BACK ILLUMINATED SYSTEM-ON-CHIP FOR NIGHT VISION

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ABSTRACT

Back Illumination (BI) technology is widely used in consumer imaging to compensate the reduction in sensitivity consequence of continued pixel shrink. Some applications such as night vision need implementation of larger pixels but the BI is justified by other criteria more oriented towards improving the image quality. For example the use of wide optical lenses for very low light conditions creates grey level non-uniformity called vignetting which is difficult to avoid with Front Illuminated (FI) technology. Taking an existing SXGA 1/1.8" CMOS Image Sensor (CIS), we have successfully adapted it to BI technology targetting the visible and Near Infrared (NIR) range. Image quality improvement was quantified using the Signal-to-Noise Ratio (SNR) metric involving three important parameters which are the Modulation Transfer Function (MTF), the Quantum Efficiency (QE) and the temporal noise.

1. INTRODUCTION

The market for night vision represents a wide range of applications whose purpose is to assist operators in visual analysis of a scene whilst providing requirement of mobility and low power consumption. These systems are expected to give essential information with unambiguous interpretation. Image quality and resolution are important criteria. In very low light conditions, it is essential that every available photon is converted into useful signal and that every detail of the image is properly reproduced. In technical terms the best performance metrics are QE, MTF, and SNR.

The standard image sensor CMOS technology is for Front Illumination where the incident photons pass through the layers of the CIS before being converted into electrons in the silicon. Pixel pitch reduction inherent to consumer demand of increasing resolution without changing sensor size has made the Back Illumination technology emerge as an industrial approach. As well as gaining in pixel fill factor and QE the aspect ratio of the pixel becomes taller than it is wide increasing numerical aperture. BI has additional advantages than those most often mentioned, for example improving the angular acceptance of pixels and therefore enabling the use of very wide lenses down to f/1, which offer improvement in the sensitivity of the overall system. As the electrons are photo-generated within the photodiode (PD) depletion region, the MTF is improved (see Figure 1). The deposition of an Anti-Reflective Coating (ARC) gives a degree of freedom to optimize the QE in the sensitivity range required by the application. For example, sensors for night vision will benefit from QE improvement in the NIR whereas scientific or machine vision markets will ask for UV response.

The improved QE and spatial resolution will only be meaningful if the signal to noise ratio is improved. A part of the noise is concentrated in the pixel or the first level amplification chain which is of prime importance. Improvement of technology has given very interesting results on BI devices, about 2.5 electrons RMS noise [1] allowing image capture in extreme low light conditions where the SNR is essentially determined by shot noise.
In this work we present a solid state solution for a digitized night vision system suitable for portable applications. New technologies have been tested and good performance is actually demonstrated.

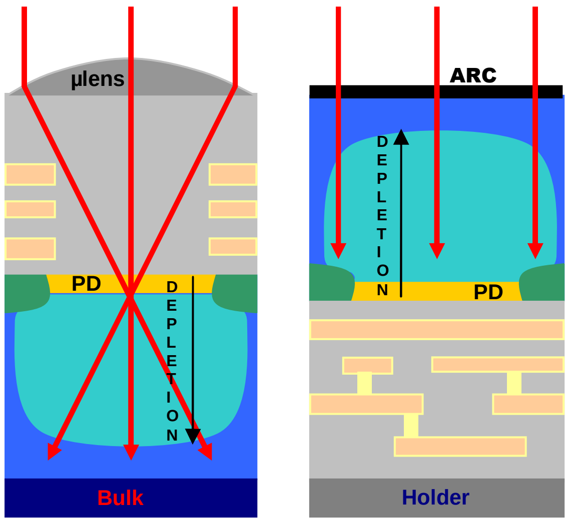

Figure 1 – Back illumination principle

2. IMAGE QUALITY METRIC

It is generally accepted in the imaging community that the metric used to evaluate the quality of an image is the Signal-to-Noise Ratio. The Standard ISO 12232 defines that acceptable and excellent images are when the SNR value are respectively 10 (20 dB) and 40 (32 dB). The elementary SNR is a good image quality metric but it does not account for the resolution of elementary patterns composing the image.

