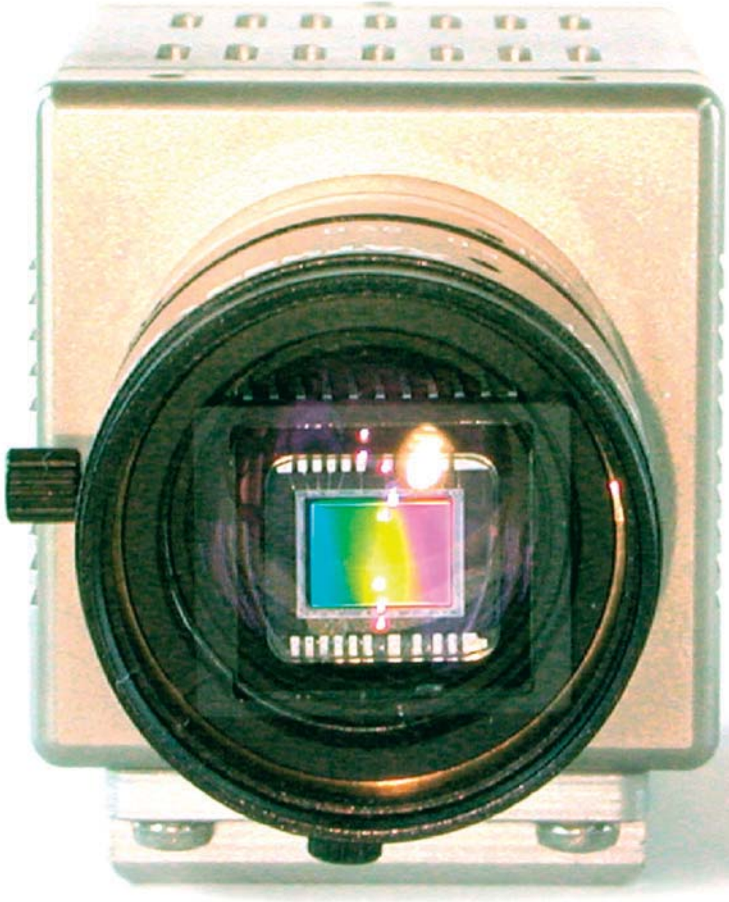
View to the future

CCD and CMOS sensors today and tomorrow



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Digital image sensors are well established in private and professional applications. But which sensor type works best, CCD or CMOS? This question enlightens passionate discussions. A more detailed analysis reveals that these sensors share many common characteristics. Both CMOS and CCD can be beneficial, depending on the application.

The widespread use of imaging systems in private and professional, scientific and industrial applications, generate a high demand for digital image sensors. In scientific applications, these camera systems are used, in addition to pure documentation purposes, to measure parameters or visualize events that otherwise would be difficult to see or could not be seen. In industrial applications, these cameras are used for quality control, observation and security. These days, nearly all mobile phones include an integrated digital camera, and there are few people who do not own a digital video camera or a still camera.

The basis for image recording, e.g., a certain distribution of light, is given by digital image sensors. They can be distinguished by their structure and manufacturing process. The CCD (charge-coupled devices) describes the nearly lossless transport of charges and CMOS (complementary metal oxide on semiconductor) describes the manufacturing process of these two types of image sensors. CCD image sensory has existed for more than twenty years, whereas CMOS sensors are much younger. The production processes of CMOS sensors have been improved over the past few years to approach the image quality of CCD image sensors. I will not discuss which of the sensors is better, because that is the wrong question. This article will illustrate the latest technology and attempt to look into the future with a focus on recent trends and application areas for the various image sensors.

