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CCD Requirements for Digital Photography

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Abstract

The performance of a digital camera is largely determined by the capabilities of its CCD. In this paper various CCD characteristics such as resolution, quantum efficiency and charge capacity are related to their eventual effect on image quality or camera capability. The CCD characteristics that would be required to produce digital cameras that compare favorably with film cameras are presented.

Introduction

Digital photography offers many unique advantages over film photography including instant image access, immediate image review and easy electronic image transmission. However, film photography still has advantages in terms of sharpness, ISO speed range, dynamic range, and aperture control. These characteristics are all dependent on the capabilities of the CCD. The sharpness depends on the resolution. The ISO speed range depends on quantum efficiency, pixel area, charge capacity and read noise. The dynamic range depends on the charge capacity, read noise and dark current. The range of aperture control depends on the pixel size and the angular response of the pixel. In order for digital photography to supercede conventional photography, the capabilities of CCDs will have to improve in these areas.

In this paper the CCD characteristics required to enable digital photography to displace film photography are presented. Separate sections are dedicated to the subjects of resolution, charge capacity, quantum efficiency and read noise, angular response, dark current, and smear. The paper concludes with comments about the likely resolutions, optical format sizes and architectures of future CCDs.

Resolution Requirements and Pixel Size Implications

One of the greatest challenges for digital photography has been to match the sharpness of film. The sharpness potential of a digital camera is determined by the resolution of the image sensor. Image sensor resolutions have increased steadily over time. The first digital cameras to be widely adopted (the Casio QV-10 and Epson Photo-PC), had resolutions of 250,000 and 330,000 pixels. The industry standard is now two million pixels, and a number of 3.2 megapixel cameras have been announced.

Thirty-five millimeter film has much more resolving power than needed to print sharp pictures. The resolution requirements for printing sharp pictures in the most popular formats are shown in figure 1. In this figure, the vertical axis indicates the print resolution in pixels per inch. The threshold for excellent perceived sharpness is 200 ppi. The horizontal axis in the figure indicates the resolution of the CCD. More CCD pixels are required than print pixels because the CCD samples only one color at each pixel location. Experiments have shown that images that have been reconstructed from color mosaic samples look as good as images which are fully sampled in each color plane, when the former are printed at 266 ppi and the latter at 200 ppi[1]. The curves that are drawn in the figure correspond to popular print formats. A 2 megapixel CCD can easily achieve excellent perceived sharpness at a 4”x6” print size. A 3.2 megapixel CCD can produce sharp 5”x7” prints. A 6 megapixel CCD would be required to produce a sharp 8”x10” print.

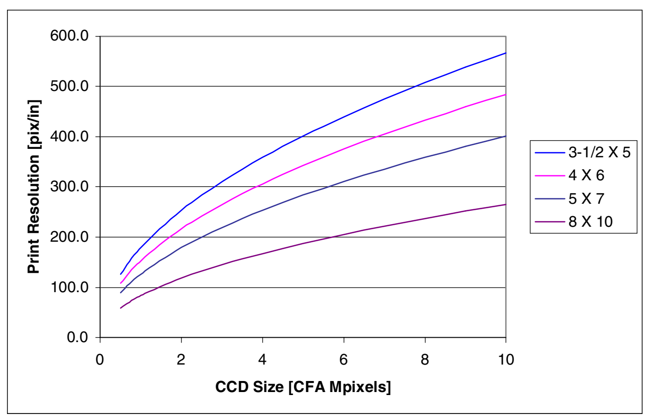

Figure 1. Print Resolution vs. CCD Size

The resolving capability of film is difficult to estimate accurately because of the variation of grain size with film speed and other effects. A crude estimate can be obtained by assuming that the effective pixel size defined by film grain is 12 microns, which is approximately equal to the diffraction spot size at f/16. On this basis the estimated equivalent CCD resolutions of several popular film formats are shown in the following table:

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Equivalent CCD Resolution (in megapixels) of Popular Film Formats

Film Format	Equivalent Resolution
disc	1.0
110	2.7
APS	6.3
35 mm	10.3

The current generation of digital cameras has approximately the same resolving power as 110-format film. A significant increase in resolution would be required to match the capabilities of 35-mm film, but it shouldn't be necessary in most applications.

