Advances in CMOS Image Sensors and Associated Processing (Part 1)

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Abstract

Part I of this presentation will review Canon technology that exploits the large size of the 35mm Full Frame CMOS image sensor with the modest spatial sampling of 1920 (H) x 1080 (V) to realize a uniquely large photosite of 19um x 19um. This facilitated development of an HD camera having unprecedented sensitivity. The final operational specification of a maximum ISO 4,560,000 setting has produced an HD camera that opens a broad spectrum of truly innovative image capture. This includes nighttime wildlife productions (many species are nocturnal), deep underwater imaging that require no lighting whatever, certain astronomical shooting, unique documentary productions, and many forms of surveillance imaging.

HIGH SENSITIVITY FULL FRAME 35MM HDTV IMAGE SENSOR

This single CMOS image sensor is a full frame S35mm with outside dimensions of 36mm x 24mm. It has been designed to originate full color HDTV with an aspect ratio of 16:9. The active image area is 36mm horizontal by 20.5mm vertical as shown in Figure 1.

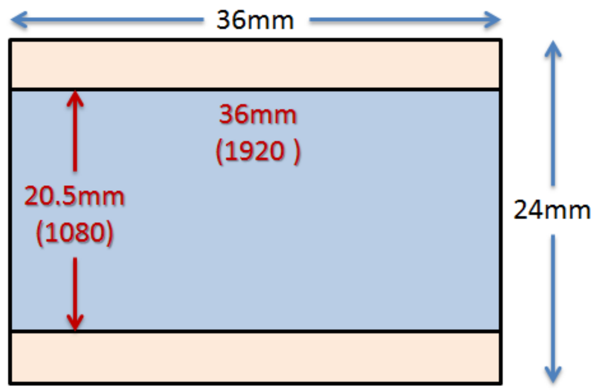

FIGURE 1: *SHOWING THE DIMENSIONS OF THE ACTIVE IMAGE AREA IN THE ME20F-SH WITHIN THE FULL FRAME 35MM CMOS IMAGE SENSOR*

The combination of the large image format size and the limited imaging sampling lattice of 1920 (H) x 1080 (V) HDTV format produces large overall photosites. Just how large can be noted from the comparison in Figure 2 with two well-established image formats

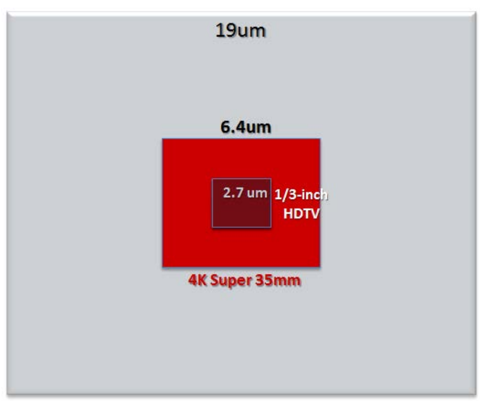

FIGURE 2: *SHOWING THE RELATIVE SIZE OF THE FULL FRAME PIXEL COMPARED TO TWO POPULAR PIXEL SIZES – THE 6.4UM OF THE 4K SUPER 35MM FORMATS AND THE 2.7UM OF THE HDTV 1/3-INCH FORMAT*

When a band of visible light wavelengths are incident on specially doped silicon semiconductor materials, electrons are released in proportion to the photon flux density impinging on the surface of a photodiode. In effect, the number of electrons produced is a function of the wavelength and the intensity of light striking the semiconductor.

THE NEW PHOTOSITE

The image sensor design sought optimization of three key attributes of the photosite:

1. Sensitivity – determined by the quantum efficiency of the photosite
2. Saturated charge quantity (sometimes termed full well capacity) – that determines dynamic range
3. Efficiency of the charge transfer (sometimes termed conversion gain) – the goal being to transfer all electrons during each reset period to ensure full sensitivity

The larger the active photosite within the individual pixel the greater the capacity for capturing photons during the normal charge period. This is the primary factor defining the sensitivity of the photosite. However, the efficiency of accumulating and transferring these electrons to the pixel output during the readout period are equally important. The total charge accumulated must then be converted to a voltage that constitutes the output of that individual pixel. The pixel size of the ME20F-SH is approximately 19um square – and the photosite is a little smaller because of associated circuitry. The quantum efficiency of the photosite is defined by the percentage of incident light photons that are converted to electrons. Figure 3 shows the spectral characteristics of the image sensor. The effective monochrome Quantum Efficiency of the ME20F-SH photosite output is 70% at 500 nm.

