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CMOS

ADVANCES IN CMOS IMAGE SENSORS AND ASSOCIATED PROCESSING

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Advances in CMOS Image Sensors and Associated Processing

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Abstract

This presentation will review two technical innovations in CMOS image sensors and their associated digital processing that have significantly enhanced motion image origination. Details of the relevant technologies will be discussed.

The first technology is a new Super 35mm CMOS image sensor specifically developed to support origination of High Dynamic Range (HDR) motion imagery. The deployment of two separate photodiodes within each photosite is central to achieving the 15-stop dynamic range. The dual photodiode also supports a unique in-sensor phase detection strategy that is followed by powerful data processing that closes a focus control loop around the cine lens. Alternatively, for those who prefer manual focus operation, a separate data processing provides a Focus Guide in the form of signaling in the viewfinder achievement of precision focus.

The second technology 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 19 um x 19um. This facilitated development of an HD camera having unprecedented sensitivity. The final operational specification of a maximum ISO 4,000,000 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) and deep underwater imaging that require no lighting whatever, certain astronomical shooting, unique documentary productions, and many forms of surveillance imaging.

1.0 New Super 35mm CMOS Image Sensor

1.1 Alternative to Algorithmic Debayering – Direct Component Readout

The traditional single wire output from a Bayer image sensor – as outlined in Figure 1 – entails formulating the serial data stream into whatever file format the individual camera designers favor. This must subsequently be decoded to create the individual RGB frames. Of necessity this decoding entails sophisticated algorithms – and even with the best of these there are inevitable residual reconstruction errors.

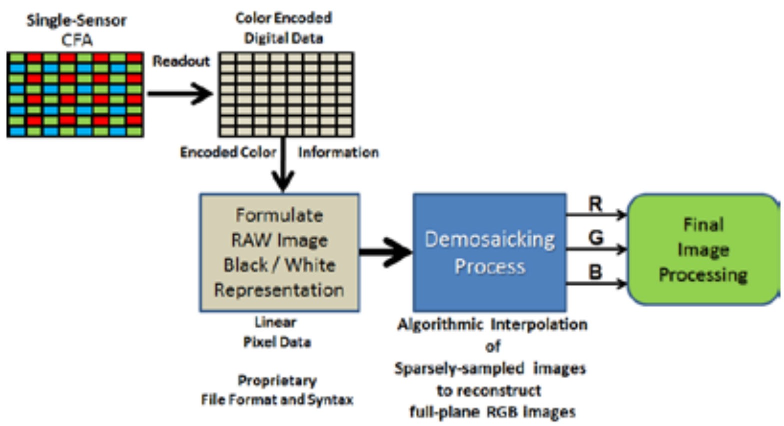

Figure 1 *Showing the traditional single wire readout of the Bayer encoded signal*

In the original EOS C300 camera the dexterity of the multichannel readout architecture of the specially developed Canon 4K CMOS image sensor implements a direct parallel read out of the four constituent 2K components that constitute the 4K Bayer sampling structure – as simplistically outlined in Figure 2.

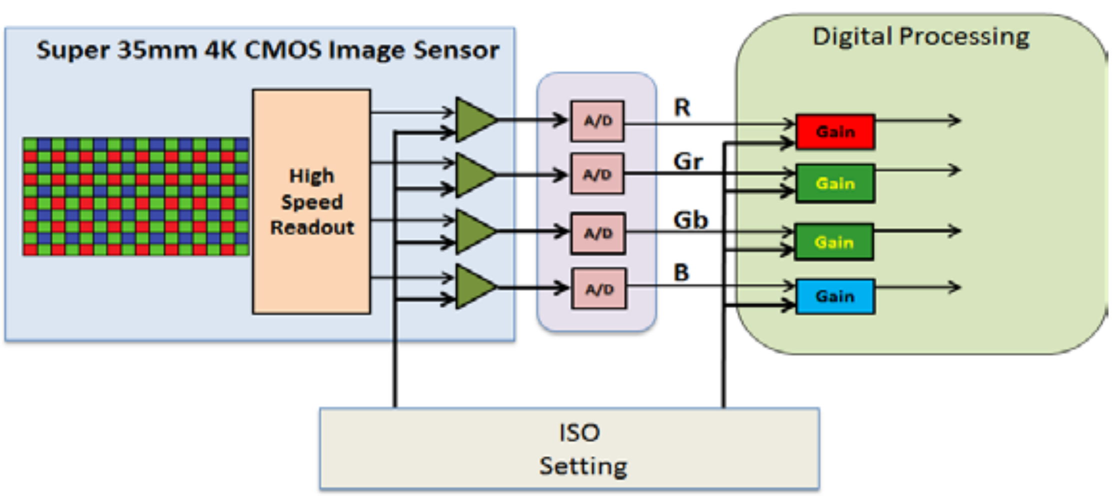

Figure 2 *Outlining the principle of the parallel readout within the image sensor of the four 2K components that constitutes a direct decoding of the 4K Bayer color sampling*

A totally new Super 35mm 4K image sensor developed for the second generation C300 Mark II utilizes the same readout strategy as the earlier image sensor in the C300 camera. The dexterity of the readout capability of the CMOS image sensor allows access to the pixel level and this, in turn, allow precision dismemberment of the 4K Bayer encoding into the four 2K constituent components of R, Gr, Gb, and B. Thus, a debayering process has been implemented that requires no downstream algorithmic decoding – which totally eliminates the traditional associated reconstruction errors [1].

1.2 Dual Pixel Strategy – Elevation of Dynamic Range

Among numerous design strategies in the Super 3m CMOS image sensor developed for the EOS C300 camera was an innovative new photosite design that employed two separate photodiodes – each being 6.4 x 3.2 micrometers. For simplicity this novel design is referred to as the Dual Pixel CMOS image sensor.

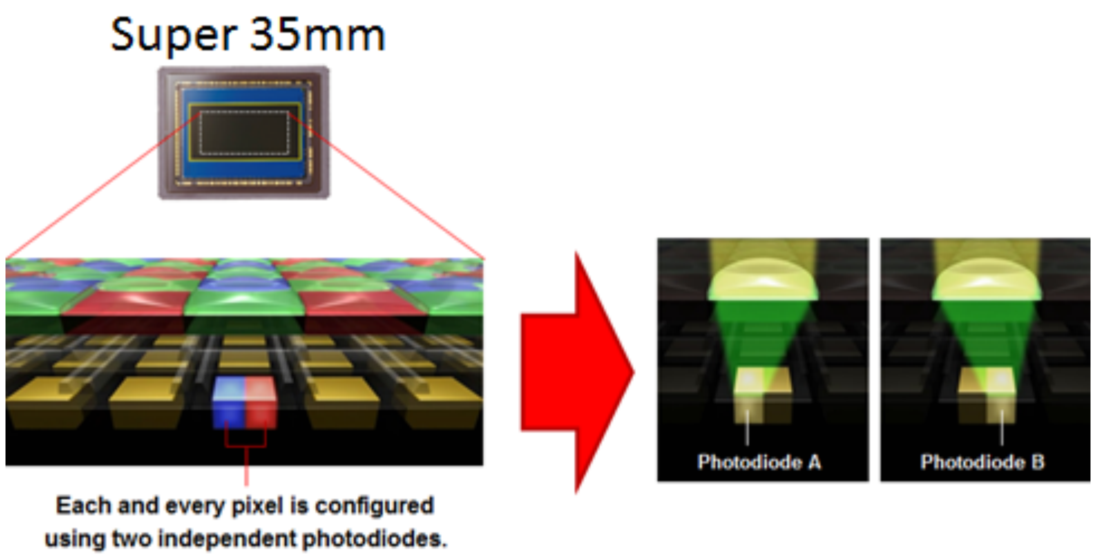

Figure 3 *A representation of the dual pixel CMOS image sensor with a specially designed microlens that optimizes the focusing of the incident light onto both photodiodes*