The metric Minimum Resolvable Contrast (MRC) is used to evaluate the resolving power of an image sensor. It is based on a subjective measurement of a snapshot image comprising of series of bars of various spatial frequencies and contrasts (1951 USAF Contrast Resolution Chart). MRC is used as a prediction for target acquisition performance based on the Johnson Criteria and reflects the noise and MTF performance of a system combined with the human eye characteristic. MRC can be modeled [2] but in practice it is a live measurement.

To evaluate the benefit of Back Illumination compared to Front Illumination technology, we used a metric based on Signal-to-Noise Ratio versus spatial frequency SNR($_{\nu}$). A periodic signal undergoes several transformations through an imager. First there is the Quantum Efficiency defined as the ratio between the quantity of incoming photons and the number of collected electrons. Secondly, an attenuation of the contrast occurs with the spatial frequency of the input signal. The output signal is divided by the temporal noise and gives SNR($_{\nu}$) as illustrated Figure 2.

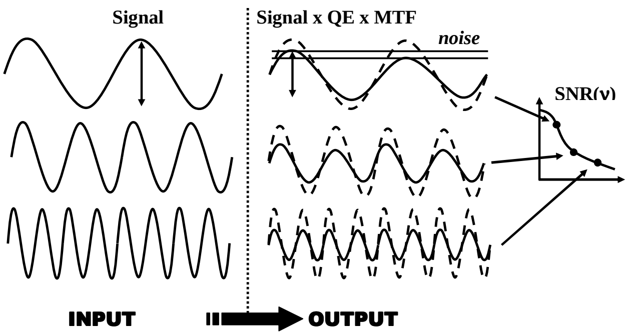

Figure 2 – SNR metric approach

SNR($_{\nu}$) is calculated versus wavelength and spatial frequency ν as :

$$SNR_{(\nu)} = \frac{\phi.QE_{(\lambda)}.MTF_{(\lambda,\nu)}}{\sqrt{\phi.QE_{(\lambda)} + \sigma_n{}^2}} \quad \textbf{(1)}$$

where Φ is the photonic flow (photon.pixel^{-1}), MTF($_{\lambda,\omega}$) is the Modulation Transfer function at wavelength λ (nm) at spatial frequency ω (mm^{-1}), QE($_{\lambda}$) is the Quantum Efficiency at the wavelength λ (nm) and σn is the RMS noise floor.

3. SENSOR DESCRIPTION

The CMOS Image Sensor has a 1/1.8" format built around a 1280x1024 pixel array. The pixel size is 5.3 µm, composed of one photodiode and five MOSFET providing both Electronic Rolling Shutter (ERS) and Global Shutter (GS) capability. Based on the System-On-Chip approach, it consists of four groups of functions including the pixel array, driving interface, timing generator and digital data post treatment. Peripheral circuits embed PLL blocks able to provide up to 480 MHz frequency from a single low frequency clock input. The frame rate is therefore more than 60 Hz. Timings are provided inside the chip to operate the pixels, the 10 bits column ADC and the parallel output data synchronously. The power consumption is less than 200 mW at 60 Hz and can be set down to 200 µW in standby mode.

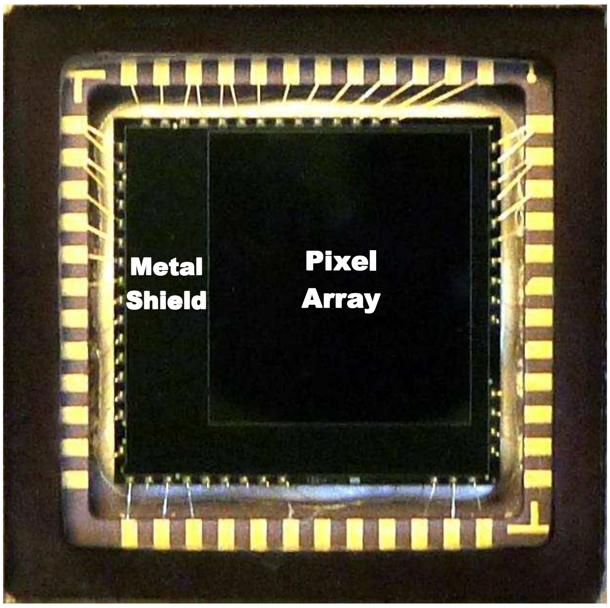

Figure 3 – Micrograph of BI chip

The Quantum Efficiency of the photodiode is extended from the visible to Near Infrared (NIR) using a deep depletion approach that combines a high sensitivity and an improved Modulation Transfer Function like for the front side version whose results have been published previously [3]. The chip features dark references to perform an on-chip and off-chip dark level clamp. The metal used for shielding is coated with ARC to avoid spurious reflection of light.