An increase in CCD resolution requires either an increase in overall sensor size or a decrease in pixel size. The trends of the industry are shown in figure 2. Pixel size has been decreased while the optical format size (1/3", 1/2" and 2/3") has been maintained. In order to obtain a resolution of 6 megapixels in the largest standard format (2/3"), the pixel size would have to be further decreased to 3 microns.

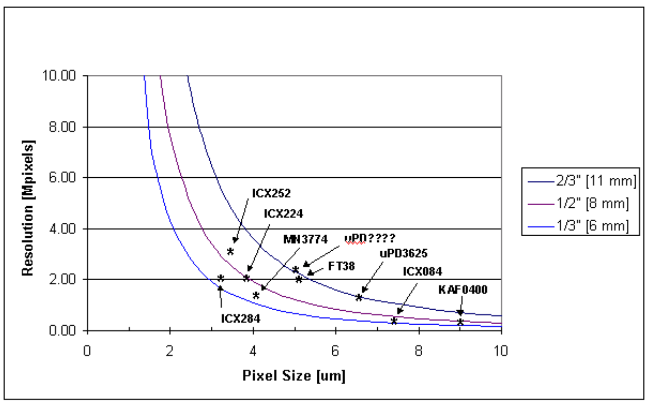

Figure 2. CCD Resolution vs. Pixel Size

There are a number of negative consequences of decreasing the pixel size. Some of these (reduced dynamic range and sensitivity) will be addressed in other sections of this paper. Another consequence that is often neglected is the potential loss of resolution due to the effect of diffraction. The diffraction spot size (in microns) is approximately equal to 2/3 the lens aperture f-number. At a 3 micron pixel size, the diffraction spot size is greater than the pixel size for all f-numbers greater than 4.5. This greatly limits the range of useful aperture control.

The resolution required to enable digital cameras to compete favorably with film cameras is about 2 megapixels for snapshot capture and 6 megapixels for general use. While decreasing the pixel size is an expedient solution to the need for greater resolution, it isn't a good long term solution. Larger sensors with ~5 micron pixels and 1" optical format will be required.

Charge Capacity Requirements

The dynamic range and signal to noise ratio potential of a digital camera depend upon the charge capacity of the CCD. The charge capacity is defined the maximum charge level at which the response is still reasonably linear (~80% of saturation). The CCD response varies too much from pixel to pixel be useful above the linear region.

The dynamic range is determined by the ratio of the charge capacity to the read noise. The dynamic range of color negative film is greater than 5000:1, however this wide range isn't required if the exposure is controlled accurately. The dynamic range that is encountered in typical photographic scenes has been studied[2]. It has been determined that many scenes have a range of over 1000:1, and some are in excess of 4000:1. Exposure errors average 1/2 of an f-stop, and errors of a full stop are common. The dynamic range of the CCD must be large enough to accommodate the both the scene range and the exposure error. The charge capacity required to capture a 1000:1 scene range with 1 f-stop of exposure error is 30,000 electrons (assuming a typical read noise of 15 electrons).

The maximum signal to noise ratio is determined primarily by the charge capacity, since Poisson statistics dictate that the image noise varies as the square root of the number of captured photons. The signal to noise ratio at mid-level gray is plotted as a function of charge capacity in figure 3. Studies have shown that groups of observers associate a mid-tone SNR of 10 with acceptable image quality, while a mid-tone SNR of 40 yields excellent image quality[3]. More than 25,000 electrons are required to obtain a mid-tone SNR of 30.