The smaller lateral dimension of the individual photodiode supports a higher charge transfer efficiency (see more detailed explanation of this later in the ME20F-SH image sensor section of this paper) which in turn facilitates a greater speed in totally emptying the accumulated charge from each during the imager reset period (the two charges are later summed following readout and A/D conversion). The photodiode was also designed as a higher density N-type which elevates the number of saturation electrons. The combination of these strategies produces an elevation of the overall dynamic range of each photosite.

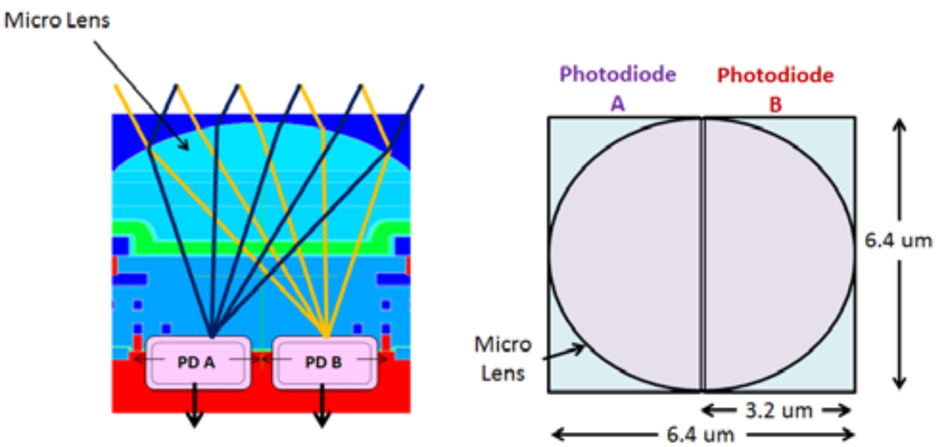

Figure 4 *Showing the dual photodiode structure of a single photosite in the 4K CMOS image sensor used in the Cinema EOS cameras*

1.3 Second Generation Dual Pixel CMOS Image Sensor – 15-Stop DR

The C300 Mark II employs a new generation Super 35mm CMOS sensor which is based on the same dual photodiode per photosite. Additional innovations within the photodiode design in combination with new on-chip noise cancellation technology have simultaneously lowered the noise floor and further elevated the saturation level of the charge well. In addition, a totally new microlens design heightens the efficiency of light direction onto the two individual photodiodes while also improving the separation between the two photodiode outputs.

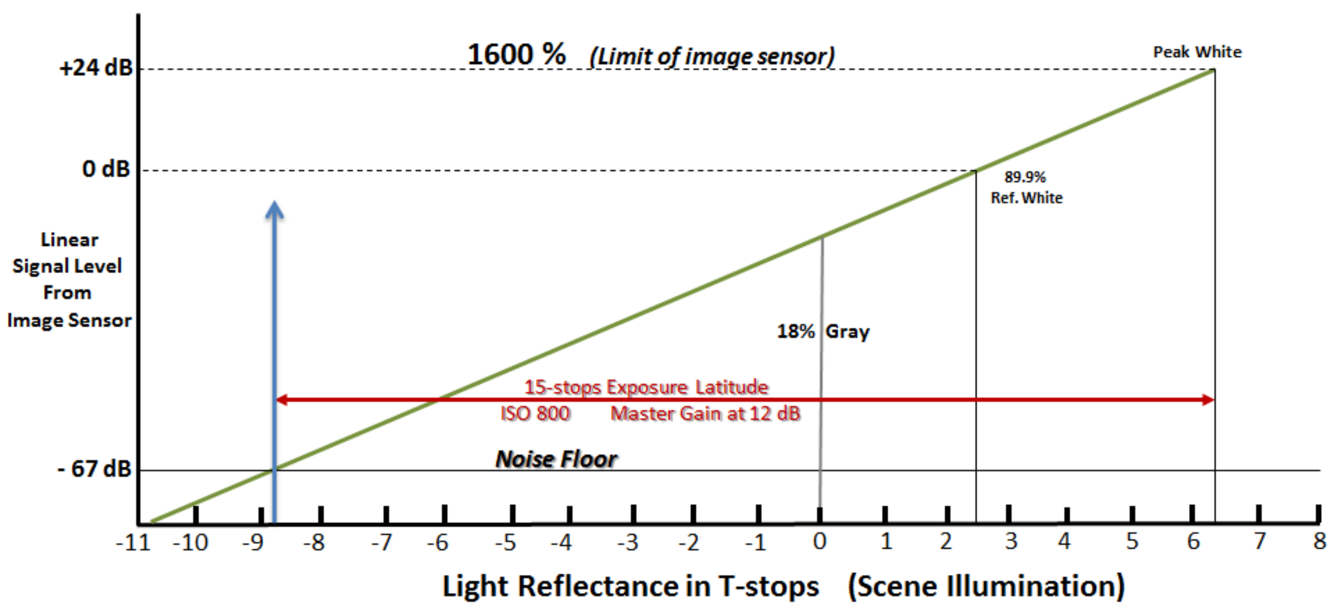

Figure 5 *Showing the linear analog signal level capability of the new CMOS image sensor*

The combination of these new design strategies contribute to a more than two-fold increase in effective photosite dynamic range. This provides a definitive ***15-Stop*** dynamic range capability in this new cinematography camera – providing one-stop capability above that of the C300 in the upper region and two stops below that of the C300 in the lower region. The more controlled noise floor allows the ISO range to be extended up to ***ISO 102,400.***