4. MEASUREMENT RESULTS

4.1. Angular response

A conventional front illuminated sensor can produce non uniformity of response on the image called vignetting. This effect described in the early 2000's [4] is connected to the angle at which light rays enter the pixel and the fact the surface of the pixel is not 100% sensitive. The incident angle is determined by the Chief Ray Angle (CRA) specific to the optics used by the application and the optical aperture. The vignetting is worse in the corner of the image array, as the angle of incidence is larger off-axis. It is possible to partly offset this effect by shifting the micro-lenses relatively to the axis of the photodiode and the distance from the array center but only when the characteristics of the optics are fixed and for F-numbers relatively high.

A standard commercial lens may have CRA of 10 degrees or more added to the half cone angle of the marginal ray at the iris exit which is 30° at f /1 aperture. On front illuminated sensors, photons will arrive with an angle up to 40° and all will not be captured by the photodiode despite the microlens shifting. Because back illuminated pixels are 100% sensitive this effect is minimized and makes possible the use of very wide optical lenses down to f/1 with almost no sensitivity loss. The difference of angular sensitivity is shown on the polar plot represented in Figure 4. The plot shows the light incident angle as well as the measured ratio of absorbed energy for FI and BI sensors.

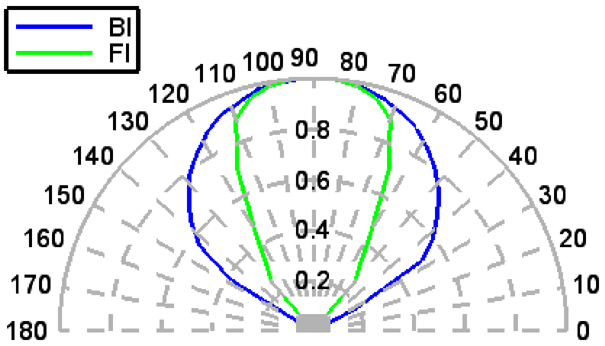

Figure 4 – Normalized Angular response

4.2. Noise floor

Noise is defined as every signal interfering with useful signal (coming from light reflected by the scene which is used to build the image). It occurs at the pixel level and all along the signal processing chain, including image display. Individual noise sources are quantified by operating specific timing diagrams. The overall RMS noise is measured at 3.2 electrons where the noise coming from the pixel itself is only 2.4 electrons at 25℃.

4.3. Quantum Efficiency

Photons interacting with a silicon semiconductor produce electron-hole pairs, known as the photoelectric effect. This process is governed by several electro-optical phenomena characterized by a conversion yield called Quantum Efficiency. The loss of photons occurs first by reflection on the surface of the sensor and secondary across the layers overlying the photodiode. When the thickness of silicon is insufficient for the rays to be fully absorbed, part of the incoming flow is lost by transmission. This is generally the case for longer wavelengths in near infrared range. The part of the absorbed radiation will produce electric charge, a portion of which will disappear by a mechanism of recombination. The remaining portion is collected and is referred to as Internal Quantum Efficiency or IQE. The collected electrons represent the useful signal which divided by the number of incoming photon yields the overall Quantum Efficiency of the sensor.