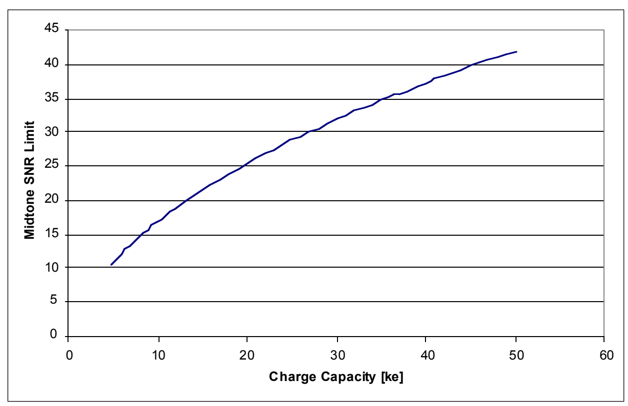

Figure 3.Midtone SNR vs. Charge Capacity

The charge capacity increases with pixel area. The measured charge storage capacity per unit area is shown in figure 4 for a number of different CCDs. Frame transfer CCDs provide a storage density of about 1.75 thousand electrons per square micron of pixel area. Interlace scan interline transfer CCDs have a charge storage density of about 1 ke/um^2 while progressive scan IT CCDs reach about 0.5 ke/um^2. The charge capacity required to achieve adequate dynamic range and SNR (~30 ke) is also indicated on this figure. A frame transfer CCDs with a 4 micron pixel or an IS-IT CCD with 5 micron pixels would have adequate charge capacity. Neither architecture has demonstrated a high enough charge storage density to provide adequate charge capacity with a 3 micron pixel.

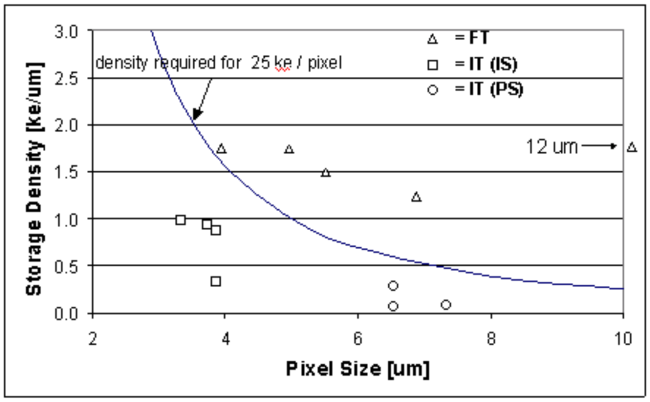

Figure 4. Charge Capacity vs. Pixel Size

Quantum Efficiency and Read Noise Requirements

The amount of light required to obtain a proper exposure varies inversely with the ISO speed of the film/camera. In digital and film photography, the image quality generally decreases as the ISO speed is increased. In order to make ISO speed comparisons meaningful, a standard has been developed which defines the ISO speed of a digital camera in terms of image quality.[4] It can be shown that the ISO speed is proportional to the product of the pixel area and quantum efficiency (QE) divided by the read noise.[5] Sensitivity increases require some combination of QE or pixel area increase and/or read noise decrease.

Based upon our measurements, interline transfer CCDs have peak quantum efficiencies of about 35%, while frame transfer CCDs have peak QEs of about 20% (both with color filters). However the IT CCD utilizes a more costly fabrication process than the FT CCD, so the QE-area/cost relationship is about the same for the two architectures.

In order to satisfy consumers, digital cameras must be able to provide the same ISO 400 speed that is routinely available in film. The peak QE in the green channel required to obtain an upper-limit noise speed of 400 is plotted as a function of the pixel size in figure 5. This curve was obtained from a model that we developed that can be used to predict the ISO speed based upon the QE curves, pixel area and read noise[5]. In order to achieve an upper-limit noise speed of 400 with currently demonstrated CCD quantum efficiencies, an IT CCD with 4 micron pixels or an FT CCD with 5 micron pixels is required.

If the pixel area is decreased in order to boost the resolution, then the quantum efficiency must increase in order to maintain the same ISO speed. A peak QE of 60% is required when the pixel size shrinks to 3 microns. This may be a difficult goal to reach, considering that typical broad-area silicon detectors have peak QEs of about 70%.

The CCDs that we have tested have had read noise levels of 8 to 15 electrons (after correlated double sampling) in a 20 MHz bandwidth. Noise originating in the camera electronics may mask any further improvements in read noise.