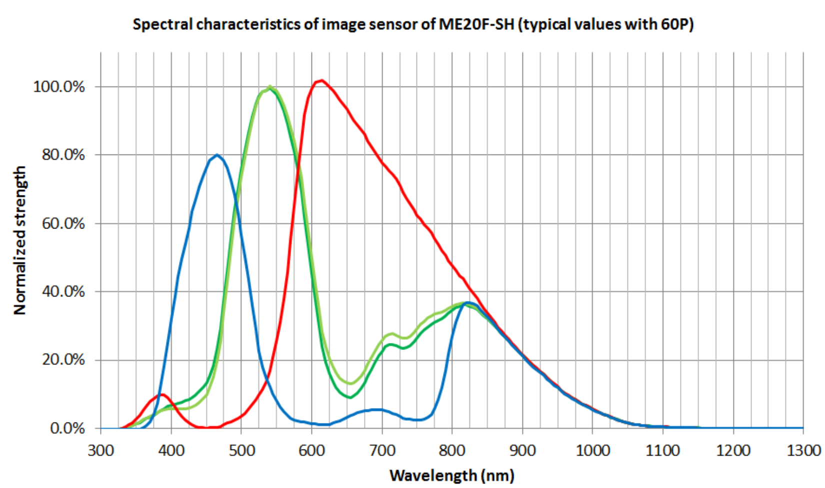

FIGURE 3: *SHOWING THE SPECTRAL CHARACTERISTICS OF THE IMAGE SENSOR*

The large photosite does, however, entail a particular challenge in achieving efficiencies in charge transfer. Electrons at different locations across the photodiode travel at different speeds depending upon the potential applied to them. The highest potential is in the vicinity of the transfer electrode.