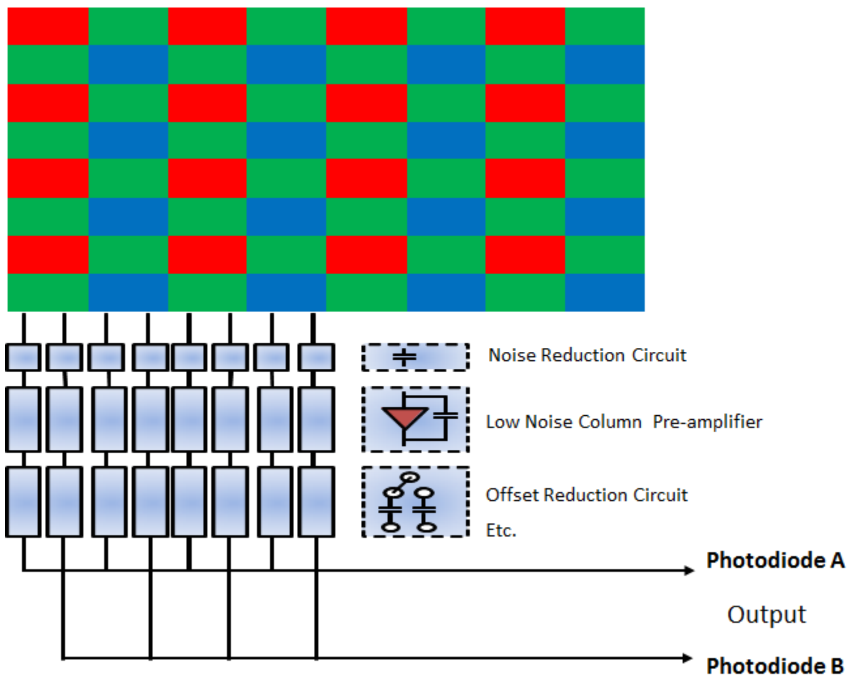

Figure 6 *Showing the principle of the dual output from each individual photosite and the associated analog processing that takes place within the image sensor itself*

In 2014 Canon introduced the second generation C100 Mark II which employed the same Super 35mm 4K CMOS image sensor as the C300 and C100. But this camera further exploited the two separate photodiodes within each photosite to empower a phase detection system that identifies the degree of defocus in an image – allowing incorporation of an innovative new Auto Focusing system having high precision. This initial implementation proved very effective under normal shooting conditions. We will first describe the basics of what is termed the Dual Pixel CMOS Auto Focus system based upon that first embodiment in the C100 Mark II camera.

1.4 Dual Pixel CMOS Auto Focus System

The C100 Mark II embodies a powerful auto focus system where the sensing of sharp focus takes place within the image sensor photsite itself. It mobilizes the dual photodiodes within each photosite to create two separate images that facilitates a phase detection system that indicates the degree of defocusing.

Figure 7 *Principle of the Auto Focus Control system where data from the dual photodiodes within each photosite constitutes a phase comparison which is processed to create a control signal for the lens focus*

Figure 8 illustrates the manner in which the sets of dual pixel outputs from the CMOS image sensor are sent to the Digic DV5 processing microcircuit that was developed by Canon. Within this processor, these streams are fed to the primary RGB video processing system (where the two photodiode signals are summed) and separately to a data processing system that makes all of the decision-making and data processing associated with the Auto Focus system.

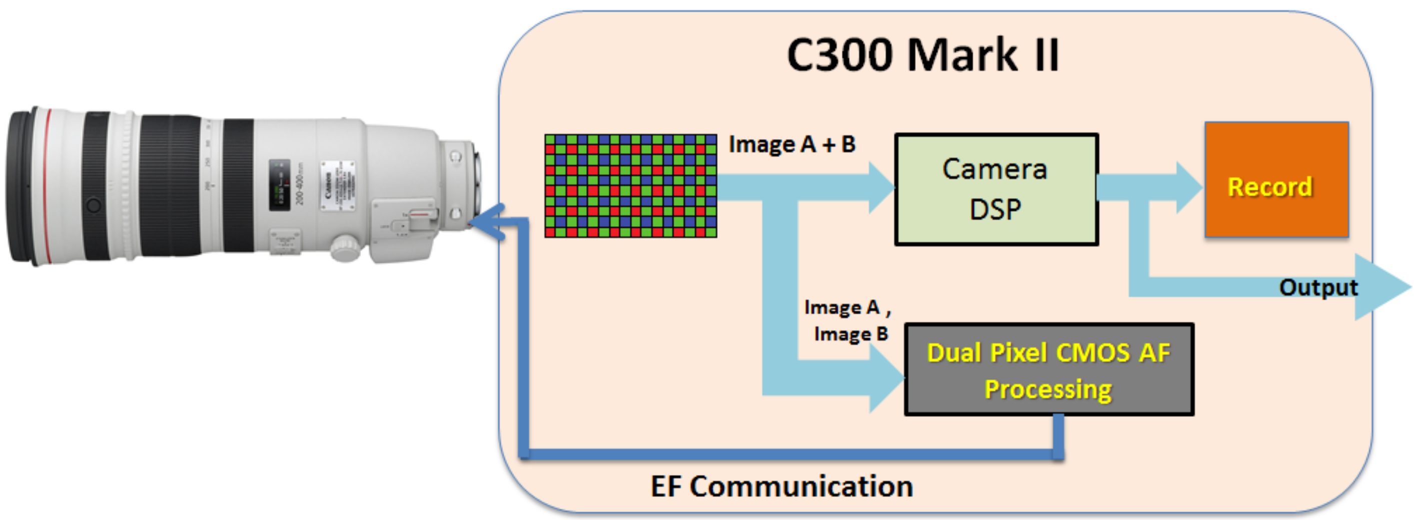

Figure 8 *Showing the separate processing of the dual pixel data from the image sensor – for video and for Auto Focus – at the entry stage of the Digic DV5 processor*

While all of the eight million photosites are delivering the "dual pixel" data the operational aspects of Auto Focus dictate that only a select number of these are activated at any given time. This is because the camera operator will make the decision on which particular subject within the overall picture frame is chosen for sharpest focus. Consequently, a cursor type system must be implemented to facilitate this choice.

In this first implementation of Dual Pixel CMOS Auto Focus (for simplicity Auto Focus is referred to as AF) system the "cursor" was fixed in the center of the image frame and had dimensions chosen based upon extensive testing.

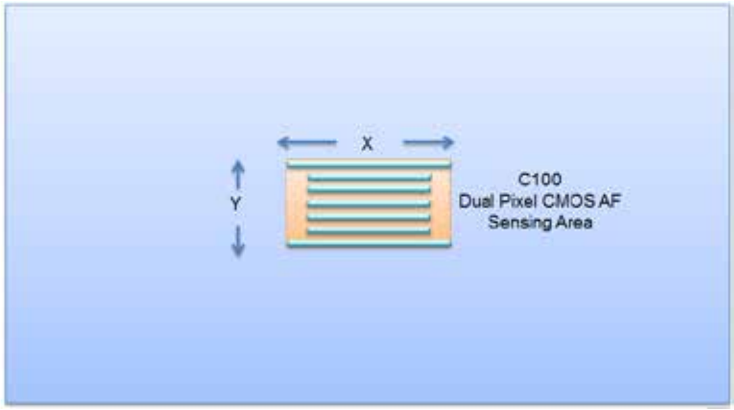

Figure 9 *Showing the fixed central activation of dual pixels in the C100 Mark II for Auto Focus – requiring that the camera frame the selected subject within this range*

The phase detection sampling lattice is made up of a number N of selected adjacent vertical samples of photosites – with each constituting an AF Sampling LINE – and then M of these Sampling LINES making up the total vertical sample.