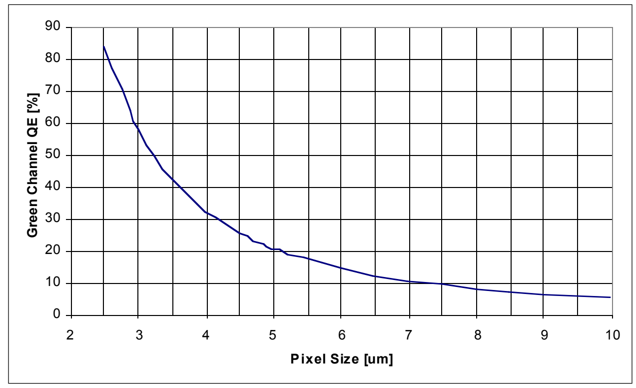

Figure 5. Peak QE Requirement for ISO 400

Angular Response Requirements

The light rays that strike the film plane in conventional cameras can have a wide range of incidence angles. The incidence angles are especially steep in compact point and shoot cameras, where the exit pupil of the lens is located very close to the film plane and the angle from the exit pupil to the edges of the film frame is large. In the center of the film frame the range of incidence angles is determined by the lens f-number (the ratio of the focal length of the lens to the diameter of the aperture stop). Specifically, the range of incidence angles is the arctangent of the inverse of twice the f-number. Lenses with low f-numbers are desirable because they admit more light. The rays that emerge from a telecentric lens have the same range of incidence angles over the entire image plane, however these lenses are more difficult to design.

The range of incidence angles that CCDs can accept is limited. Interline transfer CCDs utilize microlenses to concentrate light on their photodiodes. These microlenses expand the sensitive area of the pixel at the expense of angular response. Frame transfer CCDs do not require microlenses, however obliquely incident rays can pass through the color filter of an adjacent pixel and distort the spectral response of the sensor. The angular response curve for a typical IT and FT CCD are shown in figure 6. The angular response of the IT CCD is much narrower in the horizontal direction than the vertical direction because of the asymmetric construction of the pixel. The horizontal response of an IT CCD usually fall to 50% of its maximum value at an incidence angle of ~10 degrees (from normal). This limits the maximum useful lens aperture to about f/2.8.

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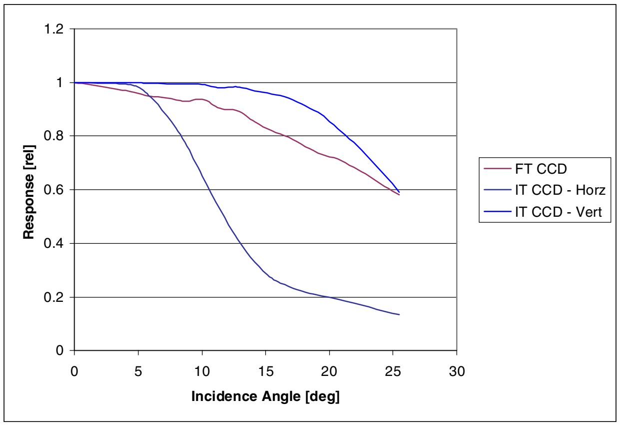

Figure 6. CCD Response vs. Incidence Angle

In order to compare favorably with film cameras, digital cameras should be able to operate effectively with apertures as large as f/1.8, corresponding to an angular response of 16 degrees in a telecentric optical system. Ideally CCDs should have angular response widths of 20 to 25 degrees so that the lens telecentricity requirements could be relaxed and the cost of the lens decreased.

Dark Current Requirements

Image charge is created in silicon CCDs when photons are absorbed. Other charge generation mechanisms also exist that do not require photons. The charge flow produced by these mechanisms is known as dark current. The dark current intensity approximately doubles with each ~5 degree C rise in temperature. Since the total dark charge that is accumulated depends on the length of the exposure period, the effect of dark current is most visible at high temperatures and long exposures.