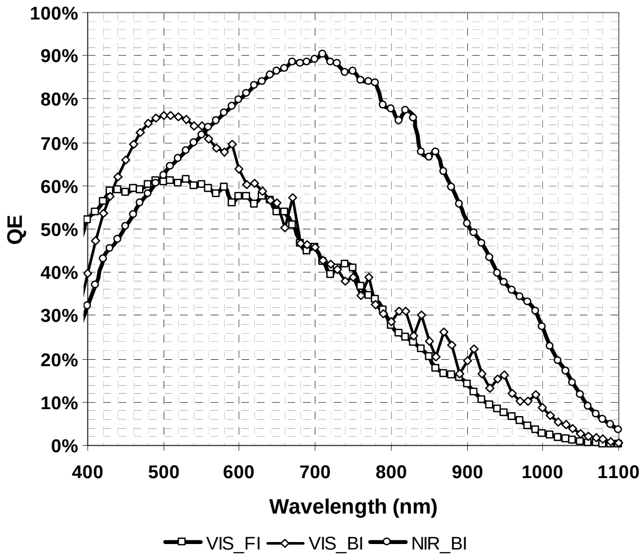

Figure 5 – BI and FI QE comparison

BI devices have almost no loss through the surface layers because light rays enter the silicon directly and the anti-reflective coating helps minimize surface reflection. In the near infrared range, Internal Quantum Efficiency is better on BI devices as the carriers are photo generated and directly collected within the photodiode depletion (see *Figure 1*). In the blue (450 nm) the tendency is the opposite, as photons are absorbed near the surface within the field free region where carriers are not directly caught and are therefore susceptible to recombine.

Figure 5 shows the Quantum Efficiency of different devices. First is the FI commercial device (VIS_FI), second is a BI version of the first (VIS_BI) and third is the near infrared optimized image sensor (NIR_BI). The VIS_BI curve is characterized by an improvement of visible QE. This performance is mainly a consequence of a better efficiency of light transmission and reduced reflection thanks to the top ARC. The NIR_BI curve presents a very high QE peak at 700 nm. This is a result of the NIR targeted ARC and deep depletion technology. The compromise is a relatively lower QE in the blue spectrum. These results demonstrate the technical potential of BI technology with substantial gains on the detection efficiency in very low light conditions.

4.4. Modulation Transfer Function

Back illuminated photodiode arrays turn out to have an excellent quantum efficiency in comparison with front-illuminated but the benefit on MTF is open to discussion. For example, the total crosstalk corresponding to charge diffusion from pixel to pixel is subject to variation with light wavelength. Simulation models show that the crosstalk is a parameter contributing to the MTF [5] which depends on whether the light comes from the front or the back of the sensor.

Figure 7 show the MTF of the same devices used for the measurement of QE. The MTF of the VIS_BI and VIS_FI are better than the NIR_BI. This is because the extension of the depleted zone of the photodiode is proportionally higher in VIS_BI and VIS_FI although in absolute terms it is less than in the NIR_BI circuit.

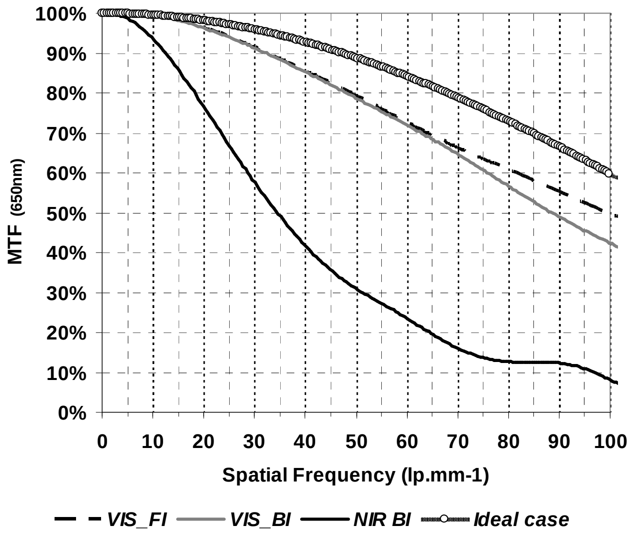

Figure 6 – Modulation Transfer function (650 nm)