Table 1: Characteristics of current high-performance image sensors

Type	CCD	CCD	emCCD	CMOS	CMOS
Manufacturer	Sony	Kodak	TI	Micron	Fill Factory
Sensor	ICX285	KAI 2001	TC285	MV-13	IBIS5
pix. clock [Mhz]	30	40	35	66	40
Resolution [MPixel]	1.3	2	1.0	1.3	1.3
QE [%]	60	55	65	25	25
Readout noise [e^-]	7	12	14	85	70
Dark current @25°C [e^-/pix·s]	1	1	20	5900	20 000
Full well [e^-]	16 K	40 K	40 K	120 K	63 K
Dynamic	2200:1	3300:1	2900:1	1400:1	1000:1
Power consumption @20MHz [mW]	150	300	200	150	350
Quant. drive voltage	6	10	12	2	1
Connection pins	20	32	28	84	280

State-of-the-art image sensors

While recent trends point to higher spatial resolutions (better image quality) and smaller pixel sizes (higher yield for manufacturers), there is an interest in high quality images even from the smallest cameras, for measuring or quality control applications. There are further optimisation criteria: dynamic range, e.g., the number of distinguishable light or grey values and the image frame rate for fast events. The differences between current high-performance image sensors are shown in table 1.

In this table, the characteristic data for two interline, progressive scan CCD image sensors, a new electron multiplication emCCD image sensor and two CMOS image sensors are shown. Looking to pixelclocks and spatial resolutions, there are no significant differences. The pixelclock values range from 30 to 60 MHz, and spatial resolutions of 1 MPixel and lower merely represent the lower limit. The quantum efficiency (QE) describes the amount of light that is necessary to generate a digital number (mostly given in ›counts‹). The differences in this parameter mainly come from manufacturing differences. For the interline CCD image sensors, a part of the light sensitive area per pixel is used by the shielded shift register, which can be compared in CMOS sensors with the area used by the read-out elements. Both layouts cause a bad fill factor. In CCD image sensors, this is usually compensated for by an additional top layer of microlenses or lenslets, a technique that is not widely applied to CMOS sensors as of yet. The read-out noise and the dark current are much better in CCD sensors compared to CMOS, although the manufacturers of CMOS sensors have improved the process within the last few years. This is to a certain extent due to the head start in experience and development, but also due to the structure. In the case of the CCD image sensor, all data must pass one or more read-out circuits, which in turn are optimized for noiseless read-out. In the case of the CMOS sensor, every pixel or smaller groups of pixels have their own read-out circuits, which because of the effort required, cannot be optimised in the same way. This would in addition use more space at the expense of the light sensitive area of each pixel.

Application	CCD	CMOS
Digital still cameras, mobile phones, toys	X	X
Professional single lens reflex cameras	X	X
Industrial image processing	X	X
Scientific imaging	X	X
Highspeed imaging	–	X
Distance measurement direct	–	X
Low light level imaging	X	–
Observation, night view	X	–

Table 2. Which sensor is best for which application?

The fullwell capacity and the read-out noise determine the image sensor dynamic range and describe the potential maximum capacity of charge carriers for each pixel. If more light falls onto the pixel, no more charge carriers can be generated and stored. Here, the CMOS sensors with their large pixels have the larger capacities. Due to the higher readout noise values, they nevertheless have the smaller dynamic range. The power consumption, given in table 1, is only related to the sensor power consumption and ignores the read-out circuits. If these are also considered, the CMOS camera systems show their advantage. When comparing only the image sensors, there is not much of a difference. The CMOS sensors have their point, if the number of required control voltages is used, since they can be controlled with one voltage level.

Finally, the number of electrical contacts is important if the image sensor application is considered. In this field, CCD sensors are better compared to the high number of digital contacts that are necessary to read out a CMOS sensor. In the table, frame transfer and full frame CCD image sensors are not mentioned. Although they are widely used in digital still cameras, as they have excellent fill factor and high QE values, they generally require an additional mechanical shutter to realise short exposure times. This is an advantage for photo cameras, because they already have these shutters, but it is not suited for image sequence recording.

