Custom CMOS Image Sensor for Use in an Extreme Low Light Level Electron Bombarded CIS

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Abstract -- EOTech and Forza have developed a Backside Illuminated CIS (BSI-CIS) optimized for use in low light level imaging cameras. The MV3.7 CIS has a 9.1 µm pixel, 1920 x 1920 pixel format, 160 Hz frame rate, and 16 bit dynamic range based on a LOFIC pixel architecture. This BSI-CIS has been incorporated as the electron bombarded anode in the ISIE19 Electron Bombarded Active Pixel Sensor (EBAPS®) for use in low light level cameras. The ISIE19 EBAPS is the most recent member of the EOTech EBAPS product family, beginning in 2004. CIS architecture for the low noise (5e-rms), high frame rate, high dynamic range CIS will be presented for the MV3.7. Results are presented for a GaAs photocathode ISIE19 EBAPS. Data presented includes: electron bombarded gain; single photon detection and low light level high dynamic range imagery. The displayed imagery is optimized with a local tone mapping algorithm to map the high dynamic range, low SNR, imagery onto a lower dynamic range display.

1. Introduction

Extreme low light level imaging has been dominated by image intensifier and EMCCD based cameras. Recent advances in low noise CIS and SPAD imaging arrays are beginning to compete with these older technologies. An alternate technology for low light level imaging is based on use of the low noise Electron Bombarded Semiconductor (EBS) gain process. EOTech (formerly Intevac) has developed the EBAPS low light level image sensor technology for extreme low light level cameras.

EBAPS based cameras target applications where camera size, power and low light level performance are critical. Key requirements include high frame rate operation and high dynamic range with single photon sensitivity with no cooling. These requirements all drive the need for improved low light level imagers.

2. EBAPS Technology

Low light level EBAPS image sensors are based on the use of a GaAs photocathode, derived from image intensifier technology, in proximity focus with a high resolution, BSI-CIS anode (Figure 1).

The high voltage (1 – 2 kV) applied between the photocathode and the anode accelerates the emitted photoelectrons to the BSI-CIS anode. Low-noise gain is achieved in the CIS anode by conversion of the high energy photoelectron into electron-hole pairs via the EBS gain process [1] [2] [3]. For silicon an electron-hole pair is generated per 3.64 eV of incident energy. The EBS gain process is deterministic and hence low noise, with a resulting excess noise factor (Kf) of 1.03 [4]. In an EBAPS where the typical operating voltage results in some loss of photoelectrons due to elastic and inelastic backscatter events and incomplete collection of the generated electron cloud the Kf is on the order of 1.2 at 1750V, with temporal noise << 1 photoelectron.

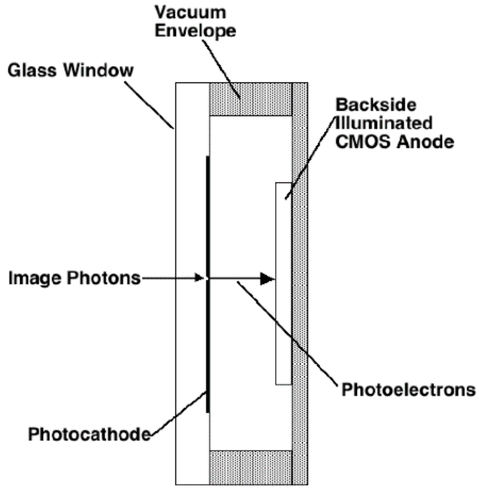

Figure 1. EBAPS Cross Section

The multiplied electrons are collected in the pixel photodiode and are subsequently read out. The EBS gain is high enough to mitigate the pixel readout and dark current noise and other temporal and fixed pattern noise sources, resulting in superior performance at starlight illumination and lower light levels relative to a low noise video frame rate CIS or EMCCD camera. The low noise EBS gain process thus enables a higher signal-to-noise ratio (SNR) at the lowest light levels and single photoelectron detection. The EBS gain process is also a linear gain mechanism as compared to a SPAD and allows signal intensity to be measured.

3. MV3.7 BSI-CIS

Performance of an EBAPS sensor is determined to a large extent by the CIS architecture and design. First, it is essential that the CIS pixel have close to 100% fill factor. Any reduction in fill factor will result in lost photoelectrons. This is equivalent to a reduction in photocathode quantum efficiency. At the lowest light levels camera performance is dictated by photon statistics. It is essential for the imager to detect the maximum number of photons for good low light level resolution and performance.