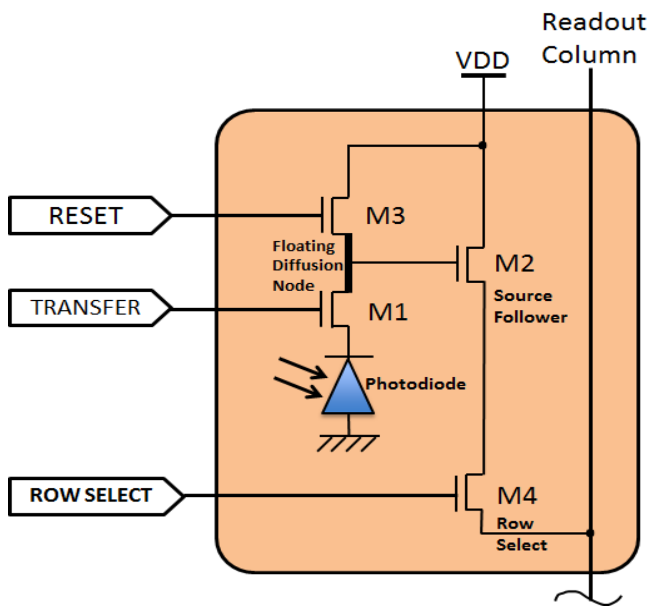

FIGURE 4: *SHOWING THE CIRCUIT CONFIGURATION OF A SINGLE ACTIVE PIXEL*

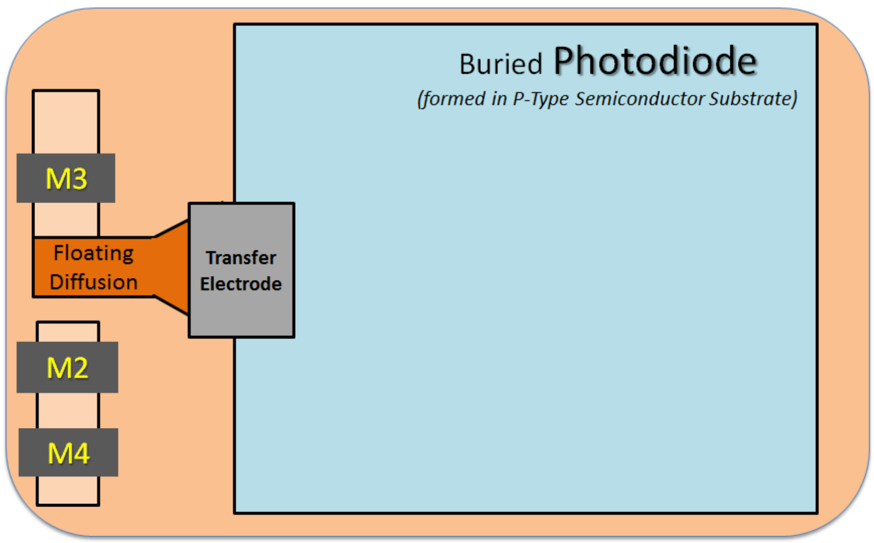

FIGURE 5: *A PLAN VIEW OF THE STRUCTURE OF AN INDIVIDUAL PIXEL AS SEEN FROM DIRECTION OF LIGHT INCIDENCE ON THE PHOTOSITE – SHOWING THE EXCEPTIONALLY LARGE AREA OF THE PHOTODIODE*

While the very large photosite is central to achieving an unprecedented level of image sensitivity it also introduces technical hurdles which must be overcome if this sensitivity is to be practically realized. The challenge lies in the fact that the electrons released by the photoconversion process during the charge accumulation period must all be collected and completely transferred during the subsequent reset period. During the charge period those electrons tend to wander within the photodiode and must be rapidly scooped up by application of an appropriate electric field.

When the MOS transistor M1 is switched to its conductive state a charge transfer channel is opened that transfers the charge to the floating diffusion region. The high potential at the transfer gate rapidly transfers those electrons close to that gate. However, electrons further away encounter a lower potential and their transfer efficiency is correspondingly lowered.

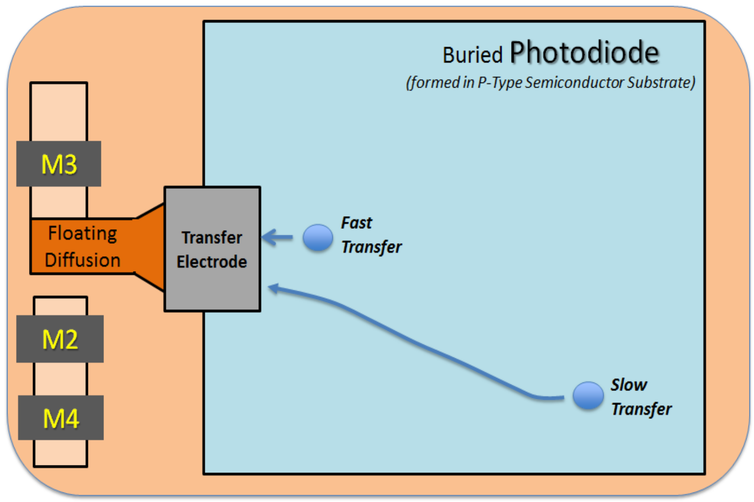

FIGURE 6: *INDICATING THE DISPARITY IN SPEED OF TRANSFER OF ELECTRONS AS A FUNCTION OF THEIR DISTANCE FROM THE TRANSFER ELECTRODE*

The solution by Canon's image sensor engineers was to create a progressively increasing electric field profile across the photosite that would accelerate the mobility of the more spatially distant electrons. There are two aspects to this innovative design – one, the steps in the electric field itself, and the second is the spatial distribution of these disparate fields. The creation of the separate electric fields was implemented in the surface region by controlling the amount of the injection rate of P-type impurity for the surface of the photodiode.

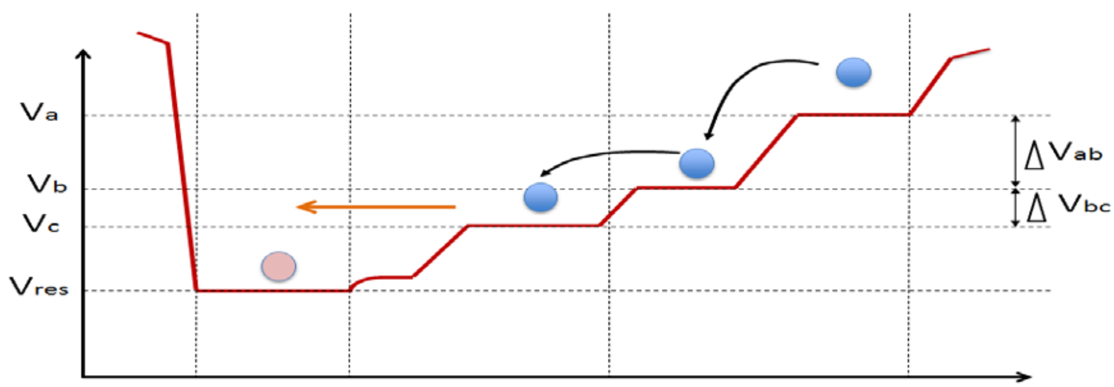

FIGURE 7: *SHOWING THE THREE POTENTIAL LEVELS AND THE PROGRESSIVE MOVEMENT OF AN ELECTRON THAT IS DISTANT FROM THE TRANSFER ELECTRODE BY ELECTRIC FIELDS GENERATED BY THE POTENTIAL DIFFERENCES*