Trends and recent developments

Driven by the wishes and requirements of the automotive industry for image processing driver assistance systems, special CMOS image sensors have been developed, which allow the display and recording of huge light dynamic ranges. Some examples include the HDRC (High Dynamic Range) CMOS image sensor from IMS Vision (www.hdrc.com), Stuttgart, Germany, with its logarithmic sensitivity curve and the dual slope read-out process for CMOS sensors from FillFactory, Mechelen, Belgium. With these sensors, response curves can be generated that deliver a 10- or 12-bit output image but increase the light signal range or dynamic range significantly. A classic example is the contrast range exhibited when entering or exiting a tunnel. Both methods were developed in the 1990s and have now reached real applications. Figure 1 compares standard image recordings with exposure optimisation to the inner or outer scene in the laboratory image (shown using the dual slope read-out method). It can be clearly seen that the dual slope method achieves a good »

Figure 1. Comparison of conventional images with exposure optimisation to the dual-slope method; left: conventional image exposed with the focus outside the laboratory; middle: conventional image exposed with the focus inside the laboratory; right: dual slope image (source: FillFactory, Belgium)

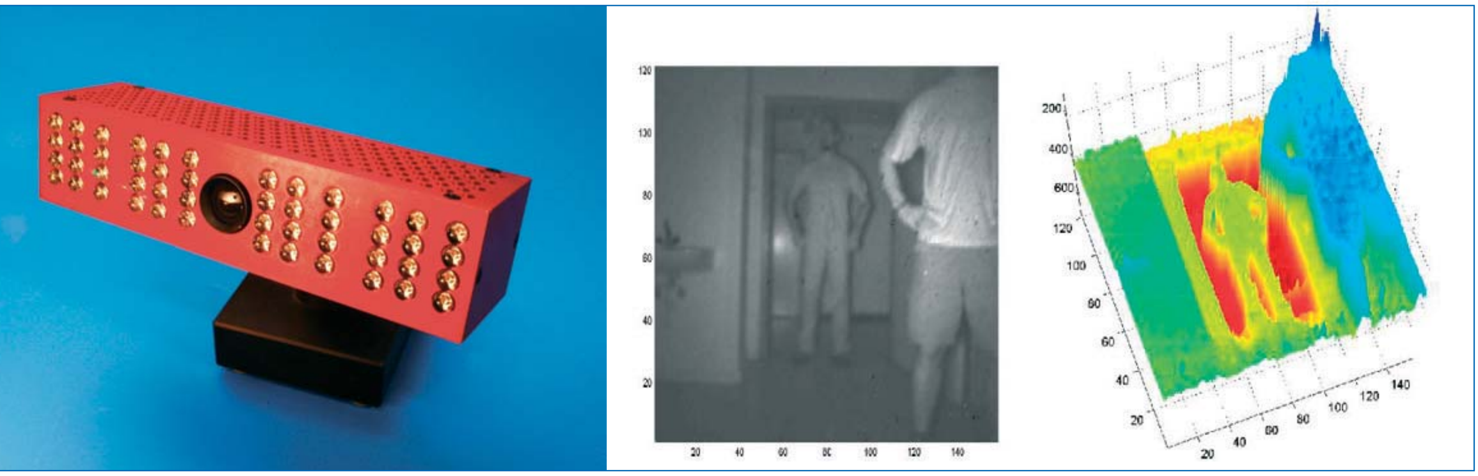

Figure 2. Swiss Ranger SR-2 3D camera of CSEM; left: the camera with IR LED as light sources; middle: light intensity image recorded with the SR-2 camera; right: distance image of the same scene, recorded with the SR-2 camera; (source: CSEM, Zurich, Switzerland)

display of this difficult light situation, which otherwise would have required the combination of two single images at different exposures.