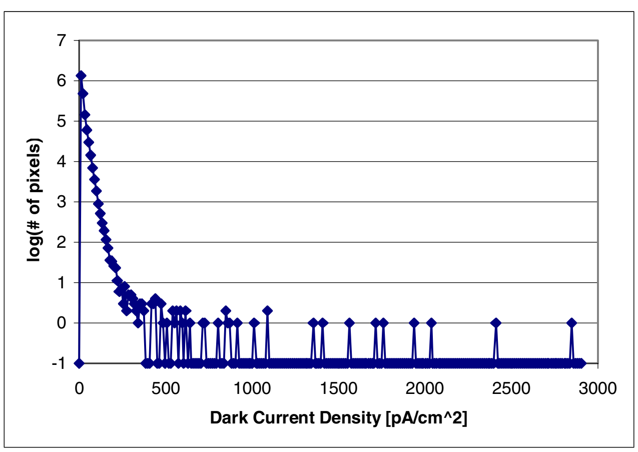

Figure 7. FT CCD Dark Current Distribution

In the frame transfer CCD, the vertical CCD is used both to collect charge during exposure and to transport the charge during readout. The dark current density distribution for an FT CCD at room temperature is shown in figure 7. The mean dark current density is approximately 20 pA/cm^2. The distribution includes a large number of pixels with low dark current, and a much smaller number of pixels with high dark current. Dark current images often resemble pictures of the night sky, with stars of different magnitude representing the pixels with high dark current.

In the interline transfer CCD, charge is collected in photodiodes during exposure and then transferred to the vertical CCD for readout. The dark current density distribution for both the photodiodes and the vertical CCD of an IT CCD at room temperature are shown in figure 8. The mean dark current density for the photodiodes is only 15 pA/cm^2, but the mean dark current of the vertical CCD is 200 pA/cm^2. The vertical CCD dark current is much higher in interline transfer CCDs than in frame transfer CCDs. However, the dark charge accumulated during readout is a sum of contributions from individual vertical CCD stages, in which the variation is averaged out.

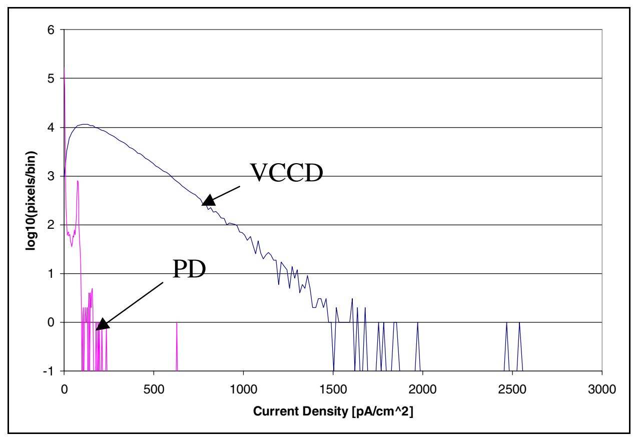

Figure 8. IT CCD Dark Current Distribution

The dark current requirement for digital photography can be analyzed in terms of the worst case scenarios: short exposures at high temperature or long exposures at low temperatures. The combination of high temperature and long exposure is unlikely to occur, as it is usually bright or confined (so that a strobe can be used) when the environment is hot. The dark charge accumulated during a 1/60th second exposure at 60C is roughly equivalent to the charge accumulated during a 1 second exposure at 30C. Under these conditions, the average charge generated by the dark current densities we have measured would only be about 60 electrons, which is less than 1% of the charge capacity. Interpolated values can be used to replace the pixels with high dark current, or dark frame subtraction can be used to cancel out the dark current. These dark current levels are adequate, as the current generation of digital cameras have demonstrated.

If the dark current of the vertical CCD in an IT-CCD is too large, the shot noise of the dark current will overwhelm the read noise and reduce the ISO speed of the camera. In order to keep the shot noise of the readout dark current below 20 electrons (assuming a ~0.1 second readout: 2

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megapixels at 20 MHz, and a temperature of 60C) the VVCD dark current density at room temperature must be less than 20 pA/cm^2. Further improvements in IT-CCD technology will be required to reach this goal.

Smear Requirements

Photons that are captured by the CCD during the frame readout process produce vertical streaks in the image that are referred to as smear. Smear is completely eliminated in most digital cameras by the use of a mechanical shutter that isolates the CCD during the readout of the full image frame. However the shutter isn't suitable for use in preview, auto-focus and exposure metering modes which require high frame rates.

Interline transfer CCDs that are designed for digital photography usually have a special progressive scan mode that can be used to obtain a sparsely sampled preview image. The vertical CCD registers are covered with a light shield that reduces smear to < -80 dB[6], as long as the angular spread of the incident beam is restricted. The smear level increases significantly at wide lens apertures.