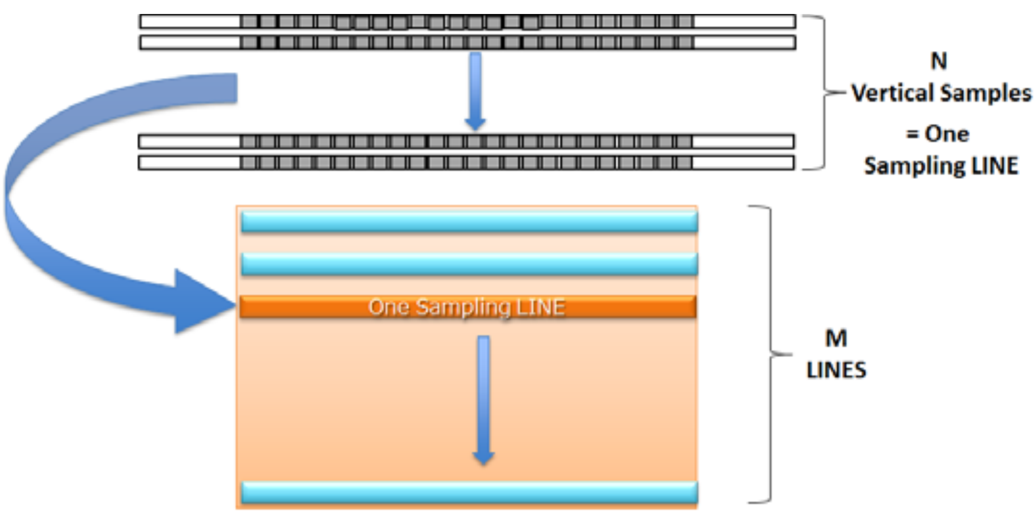

Figure 10 *Showing the spatial structure of the Auto Focus sampling lattice within the CMOS image sensor*

This system worked remarkably well in the C100 Mark II. However, a broadening experience revealed an extensive range of shooting situations that are encountered in the real world of program origination that challenged the reliable performance of the Dual Pixel CMOS AF system. Analysis of these yielded a range of recommendations:

1. Broad request to provide spatial movement of the sampling area – so that different subjects within a given scene can be selected for sharpest focus
2. Ranging performance improvement is needed in low scene illumination situations
3. Improvement in accuracy of the system as ISO setting increased
4. Auto Focus should ideally be a realtime action (or as close as possible to realtime) so speed of calculations should be increased
5. Improvement in the calculating algorithm to elevate reliability

As part of the development of the new generation Super 35mm 4K image sensor for the second generation C300 Mark II a totally new Dual Pixel CMOS AF system was developed in concert. A denser sampling lattice was developed to increase sensing sensitivity and accuracy over a wider range of scene illumination and camera ISO settings. The new sampling lattice is actually a matrix of nine adjoining photosite arrangements as shown in Figure 11.

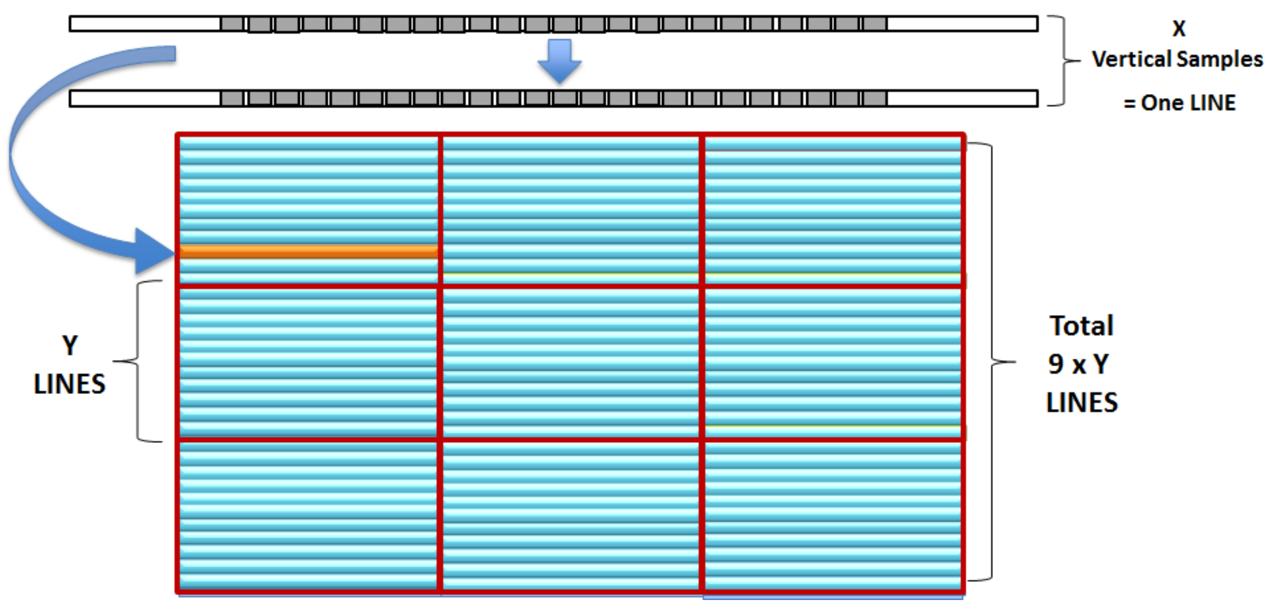

Figure 11 *Showing the substantially larger sampling lattice that makes up the AF detection in the C300 Mark II image sensor*

Each sub arrangement has been increased to Y Lines (compared to N lines for the earlier system). With nine such arrangements that becomes a total of 9xY selected lines of photosites. Operational flexibility was significantly broadened by allowing that sampling lattice to be repositioned (via a controlling joystick) across 80% of the total photosite structure of the image sensor – as shown in Figure 12.

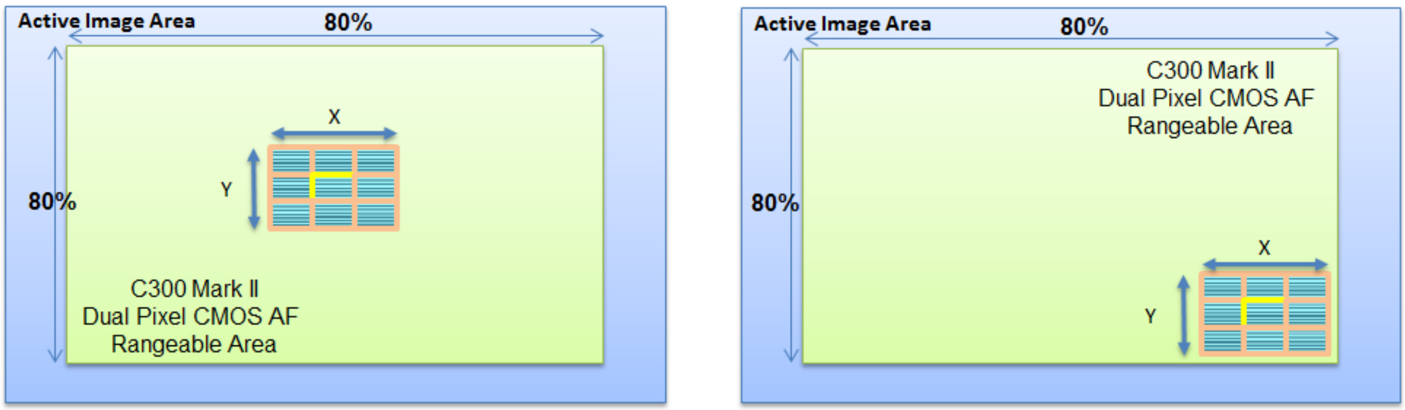

Figure 12 *Showing that the Dual Pixel CMOS AF selection area can be moved around some 80% of the active image frame to allow selection of different subjects within the scene for sharp focus*

