The Perfect Imager for Digital Still Cameras

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Abstract

This paper reviews the imaging performance of CCDs and CMOS sensors for application in consumer digital still cameras (DSCs).

Introduction

In a DSC, the primary function of the imager is to deliver the best quality, full-resolution, single-shot image. But the imager should also be able to generate information which can be used, prior to the capture of the full-resolution image, for camera functions such as auto-exposure, auto-focus and electronic viewfinder. A third function is the generation of video clip images. In our comparison, a wide range of criteria is considered: resolution, pixel performance, noise, flexibility, power consumption, optical and electronic system integration, cost, etc.

Basic Architectures

A frame-transfer (FT) CCD imager for DSC is presented in Fig.1, [1]. Real-time sub-sampled images are generated by reducing the vertical resolution during the frame shift at the image-to-storage transition.

An interline-transfer(IL) CCD for DSC is shown Fig.2, [2]. Typically, one four-phase cell of the interline transfer register is designed per two photodiodes. The full-resolution image is obtained by merging the two fields obtained sequentially by interlaced readout. Sub-sampled images are obtained by reading out only selected lines, defined by a split of some of the vertical electrodes.

Integration on the CMOS focal plane (Fig.3) is different from the CCD integration. For basic CMOS APS imagers, the start and the end of the integration cycle is different for every pixel. This effect, known as a rolling integration cycle, can be tolerated for movie applications, but it is unacceptable for DSC applications. To overcome this shortcoming, a pixel with in-pixel storage capability is needed, which can be realized at the cost of an extra transistor and extra capacitor within every pixel. In most cases, this brings the total to 4 transistors per cell. In some cases the extra storage possibility can be exchanged with CDS capability: 2 modes of operation are possible, being synchronous integration or CDS.

Image Pixel Size

To achieve a compact 2-M or 3-M pixel DSC camera, the image diagonal should not exceed 1/2”. This requires pixel sizes in the order of $4.0\times4.0\mu m^2$ to $3.3\times3.3\mu m^2$. FT-CCD pixels can be made as small as $2.4\times2.4\mu m^2$, since they combine charge integration and transport into a single cell [3]. The smallest pixel size presented in an IL-CCD for DSC is $3.15\times 3.15\mu m^2$ [4]. Currently, in a $0.25\mu m$ technology, CMOS imagers require $3.3\times3.3\mu m^2$ for a 3-T cell [5] and $4.5x4.5\mu m^2$ for a 4-T cell.

Image quality

The fundamental function of an imager is good optical sensitivity. Ideally, microlenses on IL-CCD or APS pixels would focus all the incident light directly on the photodiode, thus they can achieve a higher quantum efficiency than on FT-CCD where the light has to pass through a gate electrode.

The dark current generation in the pinned photodiodes of an IL-CCD is typically 5 times lower than in a FT-CCD pixel. However, the long readout times associated with high-resolution CCDs implies that the very high dark current in the interline registers becomes significant. The dark current in the pinned photodiodes of APS sensors is typically more than an order of magnitude higher than in the FT-CCD pixels.

At least 10 bit dynamic range is required for DSC imaging. With a noise floor in the order of 15 electrons, this can be easily achieved in a FT-CCD pixel of $3.3\times3.3\mu m^2$ with a charge capacity of 25 000 electrons. For the same pixel size, the charge capacity of an IL-pixel is typically half of that of FT-CCD. With a similar noise floor, only 9 bit dynamic can be achieved with IL-CCD pixels smaller than $3.6\times3.6\mu m^2$. In an APS imager, Vsat is at this moment not limiting, because of the higher doping and therefore higher storage capacitance. For future processes going to lower supply voltages, Vsat will become an issue [6].

Flexibility

For the LCD viewfinder as well as for the camera exposure controls (e.g. auto-focus, auto- exposure), and more recently, also for video clips, the required frame rate is high, while the full resolution is often not required.

Here the full flexibility that can be achieved with a CMOS XY addressed imager is a definite advantage. FT-CCDs with flexible vertical subsampling are second, the IL-CCD is least flexible. The lack of flexibility in horizontal readout is a serious problem to achieve high frame-rate VGA or NTSC-like video clip images in high-resolution CCDs.

In preview or video clip modes, the exposure times are limited by the required frames per second. Since full resolution is not needed, charge binning is an option to increase the sensitivity of the small pixels. Color information should be maintained. Combining vertical binning and sub-sampling is easy in FT-CCD, it requires a further split in the vertical electrodes of an IL-CCD. In an APS sensor, binning in the charge domain is not possible.

Optical System Integration

The wide angular response of the FT-CCD with its intrinsic high aperture allows a more compact and less expensive zoom lens, the most expensive component in a DSC camera. Fig. 4 shows the angular response for an FT-CCD and an IL-CCD, both with $3.9\mu m$ pixels with on-chip microlenses. The small intrinsic fill factor for 4-T APS pixel cells smaller than $4.0\times 4.0\mu m^2$ combined with the large stack height in CMOS processes makes it very difficult to match the wide angular response of FT-CCDs.

Electronic System Integration

The low power consumption, the single low voltage requirements and the high level of integration in a CMOS imager are of course a significant advantage in mobile applications.

Conclusions

Table 1 summarises the comparison. For each issue, a weight factor is given (higher= more important), and a ranking (3= best). The total performance indicator is the sum of the rankings, multiplied by the weight factor. The perfect imager for DSC would be a low-power CMOS imager with $3.0\mu m$ size pixels, with the low dark current of an IL-CCD pixel, the high dynamic range and excellent angular response of a FT-CCD, the low noise and the instant-shutter function as in CCDs. Unfortunately for the consumer, this device does not yet exist. Until then, CCD, especially of the FT-type, are viable solutions for high-quality consumer DSC cameras.