Frame transfer CCDs that are designed for digital photography usually have a storage section to which a section or sampled version of the full image can be rapidly transferred. Performing the frame shift rapidly can reduce smear, however it is difficult to reduce smear below -60 dB in large arrays and still obtain high charge transfer efficiency.

The effect of smear is greatest when the scene brightness is high and the exposure period is at its minimum value. Under these conditions specular highlights in the scene are likely to produce visible smear streaks that can degrade the quality of the preview image, or confuse the auto-focus system. The smear streak produced by a specular highlight depends on both the intensity and size of the highlight. Specular highlights that are 10 times as intense as the level required to saturate the CCD (during exposure) and 10 pixels in size aren't unusual. Such a highlight would produce a visible streak unless the smear level of the CCD was < -120 dB. For this reason digital cameras are likely to continue to use mechanical shutters.

The smear requirements in the preview and autofocus modes are less stringent. The specular highlight described in the previous paragraph would produce a streak with an intensity of only 1%, if the smear level was –80 dB. This low level of smear has already been demonstrated in interline transfer CCDs. In order to provide adequate performance under all circumstances, frame transfer CCDs will require further development.

Conclusion

The number of CCD pixels utilized in consumer digital cameras continues to grow. By the time of this conference, many 3.2 megapixel cameras will have appeared on the market. These cameras have 10 times as much resolution as the pioneers like the Casio QV-10 and the Apple Quick-Take 100. The resolution requirements for digital photography will continue to increase, but not as explosively as in the past. Approximately 6 to 10 million pixels are required to obtain the same sharpness as consumer film cameras (APS, 35mm). This resolution will be more than adequate for snapshot prints and basic enlargements.

The CCDs that are used in today's consumer digital cameras all have relatively small optical format sizes. By convention, the optical format size is approximately 1.5 times the image diagonal length. Today's consumer digital cameras use CCDs with 1/3", 1/2" and 2/3" optical formats. In order to reach 6 megapixels with a 2/3" optical format, the pixels must shrink to 3 microns[7]. Pixels of these small dimensions do not have adequate charge capacity and sensitivity and they do not allow adequate aperture control. For these reasons the optical format sizes of CCDs will have to increase in the future.

A CCD figure of merit that is defined as the product of the ISO speed and the resolution divided by the cost can be used to compare different sensors. The figure of merit is proportional to ratio of the quantum efficiency and cost per unit area. Interline transfer and frame transfer CCDs have roughly the same figure of merit because IT CCDs have higher quantum efficiency, but FT CCDs utilize a less costly process. In other regards, FT CCDs offer more charge capacity and have a broader angular response. Even though most of today's consumer digital cameras use IT CCDs, FT CCDs should become more widely adopted in the future.

References

1. Jack Holm, private communication.
2. Jack Holm, private communication.
3. Jack Holm, "The Photographic Sensitivity of Electronic Still Cameras", *J. of the Society of Photographic Science and Technology of Japan*, Vol. 59, No. 1, pg. 117. (1996)
4. ISO 12232: Photography - Electric still-picture cameras – Determination of ISO speed. (1998)
5. Richard L. Baer and Jack Holm, "A Method for Calculating the Potential ISO Speeds of Digital Still Cameras based upon CCD Characteristics", *Proc. PICS*, pg. 35. (1999)
6. Albert J.P. Theuwissen, *Solid-State Imaging with Charge-Coupled Devices*, Kluwer Academic Publishers, 1995, pg. 236.
7. Herman Peek, "A Low Dark Current Double Membrane Poly-Si-FT-Technology for 2/3" 6M Pixel CCD Imagers", *Proc. IEDM*, (1999).

Biography

Richard Baer received his B.S. degree in Electrical Engineering from the Massachusetts Institute of Technology in 1977 and a Ph.D. in Electrical Engineering from Stanford University in 1983. Since 1983 he has worked at Hewlett-Packard Laboratories in Palo Alto, CA. For the last four years he has worked on digital photography, concentrating on CCD characterization and camera design. He is a member of the IEEE.