An electron released in the vicinity of the transfer electrode is influenced by a high electric field caused by the reset voltage Vres and is speedily transferred to the floating diffusion node. A released electron in a region furthest away from the transfer electrode has the minimum potential Va in the charge accumulation region and moves primarily by diffusion until it encounters an electric field due to Delta Vab and then a second field due to Delta Vbc. A complex relationship exists between transfer efficiency, saturated charge quantity, and sensitivity. Optimization of the magnitude of all three parameters is best satisfied when Delta Vab > Delta Vbc.

The spatial arrangement of the three semiconductor regions is also critical to assembling the disparate electrons across the photodiode and achieving their expeditious transfer to the floating diffusion node. The particular spatial arrangement designed by Canon image sensor scientists is shown in Figure 8.

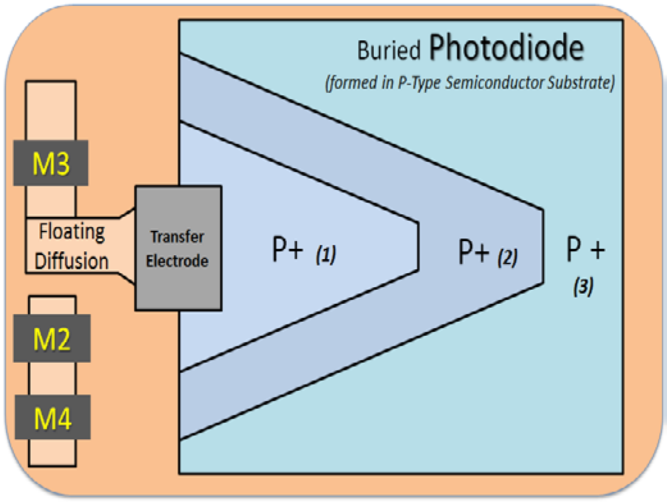

FIGURE 8: *SHOWING A PLAN VIEW OF THE PHOTOSITE AND ASSOCIATED CIRCUITS AND OUTLINE THE TRAPEZOIDAL SHAPE OF THE TWO SEMICONDUCTOR REGIONS CLOSEST TO THE TRANSFER ELECTRODE*

The ME20F-SH Camera

This unique CMOS image sensor design allowed an unprecedented high sensitivity camera ME20F-SH to be developed by Canon. It utilizes the EF-mount to ensure availability of a wide range of lenses that can cover the large image circle.

FIGURE 9: *SHOWING THE ME20F-SH HIGH SENSITIVITY HDTV CAMERA THAT UTILIZES A FULL FRAME 35MM IMAGE SENSOR HAVING A 16:9 ACTIVE IMAGE*

The Camera covers a broad range of scene illumination with particular capabilities in very low illumination as shown in Figure 10.