Close to 100% fill factor can be achieved in a properly designed BSI-CIS. Frontside illuminated CIS are not used in an electron bombarded mode, both due to lower fill factor relative to a BSI-CIS and because the metal / dielectric stack will block the photoelectrons from reaching the silicon at moderate acceleration voltages (1 - 2 kV). The BSI-CIS silicon surface is passivated to reduce carrier recombination at the surface. A properly designed pixel will allow the generated charge to be collected by the pixel photodiode regardless of photoelectron impact position in the pixel.

Second, the CIS architecture must maximize integration of the image photons with close to 100% temporal duty cycle. This requirement when combined with high fill factor enables the collected signal to be maximized for good low light level performance.

Another critical requirement is high dynamic range to accommodate the intra-scene dynamic range of a nighttime scene with lighting (on the order of 10^5 or 10^6). This results in the capability to better observe scene detail in dark areas of scenes which contain light sources.

Final requirements for a high performance low light level camera include high frame rates (>120 Hz) for use in Augmented Reality (AR) systems, low dark current, megapixel format and large pixel size (~10µm) for increased low light level performance.

The MV3.7 was developed for use in an EBAPS to meet these requirements. The maximum frame rate was increased from 60 Hz for previous generation ISIE11 EBAPS to 160 Hz for the MV3.7 (ISIE19) while CIS noise floor was reduced to improve single photoelectron detection efficiency. The linear dynamic range was increased from 10 bits for the ISIE11 to 16 bits for the MV3.7. The imager format and size was increased to 3.7 megapixel from 2 megapixel for ISIE11.

The MV3.7 is fabricated in a standard 110nm design rule BSI-CIS process. The MV3.7 floorplan is shown in Figure 2. The active image array size consists of a 1920 x 1920 array of 9.117 µm square pixels with additional rows and columns included at the periphery of the array. 66 shielded dark columns are included to enable off-chip row temporal noise correction in the camera Image Signal Processor (ISP). An additional boundary of 15 rows and columns on each side of the active imaging array are included to ensure uniform response in the active image array.

A Lateral Overflow Integrated Capacitor (LOFIC) pixel architecture was chosen for the MV3.7 CIS. The LOFIC architecture enables a high, linear, dynamic range for the CIS. The LOFIC HDR approach retains all charge generated by the photodiode in the overflow capacitor thereby insuring accurate capture of fast transient flashes.

The LOFIC pixel can be used in a standard 4T configuration to enable a low noise Correlated Double Sampling (CDS) readout of the floating diffusion. The pixel incorporates a dual-Transfer Gate (TX) structure to enable charge flow into the overflow (OF) capacitor once the photodiode is saturated. The TXOF voltage is set so charge preferentially flows onto the capacitor and not through the TX onto the floating diffusion. In this mode of operation no charge is lost. At readout the LOFIC pixel is sequentially read, first a "low light level" read is performed to sample the floating diffusion followed by a "high light level read" of the capacitor. Both reads are independently digitized via 11 bit ADCs. The ADCs are column parallel dual 11 bit single slope ADCs for low light and high light data reads from the LOFIC pixel.

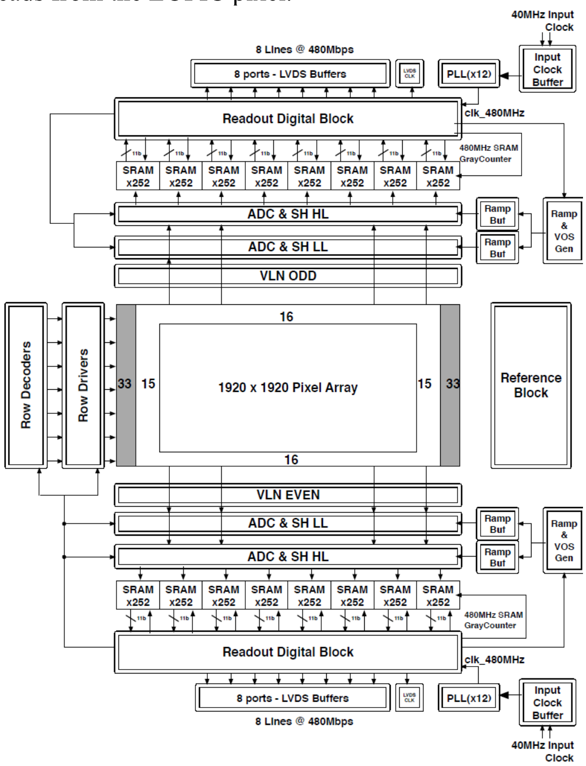

Figure 2: MV3.7 CIS Floor Plan

Both readouts are stored in on-chip SRAM. An on-chip register controlled comparator determines which readout contains useful data. The selected data is read out as a 12 bit word, 11 data bits and 1 flag bit. The flag bit indicates if the data is a low light level read or a high light level read from the capacitor. The camera ISP subsequently converts the data to 16 bits with a linear dynamic range of ~96 dB.