1.5 Data Processing for Dual Pixel CMOS Auto Focus

The data processing that is required is quite sophisticated. The two images separately created in the two photodiodes within each photosite are siphoned off the main delivery to the RGB video processing system and are processed to extract those photosites within the Dual Pixel CMOS AF sampling area. A variety of corrections and adjustments are applied to these sampled images A and B as this can aid the precision of the detection depending upon lens settings. Correlation processing then takes place that identifies the spatial separation of those processed images (the phase shift principle underlying this detection). The results are sent to a microcomputer that makes the calculations for the requisite correction signal. Experiences gained with the first Dual Pixel CMOS AF system contributed to an improved algorithm design that tests the reliability of the detection data and makes appropriate adjustments. The microcomputer also accepts the control signal from the joystick that moves the sampling Dual Pixel CMOS AF area and implements the associated variable spatial selection of the photosites.

1.6 Operational Control over Action of Dual Pixel CMOS Auto Focus

Early experiences with Dual Pixel CMOS AF in the C100 Mark II camera exposed the reality that there are a wide range of creative desires associated with acceptable actuation speed of the lens control loop. This speed depends upon the type of production and the personal aspirations of the shooter. It was explained that different projects sought different lens drive speeds. Many felt that this first generation auto focusing lens drive action was simply too fast. In addition, especially in television drama production and moviemaking – where traditionally the director and DoP often like to exercise a “feathering” control over the initial portion of a rack focus – the takeoff speed of the auto focus drive also requires some choices.

The new Dual Pixel CMOS AF system in the C300 Mark II embodies a menu that allows two degrees of freedom in “tuning” the response time. The focusing speed itself has a choice of ten speeds selected under SPEED in the menu – consisting of a Standard speed and then a choice of two faster speeds and a choice of seven slower speeds. This capability is only possible with those EF lenses that have slow-speed drive capabilities. Separately, what is termed the RESPONSE setting is a separate setting of the system that offers a choice in how quickly a focusing action is initiated – thus adding a creative dimension to a rack focus between two subjects within the scene.

1.7 Focus Guide System

For the cinematographer who prefers traditional creative manual focus operation the dual pixel system can alternatively be switched from the Auto Focus control loop to an open loop system that utilizes the Dual Pixel CMOS AF data processing to instead transfer precision signaling in the camera viewfinder.

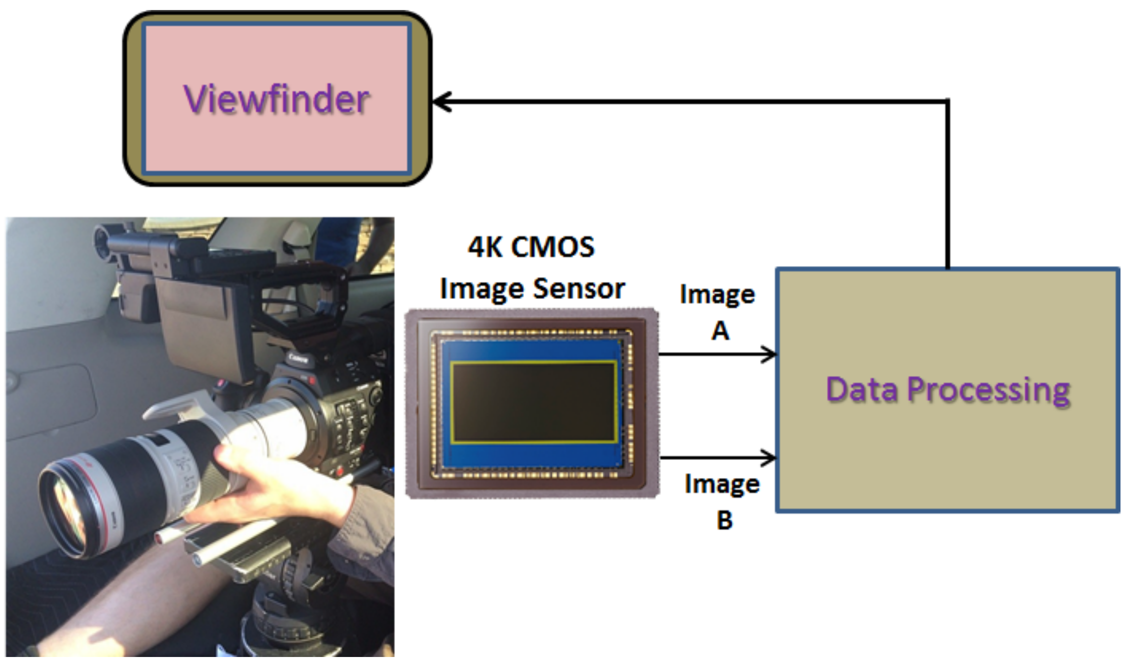

Figure 13 *Outlines the principle of the Focus Guide system – where manual actuation of the lens focus control is detected by the image sensor and the data processing signals the viewfinder*

The following outlines the nature of the signaling in the camera viewfinder. In this mode, three gray colored arrows appear around a box cursor that is centered on the subject chosen for precision focus. The arrow’s direction signals the direction to turn the focus ring to achieve the sharpest look. When precision focus is reached the viewfinder cursor and the indicating arrows snap to a green color.

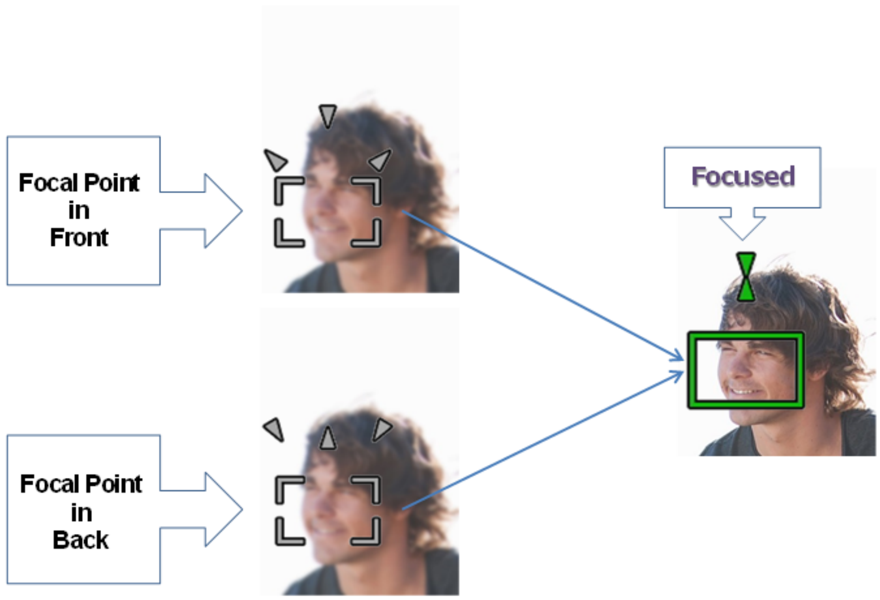

Figure 15 *Shows the guide cursor detail which uses three arrows to indicate to the camera operator the direction to rotate the focus control. At the point of precise focus on the chosen subject the cursor snaps to a green color.*

The implementation of the Focus Guide system is outlined in Figure 16.