Another interesting development of CMOS sensors is the technical 3D view or measurement. At the end of the 1990s, new detectors had been developed for this purpose that achieve a temporal distribution of the incoming light signal. A new detector element has been created. Prof. Dr.-Ing. Rudolf Schwarte of the University Siegen, Germany, called it a ›Photo-Mixing-Device‹ (PMD), because it allowed for the demodulation within the light detector. He and his team developed a photo diode, where a corresponding external modulation signal determined whether the generated charge carriers are guided to the left or right contact electrode. Therefore, this detector acts as a differential amplifier. At the CSEM (Centre Suisse d'Electronique et de Microtechnique) in Zurich, Switzerland, a similar device has been simultaneously developed, which combines CMOS and CCD technology. The device uses an external control signal to conduct the generated charge carriers into one of up to four CCD buckets, which are arranged around the photodiode in a circular manner. Both concepts allow for direct distance measurement. For this purpose, sinusoidally modulated light is emitted. This light is reflected by each obstacle in its path, and only part of the reflected light reaches the detector. Depending on the distance, and therefore on the time of flight, the phasing of the sinusoidal light is shifted compared to the emitted light. With the above-mentioned detector, it is now possible to measure the phasing of the light signal and, using the speed of light, to calculate the distance the light has covered. Meanwhile, the first cameras with CMOS pixels based on this principle have been developed, and it is possible to record images, where each pixel comprises the distance information (see figure 2). The technology is of great interest to the automotive industry (seat occupancy and airbag control) and in robotics, where previously, laser scanners to measure distance had to be used.

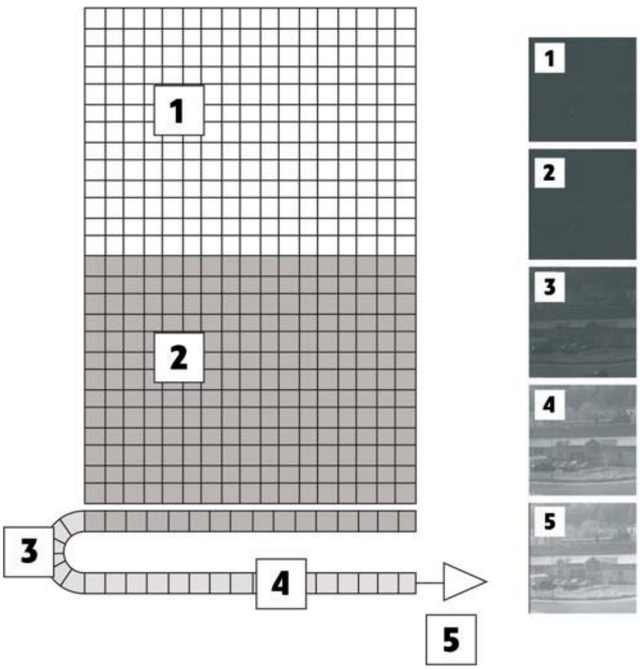

Figure 3. Frame transfer emCCD image sensor and the images, which can be seen at various times in the read-out chain; 1: the incoming light is converted into charge carriers; 2: the charge carriers are shifted into the shielded memory area; 3: each row is serially shifted into the gain section; 4: the charge carriers are multiplied by impact ionisation; 5: the charge carriers are converted into voltage signals at the output amplifier to be further digitized

The term ›smart sensors‹, related to image sensors, has been widely used over the past few years. These are not discussed in this article, because the term usually describes normal image sensors with an on-chip integrated pre-processing that is optimised for a specific application. This might be interesting for high volume applications, but only replaces additional circuits that would have been added, and it is less general.

In the late 1990s, Texas Instruments and E2V Technologies discovered a CCD image sensor phenomenon, which had only been known to exist in avalanche photodiodes – impact ionization (see figure 3). In these image sensors, which are called emCCD (em = electron multiplication), a chain of gain read-out register cells has been added to the serial shift, our path of a frame transfer CCD. In this chain, the charge packages are shifted at much higher voltages compared to the standard read-out process (see figure 3). As a result, a statistically distributed amplification of the signal occurs on the chip. Therefore, the signal can be amplified before it is read out, allowing the read-out noise to be ignored when measuring the event.