MV3.7 CIS performance values are given in Table 1. The dark current of the pixel at 65°C is higher than desired, but the noise on the dark current is significantly lower than the expected single photoelectron generated signal in the MV3.7 due to the EBS gain. This enables the ISIE19 to remain photocathode dark current limited up to the maximum camera operating temperature.

Parameter	Performance
Pixel Size	9.117 microns
Image Format - CIS	1950 x 1950 pixels
Image Format - EBAPS	1920 x 1920 pixels
Maximum frame rate	160 Hz (Full frame)
Read Noise	5.1 e-
Full Well Capacity (Overflow capacitor)	348,000 e-
Dynamic range	>68,000 or 96dB
Image lag	<1.5 e- average after a saturated frame
Conversion gain – low light level read	64.6 μV/e-
Conversion gain – high light level read	3.0 μV/e-
Pixel Dark Current (65°C)	5286 e-/pix-s

Table 1: MV3.7 CIS performance

4. ISIE19 EBAPS

The ISIE19 uses a GaAs photocathode to achieve low dark current at elevated temperatures [5]. A typical spectral response curve is shown in Figure 3. Emitted dark current is ≤50 fA/cm^2 at 40°C or 0.3 e-/pix-s.

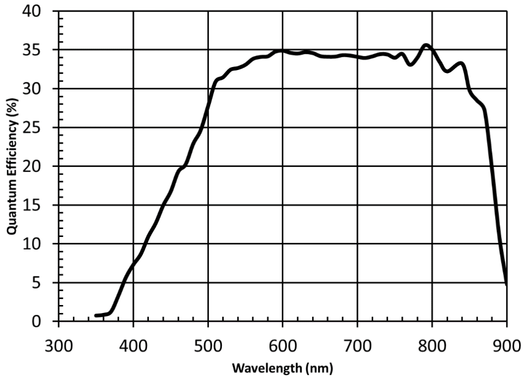

Figure 3: GaAs photocathode Spectral Response

The ISIE19 is operated with 1,750V applied between the photocathode and the CIS anode. The low noise EBS gain process enables a key characteristic of EBAPS: the ability to detect single photoelectrons independent of CIS frame rate. This capability is a function of the ratio of low noise electron bombarded gain to CIS noise floor. Electron bombarded gain increases with voltage applied between the photocathode and the CIS anode.

Figure 4 is a plot of EBS gain versus applied voltage between the photocathode and the electron bombarded MV3.7 anode derived from measurements on several EBAPS. For the ISIE19 the EBS gain is on the order of 300 at the 1,750V operating voltage with the MV3.7 read noise floor on the order 5.1e-. The maximum theoretical EBS gain at 1750 eV incident photoelectron energy is 481 assuming all of the incident energy is dissipated in the silicon with all of the generated electrons collected by the CIS photodiode.

Figure 5 is a series of pulse height distribution curves versus applied voltage between the photocathode and the MV3.7 anode at 120Hz frame rate. As the applied bias voltage is increased, photoelectrons strike the anode with higher energy increasing the number of generated electron-hole pairs (EHP) and the depth into the silicon at which the median EHP is generated. The number of detected electrons (x-axis of figure) was calculated by multiplying the DN value with the responsivity of the analog conversion voltage measured for the MV3.7. The 0 V curve represents the black level of the camera.