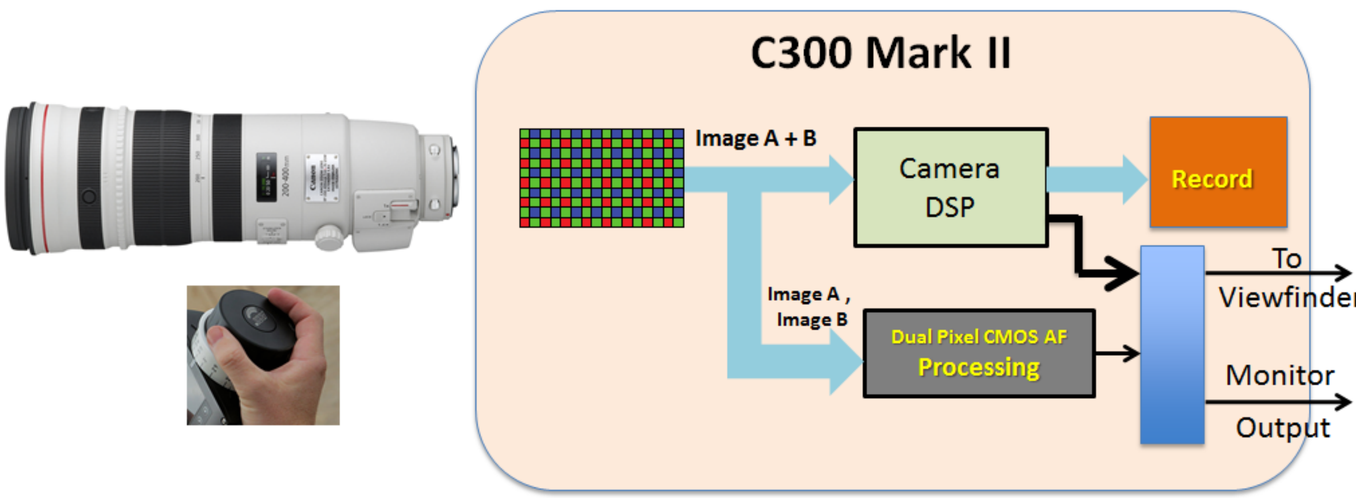

Figure 16 *Showing the Focus Guide mode of operation – that opens the control loop to the lens and instead the data processing sends signaling to the viewfinder and monitor output feed that guides the manual focus action*

2.0 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 17.

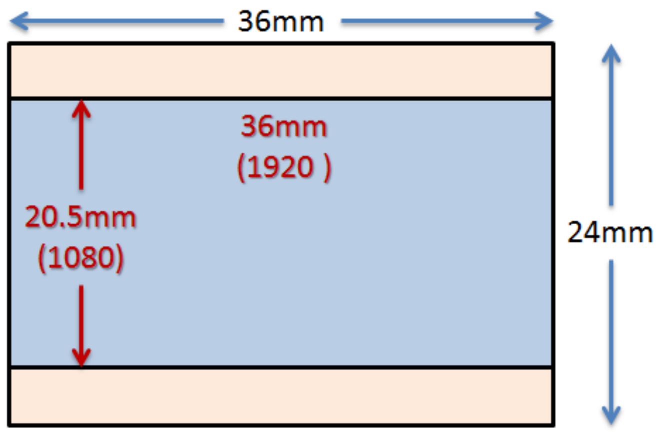

Figure 17 *Showing the dimensions of the active image area in the ME20F-SH within the full frame 35mm CMOS image sensor*

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 21 with two well-established image formats

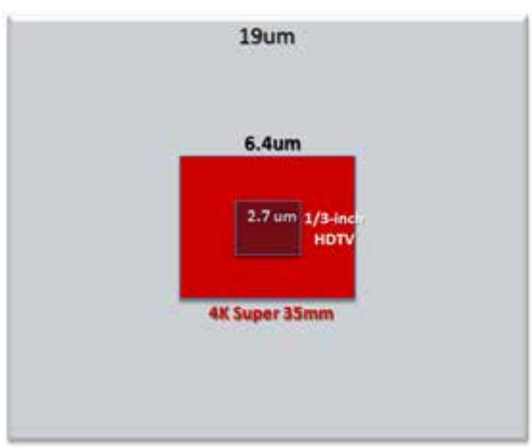

Figure 18 *Showing the relative size of the full frame pixel compared to two popular pixel sizes – the 6.4um of the 4K Super 35mm formats and the 2.7um of the HDTV 1/3-inch format*

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.

2.1 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 19 shows the spectral characteristics of the image sensor. The effective monochrome Quantum Efficiency of the ME20F-SH photosite output is 70% at 500 nm.

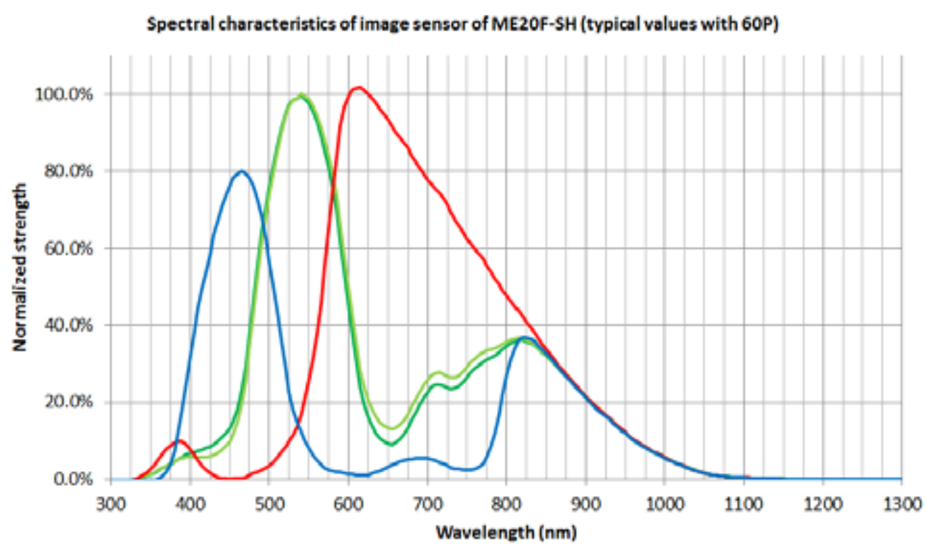

Figure 19 *Showing the spectral characteristics of the image sensor*

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.