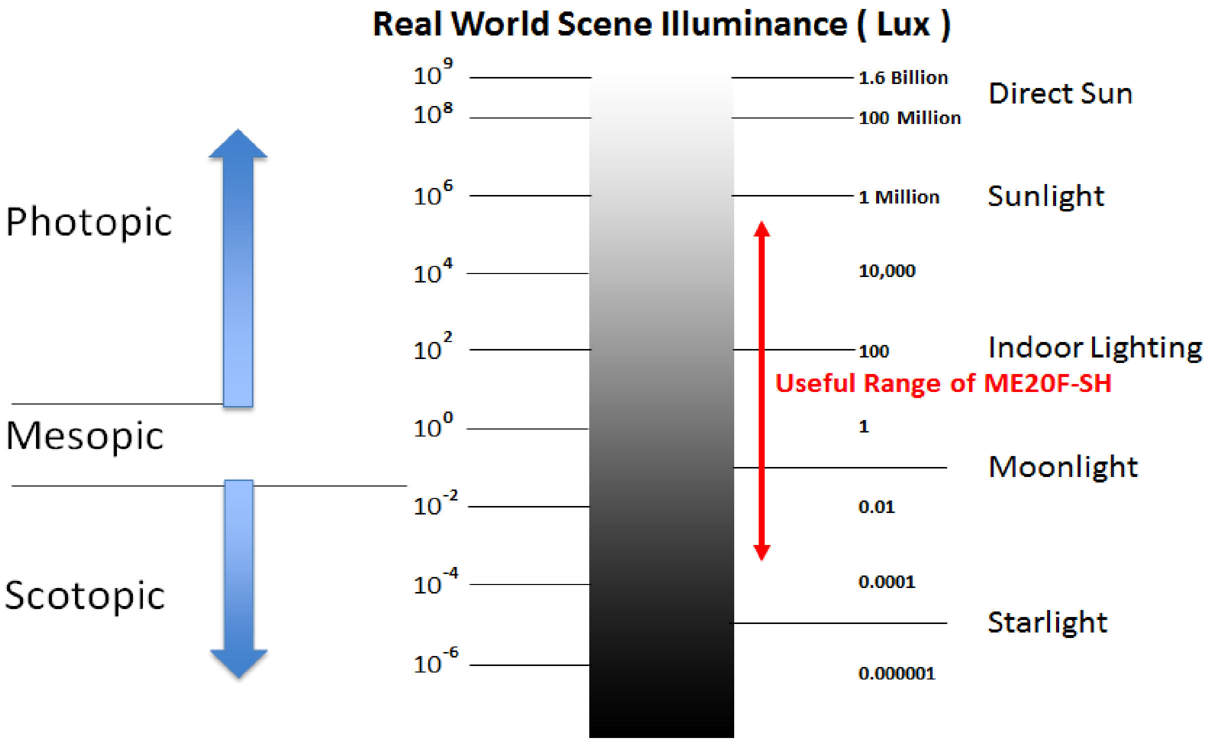

FIGURE 10: *SHOWING THE UNPRECEDENTED OPERATIONAL RANGE OF SCENE ILLUMINATION LEVELS OF THE ME20F-SH CAMERA*

The ME20F-SH has a nominal sensitivity that is defined as follows:

Under 2000 lux 3200 degrees Kelvin illumination the lens setting to achieve 100 IRE of Luma (with Gamma off and Master Gain at 0 dB) is F-10.

The camera embodies two ND filters – one having +3-Stop and the second +6-Stop. The combination of these (to handle high illumination scenes) and a Master Gain range up to 75dB (in 3 dB steps) to handle progressively lower scene illumination levels endows the camera with the ability to operate over a very large range of scene illuminations that is summarized in Figure 10. This illumination range is further outlined in Figure 11 below.

Light	Illuminance (Lux)	Lens Aperture	Master Gain	ND Filter
BRIGHT SUN	619,520			+ 6-stop
	77,440			+ 3-Stop
HAZY SUN				
BRIGHT CLOUDY	9,680	F-22		Clear
DULL CLOUDY	4,840	F-16		
	2,420	F-11.0		
	2,000	**F-10**		
	1,210	F-8.0		
VERY DULL DAY	605	F-5.6		
	303	F-4		
SUNSET	151	F2.8		
DUSK	76	F-2		
	27	F-1.2		
TWILIGHT	9.58	F-1.2	+ 9 dB	
	2.395		+ 21 dB	
MOONLIGHT	0.5987		+ 33 dB	
	0.1497		+ 45 dB	
DARKNESS	0.0374		+ 57 dB	
	0.0094		+ 69 dB	
	0.0047		+ 75 dB	

FIGURE 11: *BENCHMARKING THE OPERATIONAL SENSITIVITY RANGE OF THE ME20F-SH CAMERA IN THE CONTEXT OF A RANGE OF REAL WORLD SCENE ILLUMINATION LEVELS*

SUMMARY

This CMOS image sensor was specifically developed to allow implementation of an HDTV camera that can deliver full color images in extraordinarily low scene illumination levels. It achieves this by using a 16:9 sampling lattice within a single 35mm full frame image sensor (that utilizes a Bayer color filter array) – which supports a very large photosite. This, in turn, provides a large number of electrons released by the photoconversion process. Special design strategies are mobilized to ensure efficient capture of all of those electrons during each reset period – thus enabling an HDTV camera of extraordinary sensitivity. The anticipated uses of the ME20F-SH multipurpose HDTV camera are many – and they include documentary production, natural history (especially capture of nocturnal and deep water animals), special scenes in movie and television episodic origination, and a variety of military and law enforcement applications that entail unusually low scene illumination.