photodiode based CMOS has no maximum pixel size limit.

The pixel size used in a production sensor is determined as much by economics as performance. CCDs tend toward the smallest size pixel possible to try and offset the added processing expense and the inability to use larger wafers without a huge capital expense. While this reduces sensor cost it demands more expensive lenses and sacrifices sensitivity. CMOS, on the other hand, tends to have larger pixel sizes to take advantage of the lower processing costs while keeping lens costs at a minimum and improving sensitivity. From a practical point of view, CMOS has a performance advantage based on light collecting ability.

The other factor impacting sensitivity is noise floor. CCDs can be extremely low noise devices, but only at great expense. CCDs meant to compete in the high volume cost constrained world of Digital Stills Cameras represent a designer's choice trade-off between sensitivity and cost. Over the years of CCD evolution designers have learned what the noise reduction mechanisms are, and exactly which to include and which to omit for a desired cost/performance sensor.

The CMOS design community has not had the luxury of years of experience and a full cupboard noise reduction techniques. New and more effective noise reduction techniques for CMOS are being invented and applied on each succeeding generation of CMOS products. Even at such an early stage of technology maturity, one recently disclosed CMOS mega-pixel sensor promises an ASA 400 equivalent rating in a camera that is intended to retail for under 400 dollars. Such performance would give the practical sensitivity performance advantage to CMOS.

Microlensing is the technique used to increase the fill factor of a pixel by redirecting a large portion of the light that falls on the non-light collecting area of a pixel to the light collecting area of a pixel. Some portion of a pixel, be it CMOS or CCD, must be used for non-light collecting purposes. For any given pixel design and process, the smaller the pixel, the higher percentage of the non-light collecting area. Because the minimum feature size of the CMOS process can be very much smaller than CCD processes, CMOS has an advantage in fill factor. Even so, microlensing is required for small pixels, and is used extensively in both technologies.

While microlensing can increase fill factor, it is only effective if the light falling on the pixel is reasonably orthogonal to the pixel surface. As the incident light angle grows, the microlens ceases to direct all the light onto the light collecting area of the pixel and begins to direct it to other places where it shows up as noise. Small microlensed pixels, therefore, are limited to use with reasonably narrow field of view lenses or with expensive telecentric lenses.

Conversely, large pixels not only do not need microlenses because their fill factor is already high, but can be used with lenses of any field of view and do not require the added expense of manufacturing the microlenses as a part of the sensor. As noted earlier, large pixels are the exclusive domain of CMOS, giving CMOS yet another performance advantage.

The CMOS performance advantages discussed thus far have all been related to image capture performance. In terms of system performance, the other ICs in a Digital Stills Camera are all moving to the advanced 3.3 volt CMOS processes. The mega-pixel CMOS sensor announced by VLSI VISION in February 1998 also operates on 3.3 volts. By having all system components operate from the same supply, system performance is optimized. At the same time the potential noise source of power conversion electronics is eliminated.

Integration when used for noise reduction has been discussed. Integration can also deliver functionality that can otherwise prove difficult and expensive to achieve. Multi-mode operation is one such example. A Digital Stills Camera is often required to operate in two separate modes; a full resolution mode that acquires a still image, and a low resolution video mode that drives the LCD viewfinder. The integration capability of CMOS allows either operation to be sourced directly from the sensor, thus simplifying system operation.

Simplification is a major benefit of CMOS over CCD. A CMOS sensor does not require an onboard memory equal to the size of the photoplane, there are no serial shift

registers, there are no pixels exposed to light as they pass through other pixels enroute to the output register, and there is no need for multiple external clocks nor multiple external bias voltages. CMOS is a less complex image capture technology.

Evaluation and Characterization

An issue with all sensors, CCD or CMOS, is the ability to easy evaluate their performance and characterize them over all possible operating conditions. The path toward the development of a successful product includes answering the questions, "how good is good," and "how good is good enough." There are three possible methods for reaching answers to these questions.

The first is to extensively test an existing complete camera product. While this may give important insight into how well a competitors design team performed, it can give very little quantitative data on how well any specific element of the product can perform.

The second approach is to design and build a camera from scratch, test it, improve it, test it again, and so on until all the needed quantitative data is collected. This is a very good learning experience, but time consuming and expensive.

The third approach is to utilize an evaluation and characterization system supplied by the sensor manufacturer. These systems provide total operational and parametric control of a sensor through software running on a PC. Figure 5 shows one such system, the 6850 VTD that VLSI VISION supplies for its Photography class CMOS sensors.

Figure 5, 6850 VISION Technology Demonstrator

Enabled Market Segments

At the beginning of 1998 there were two generally recognized categories of Digital Stills Cameras, the so-called Professional segment and Conventional segment. The professional segment emphasizes performance above all and is generally willing to pay for that performance. This segment tends to apply scientific or near scientific grade CCD sensors to achieve their performance goals.

The conventional segment strives to place Digital Stills Cameras in the hands of amateur photographers, others who are interested in photography, and computer users who wish to supply their own image content to their documents. This category of users demands only photo-album quality but don't wish to pay more than they would for any other quality computer peripheral. Providing photo-album quality at this price point has proven difficult, but providing features unique to digital imaging (such as LCD viewfinders, sound bite recording, and image manipulation software) has made this category popular.

The application of CMOS technology to this category is expected to upgrade it from one composed of early adopter computer users to the amateur and interested photographers to which it has been targeted. CMOS performance promises to provide the required quality while CMOS costs promise to provide the required affordability. CMOS is expected to enable this segment to reach its full potential.

In early 1998 the initial product offerings of two new categories were publicly announced. Both of these categories only exist because of the utilization of the benefits of CMOS imaging.

The first of these categories is E-FILM™. E-FILM™ uses advanced CMOS technology to completely assemble all of the non-image capture functions of a Digital Stills Camera inside a package exactly the same size and shape as a 35mm film canister. Attached to this is a CMOS sensor that fits in the space of a single frame of 35mm film. The sensor characteristics are such that any existing 35mm film camera can be used for digital photography as well as for film photography. When E-FILM™ is installed the camera the photographer simply sets the ASA rating and uses his camera as he would if convention film were loaded into it. All of the lenses and accessories of the 35mm camera can be used. Even the scene as composed through the viewfinder is replicated on the resultant digital photograph. For the price of a separate conventional Digital Stills Camera the photogrpher can utilize his existing equipment to produce excellent images in either electronic or film media.

The second new category is low cost. A complete Digital Stills Camera was announced for a retail list price of $65 dollars. While this camera initially is only capable of passport/wallet sized images, the photoplane is the same as that used by the larger CMOS imagers. Thus, color quality, sensitivity and all other non-spatial resolution parameters are identical to its more expensive cousins.

Summary

CMOS imaging has become recognized as the enabling image capture technology for Digital Stills Cameras. The primary reason for this is that CMOS provides a level of performance unequaled by any other candidate sensor technology. Combining CMOS performance advantages with the inherent cost, power, and integration advantages has enabled and expanded the market sectors served by filmless photography.