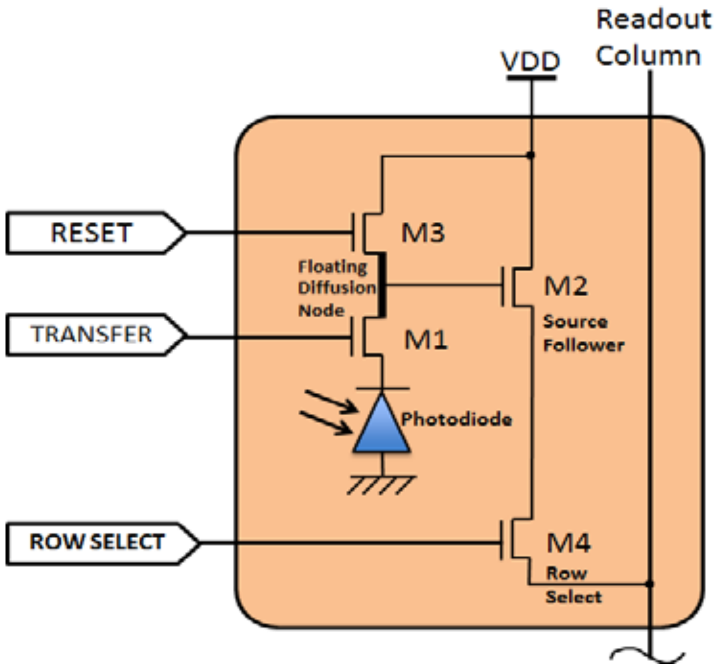

Figure 20 *Showing the circuit configuration of a single active pixel*

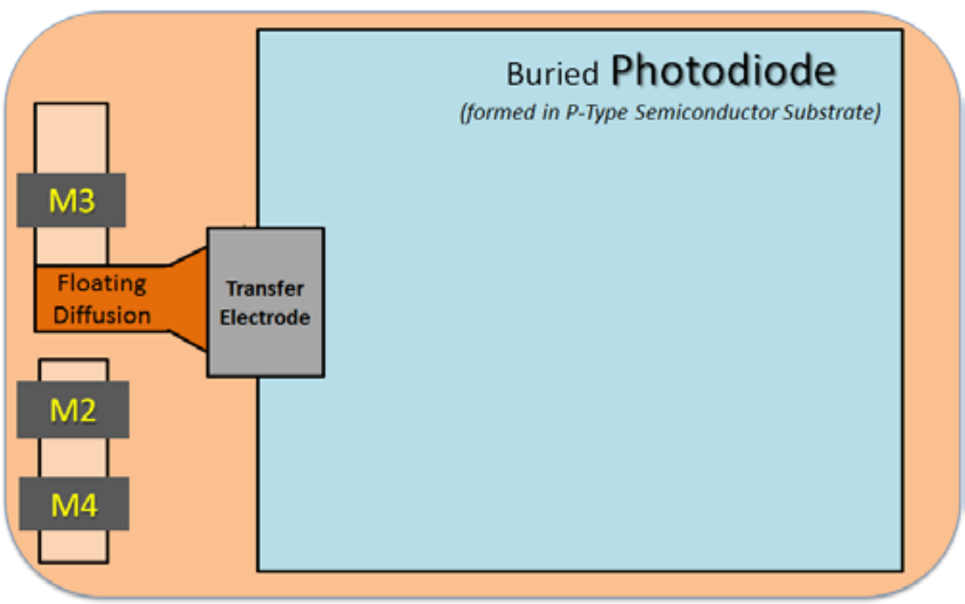

Figure 21 *A plan view of the structure of an individual pixel as seen from direction of light incidence on the Photosite – showing the exceptionally large area of the photodiode*

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.

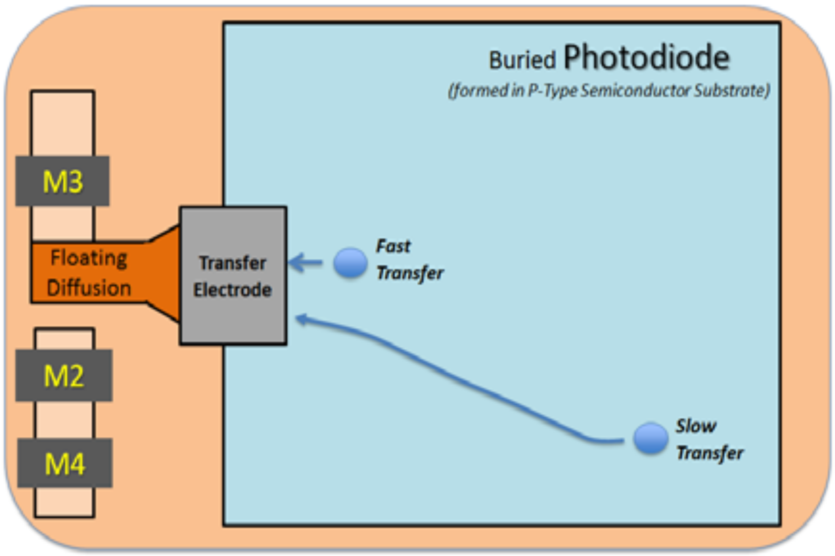

Figure 22 *Indicating the disparity in speed of transfer of electrons as a function of their distance from the Transfer Electrode*

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.

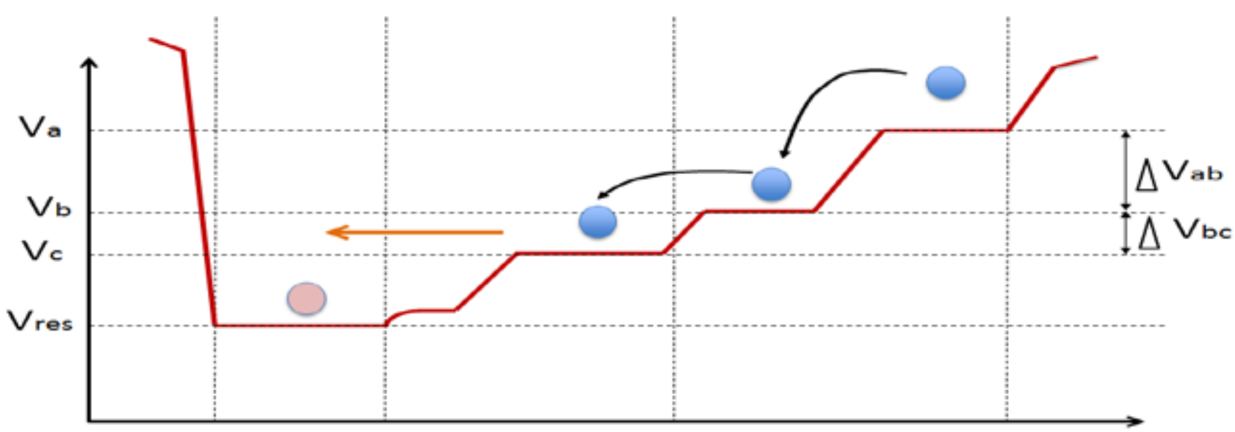

Figure 24 *Showing the three potential levels and the progressive movement of an electron that is distant from the Transfer Electrode by electric fields generated by the potential differences*

An electron released in the vicinity of the transfer electrode is influenced by a high electric field caused by the reset voltage V_{res} 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 V_a in the charge accumulation region and moves primarily by diffusion until it encounters an electric field due to Delta V_{ab} and then a second field due to Delta V_{bc}. 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 V_{ab} > Delta V_{bc}.