References

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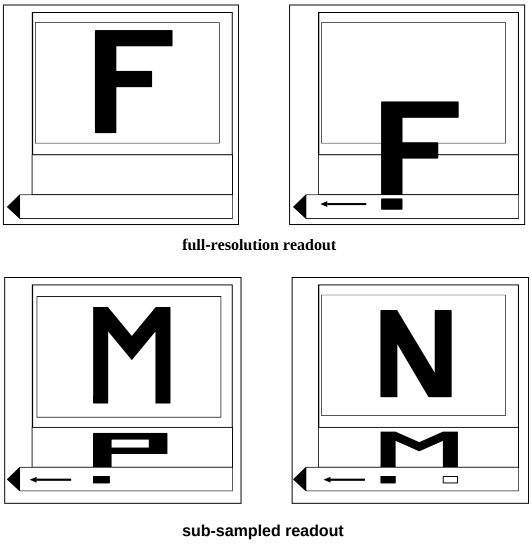


Figure 1: Schematic of FT-CCD for DSC

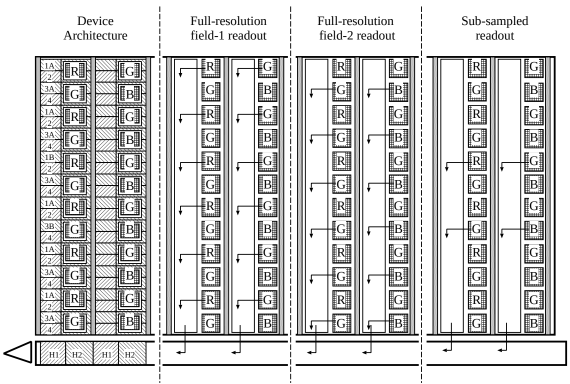
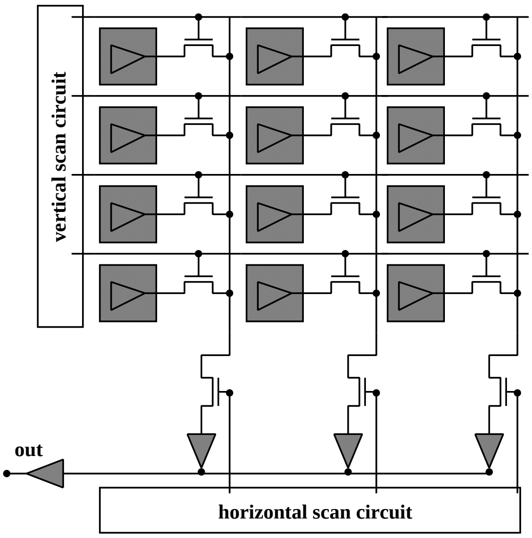


Figure 2: Schematic of IL-CCD for DSC



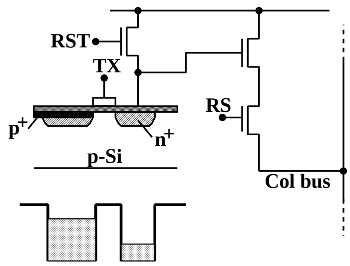


Figure 3: Schematic of CMOS APS sensor for DSC. A 4-T cell using this concept allows either instantaneous shutter action or CDS, but not both

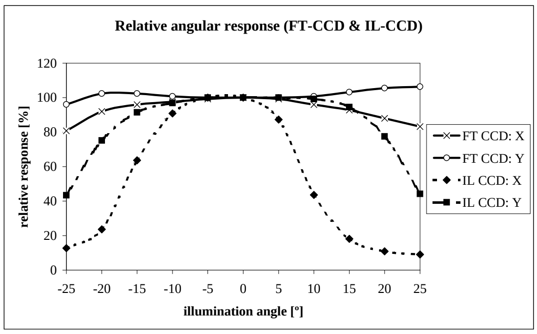


Figure 4: Angular response of FT-CCD an IL-CCD imagers with 3.9×3.9μm^2 pixels

Sensor type		**FT-CCD**		**IL-CCD**		**CMOS APS**	
	weight	issue	rank	issue	rank	issue	rank
				Image Pixels			
Min. dimensions[μm]	5	2.4	3	3.2	2		1
Max. resolution	5	6M	3	5M	2	3M	1
Quantum efficiency	5	lens-insulator-gate	1	lens-insulator	3	lens-insulator	3
Angular response	5	excellent	3	poor	2	poor	2
				Image Quality			
Charge capacity	5	excellent	3	poor	2		2
Pixel dark current	5	optimised technology	2	pinned photodiode	3	pinned photodiode	1
Readout dark current	3	same low level as integration	3	high due to interline register	2		1
Highlight handling	3	excellent	3	excellent	3	excellent	3
Single-shot capability	5	full reset	3	full reset	3	rolling shutter	1
				Flexibility			
LCD preview	5	vertical sub-sampling	2	vertical sub-sampling	2	fully addressable	3
horizontal binning	3	not possible	1	not possible	1	fully addressable	3
vertical binning	3	flexible	2	non-flexible	1	fully addressable	3
video clip	4	part.flexible	2	non-flexible	1	fully addressable	3
smear in video mode	2	high	1	low	2	none	3
				System Integration			
Low voltage	5	no	2	no	2	excellent	3
Single power supply	5	no	2	no	2	excellent	3
Power consumption	3	medium	2	medium	2	low	3
System Cost	5	many external components	2	many external components	2	fewer external components	3
Performance Indicator		**173**		**160**		**172**	

Table 1: Performance Overview of Imagers for DSC