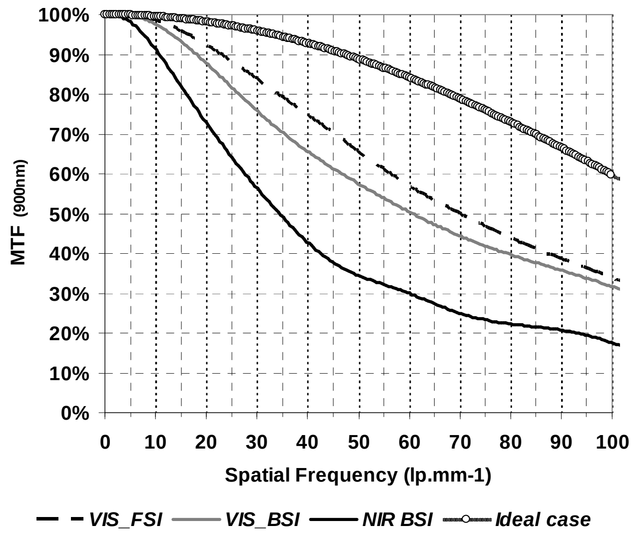

Figure 7 – Modulation Transfer function (900 nm)

4.5. $SNR_{(v)}$ comparison

Referring to Equ.1, several contributors combine to make Signal-to-noise Ratio $SNR_{(v)}$. The results are given for a signal Φ=100 photons per pixel at 650 nm and 900 nm, corresponding to Figure 8 and Figure 9.

At 650 nm NIR_BI has the best SNR at low spatial frequency and VIS_BI and VIS_FI become better for higher frequencies.

At 900 nm NIR_BI outperforms all other devices. This result is obtained mainly by the excellent quantum efficiency in the near infrared

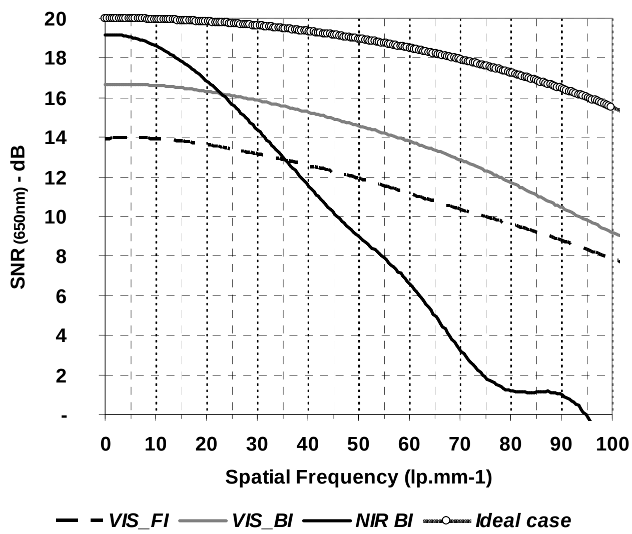

Figure 8 – $SNR_{(650nm)}$

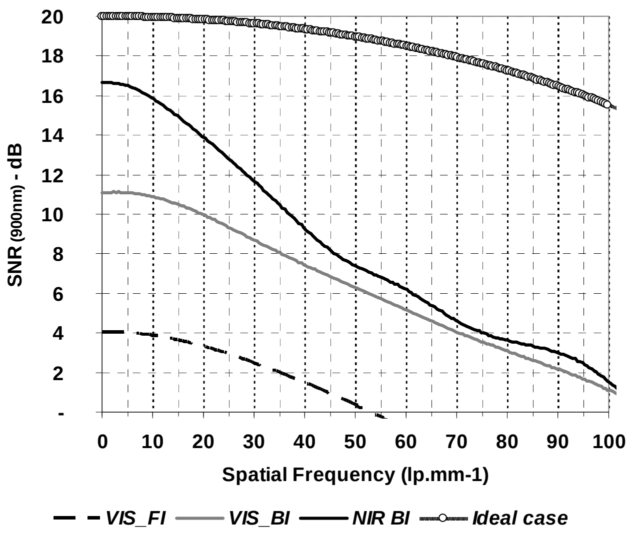

Figure 9 – $SNR_{(900nm)}$

5. CONCLUSION

In this paper, we compare the performance of Front and Back Illuminated sensors. The result is a significant increase of Signal-To-Noise ratio of BI devices capable of producing better image rendering including small details. The experimented technology that combines deep depletion photodiodes and Back Illumination provides a clear differentiation in the infrared domain and is particularly adapted for night vision.

Work is underway to improve the noise level and spectral coverage of the anti-reflective coating, for even better performance under low light conditions and applicable on future BI image sensor.

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