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 25.

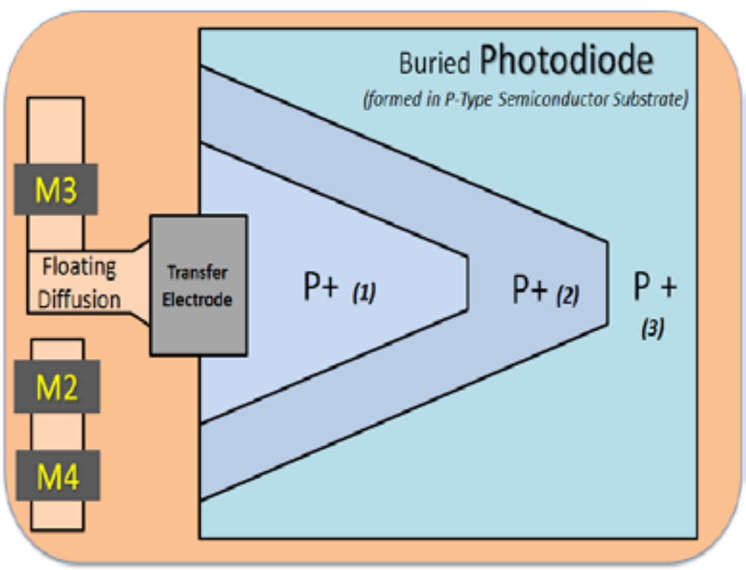

Figure 25 *Showing a plan view of the photosite and associated circuits and outline the trapezoidal shape of the two semiconductor regions closest to the transfer electrode*

2.2 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 26 *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 27.

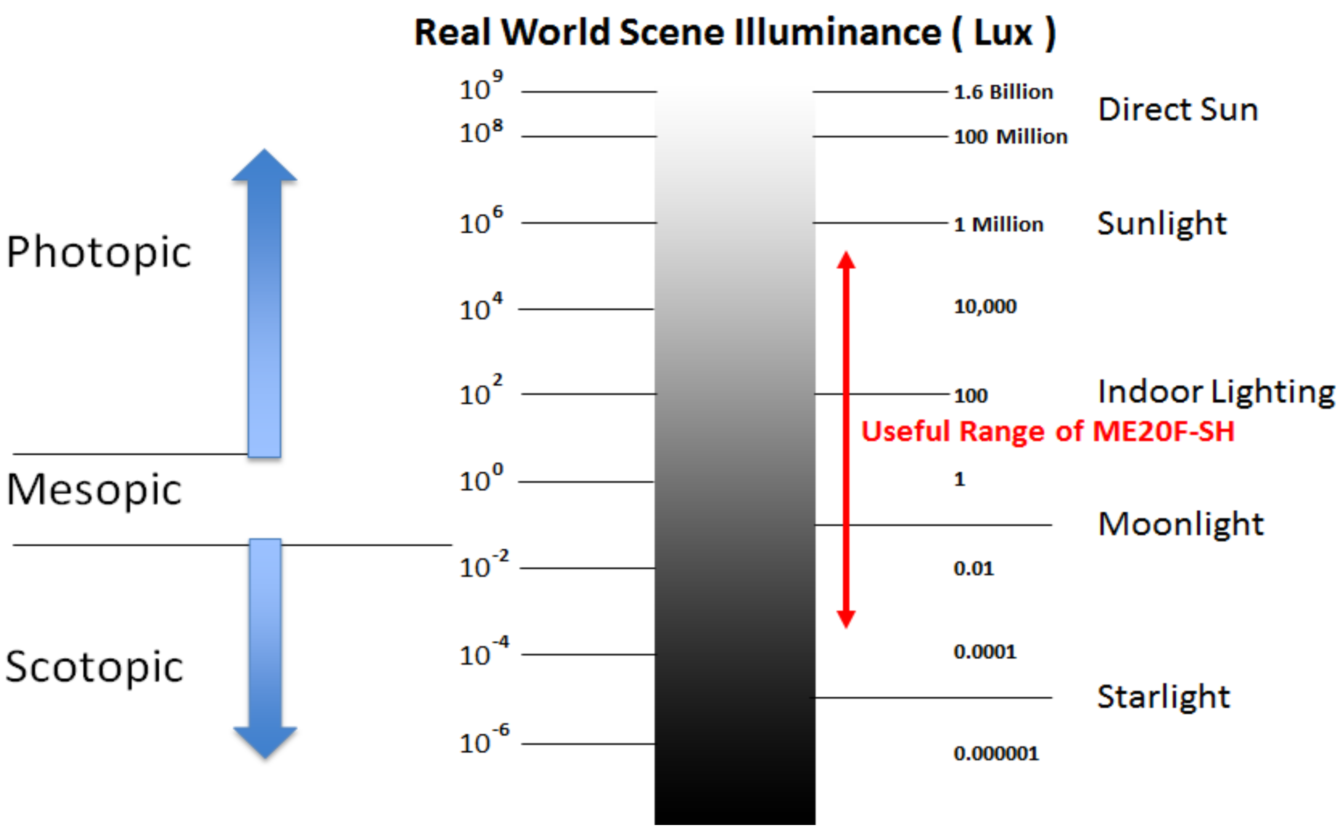

Figure 27 *Showing the unprecedented operational range of scene illumination levels of the ME20F-SH camera*

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 27. This illumination range is further outlined in Figure 28 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 28 *Benchmarking the operational sensitivity range of the ME20F-SH camera in the context of a range of real world scene illumination levels*

Summary

This paper outlined two quite separate designs for CMOS image sensors. One is specifically tailored to enhancing the overall performance of a Super 35mm digital motion imaging camera intended for production of theatrical motion pictures and high end television program production. The second is intended to significantly extend the capabilities of an HDTV camera by offering a breakthrough in operational sensitivity.

The first is a 4K Super 35mm sensor that can switch between 4K (4096 x 2160 with a 17:9 aspect ratio) and UHD (3840 x 2160 with a 16:9 aspect ratio) spatial sampling. Each of those approximately eight million photosites utilizes two separate photodiodes. By expediting efficiency in charge well readout this duality ensures an effective elevation of dynamic range. This image sensor delivers 15-stops of dynamic range supporting HDR functionality in the C300 Mark II camera. At the same time, this photodiode duality also offers an in-sensor phase detection which is subsequently processed to close a control loop around the camera lens thus providing a very precise auto focus system.

The second 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.

REFERENCES

R.B. Wheeler and N. Rodriguez “*The Effect of Single-Sensor CFA Captures on Images Intended for Motion Picture and TV Applications*” SMPTE J., 2007