The first camera systems with these emCCD image sensors have been on the market for two to three years (TI: ›TC253‹& ›TC285‹ and E2V: ›CCD87‹ & ›CCD97‹). They are entering the domain of image intensifier camera systems, which they will replace in the near future for low light applications. Since they amplify pixel-wise, the spatial resolution is as good as the sensor itself, and is not smeared by the phosphor screen like image intensifiers. Additionally, the emCCDs cannot be destroyed by large light signals as in the case of image intensifier tubes. With the first back-illuminated-emCCD image sensors (E2V: ›CCD97‹), which are used and illuminated from the substrate side (no transmission losses due to the gate electrode structure), QE values of up to 95% have been achieved. Now, single photon counting with a digital camera is possible.

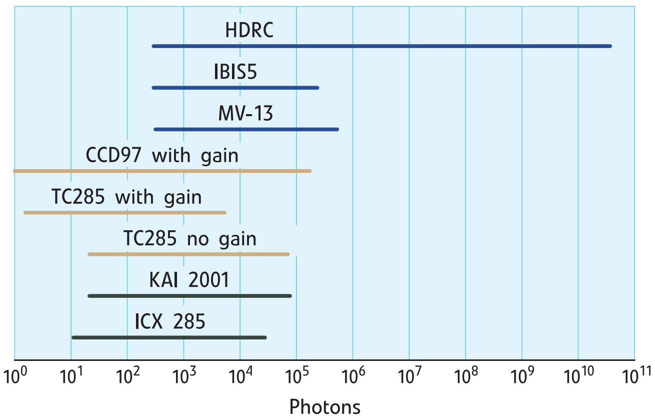

Figure 4. Dynamic ranges of various image sensors. CCD: Sony ICX 285 and Kodak 2001; emCCD: Texas Instruments TC285 and E2V Technologies CCD97 (back illuminated); CMOS: FillFactory IBIS5, Micron MV-13 and IMS Vision HDRC

Figure 4 shows a comparison of the image sensor dynamic ranges related to the amount of incoming photons necessary to generate an image. Obviously, CCD image sensors are better suited for low light level applications. In particular, the emCCD image sensors open the lowest light range for imaging applications. On the other hand, the huge dynamic range of the HDRC-CMOS image sensor can be seen, which is favourable if enough light is available.

Which sensor is the best?

The features and characteristics of each sensor clearly show that there is not a general answer to such a question. Even if fiery arguments are started regarding this topic, the real question ought to be: which is the best sensor for the specific application? Table 2 attempts to answer this question.

In digital still cameras, mobile phone cameras and toys, the number of CMOS image sensors will increase, because the image quality has been improving and because of their potentially low production costs. At the moment, the CCD image sensors still have a larger market share. In professional single lens reflex cameras, both sensor types are applied; here, for example, Nikon uses Sony CCD image sensors, while Canon produces their own CMOS sensors. For scientific applications, it depends on the experiment itself: if it is a low light level application, CCD camera systems will be used; if it is a photon noise limited application, CMOS systems can also be applied. For high speed imaging and for recording sequences with high frame rates, there will only be CMOS camera systems, since the CCD read-out structure does not allow such high image rates. On the other hand, absolute low light level applications with a demand for high quantum efficiency and low read-out noise will remain the domain of CCD camera systems. It will be interesting to see how CMOS sensors designed for distance measurement will mature.

Summary

CCD and CMOS image sensors share many features and can therefore be used for similar applications – particularly for consumer applications such as digital still cameras, mobile phones and toys. CMOS image sensors are not suited for low light level applications because of their lower quantum efficiency, higher read-out noise and lack of homogeneity. The higher dark current also prevents the application of CMOS sensors for this purpose. CCD image sensors are not suited for high speed applications, because they do not allow high data rates due to their serial read-out process. In addition, the increasing smear observed with short exposure times is troublesome. Also, if special functionality on the chip or special modulation capabilities are required, e.g., 3D measurement, CCD sensors are not suitable.

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