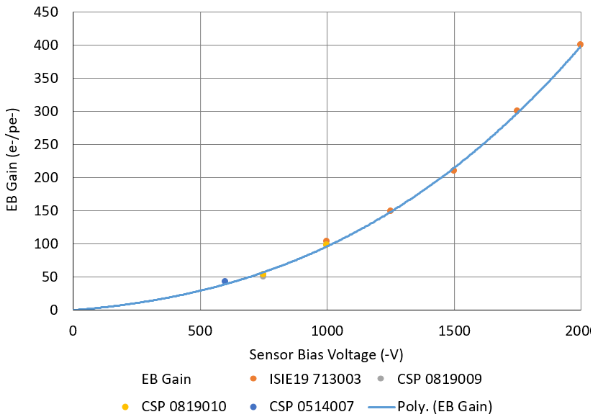

Figure 4: Electron bombarded gain versus voltage

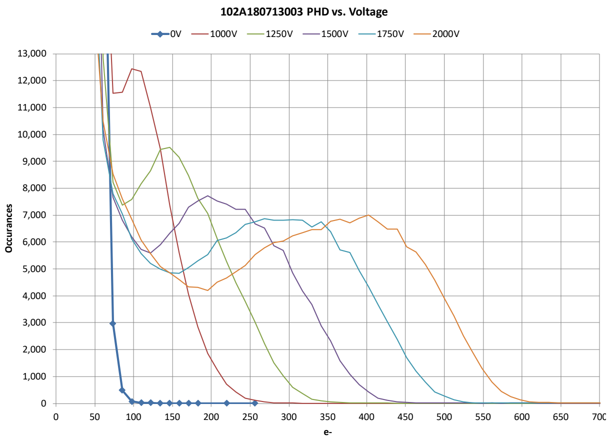

Figure 5: ISIE19 histograms as a function of voltage

At low light levels the LOFIC pixel is in the high sensitivity range. As light level increases the pixel crosses into the high light level range where the MV3.7 read noise is significantly higher, on the order of 100 e-. Cross-over on the LOFIC pixel is determined on a per pixel basis as discussed in Section 3. The cross-over is set at a DN value of ~784DN in the LL channel and ~36DN on the HL channel. At an EBS gain of 300, this equates to ~25 detected photoelectrons with a signal shot noise of ~5 photoelectrons. The signal shot noise after EB gain is well above the input referred read noise of the HL channel. At this cross-over, the HL channel is photoelectron shot noise limited with good SNR.

Figure 6 compares high dynamic range imagery captured with the ISIE19 and the previous generation ISIE11. Both cameras used the same objective lens.

The lens is optimized for low light imaging applications over the GaAs photocathode spectral response range with a 38° horizontal field-of-view for both cameras. The dark corners in the Figure 6 imagery is a result of the lens relative illumination falling off at the ISIE19 and ISIE11 image sensor corners. The ISIE19 was operated at 120 Hz frame rate versus 60 Hz frame rate for the ISIE11 camera. For presentation purposes 12 frames were averaged for the ISIE19 camera and 6 frames for the ISIE11 camera, both representing 1/10th second of imagery. This has been found to result in still images very similar to observation of live video. The scene was challenging as it was to the west an hour after sunset. The high dynamic range of the ISIE19 sensor is evident in the imagery. The ISIE19 ISP contains a Local Tone Mapping algorithm optimized for low SNR low light level imagery to map the camera 16 bit output to 8 bits for display.

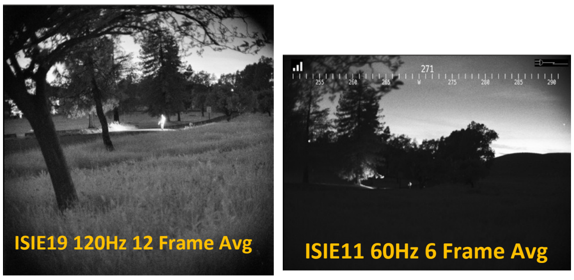

Figure 6: HDR scene comparing ISIE19 to ISIE11

5. Chip Scale Packaged (CSP) MV3.7 EBAPS

The primary motivation for the development of the CSP EBAPS is to miniaturize the sensor for those applications that cannot accommodate the physical size of the ISIE19. The CSP eliminates the ceramic package used for ISIE19 and forms the photocathode vacuum seal directly with the MV3.7 chip with the bond pads exterior to the vacuum envelope. The combination of the CSP and electronics will support a 25mm square camera module.

The focus on a small camera size drives multiple trade-space choices. A camera system includes: EBAPS; camera electronics; and a high voltage power supply (HVPS). The size and complexity of the HVPS is driven by the voltage required to bias the EBAPS photocathode. HVPS size can be reduced by minimization of the EBAPS high voltage. Optimal EBAPS performance is achieved when the electron bombarded gain of the photoelectron upon impact with the CIS greatly exceeds the CIS read noise. With a read noise of ~5.1 e- the MV3.7 was a suitable choice for prototype CSP development. At the targeted operation voltage of 750 V the EBS-to-read noise ratio is >10. Figure 7 compares the size of the ISIE19 and CSP sensors.

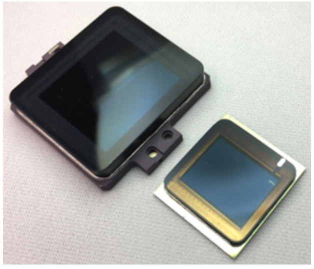

Figure 7: ISIE19 EBAPS comparison to CSP

6. Conclusion

Low light level cameras are transitioning from image intensifier or EMCCD based cameras to cameras based on low noise CIS, SPAD arrays or EBAPS. This work has developed a 3.7 megapixel, 160 Hz frame rate, high dynamic range LOFIC pixel BSI-CIS optimized for integration with a GaAs photocathode. Single photon detection capability has been demonstrated at 120 Hz frame rate to support AR system needs. Future work includes further development of the CSP and development and testing of new cameras based on the ISIE19 and CSP EBAPS.

References

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