A QuantumFilm based QuadVGA 1.5µm pixel image sensor with over 40% QE at 940 nm for actively illuminated applications.

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***Abstract* - In this work we present an image sensor with a 1280x960 array of 1.5µm GS pixels based on InVisage's latest QuantumFilm. This image sensor, implemented in a standard 130nm technology, achieves over 40% QE at 940nm and was specifically designed for outdoor near infrared applications with active illumination such as face authentication and depth mapping. High QE is fundamental in these applications as the total system SNR is normally dominated by ambient photon shot noise. Moreover, a novel way to cancel background ambient light, which leverages the QuantumFilm photoelectric characteristics, is presented.**

I. INTRODUCTION

In quantum dot film-based sensors, photoconversion of incident photons to electric charge happens in a thin film of quantum dots material, spin coated on top of conventional CMOS wafers, in which photons are directly converted to electron-hole pairs. When a sufficient electric field is applied to the material, photo-generated electrons and holes drift in opposite directions and are collected at the two opposite film electrodes. Charge can then be integrated in a capacitive storage node inside each pixel silicon section and read out using conventional CMOS imager architectures. In our current implementation, the film top electrode is common to all pixels and biased to a voltage VFilm by an on-chip programmable voltage source, while each one of the bottom electrodes is in electrically connected to a separate n+ diffusion, the pitch of which defines the pixel pitch.

II. QUANTUM FILM SENSOR

In this work, the sensor is designed to form a 1280 x 960 active array of 1.5µm pixels, which can be binned 4:1 to VGA either digitally or in the film itself.

Since the active photocharge generation happens in the film rather than in the silicon, there is enough area in the pixel silicon substrate to include 3 unshared transistors per pixel, even when using a 130nm technology node. The three transistors in the pixel are classically used as source follower, select and reset gates. Quantum Film global shutter (GS) functionality is obtained by pulsing VFilm between regions of high QE and low QE [Figure 1].

Actively illuminated applications, like depth mapping and face authentication, share similar requirements: high sensitivity in the infrared band for high SNR, high resolution in smaller image formats to allow recognition of a larger number of structured light patterns or facial features, and low crosstalk for high MTF and lower blur. The ability to run in GS mode is also an important requirement, as higher ambient rejection, lower system power consumption and increased eye safety require rapid global exposure synchronized with shortest active light pulses. For the QuantumFilm sensor here presented we measure a Quantum Efficiency (QE) over 40% at 940nm [Figure 4], and linear signal response versus exposure down to 10µs in GS mode.

When acquiring images illuminated by an active NIR source, ambient background light is usually considered noise and requires suppression. Rejection is obtained by subtracting two contiguous frames, the first with the light active and the second with the light inactive. In this type of system the signal component S (electrons) of SNR is defined as the signal after frame subtraction:

$$S = qe * (AL_{ph} + Amb_{ph}) - qe * Amb_{ph} = qe * AL_{ph}$$

where qe is the quantum efficiency, AL_{ph} is the number of photons due to active illumination and Amb_{ph} is the one due to ambient light. Likewise, noise N (electrons) is the quadratic sum of the photon shot noise components in the two frames:

$$N= \mathrm{sqrt}[(2*qe*Amb_{ph})+(qe*AL_{ph})+2*RN^2+PRNU(qe*AL_{ph})]$$

where RN is the sensor dark total temporal noise which includes pixel temporal noise, circuit read noise and dark current shot noise and PRNU is the photo-response non uniformity. Figure 2 shows a plot of SNR versus power of the active light. The comparison is done between this work (orange) and a commercial state of the art NIR CMOS sensor (blue) in two lighting conditions: low light indoors (square markers) and bright light outdoors (triangle markers). The plot is based on the sensor specifications of Table 1 and assumes same pixel size, exposure and gain. QuantumFilm achieves higher SNR in all ambient lighting conditions where the laser power is high enough to achieve a minimum SNR of 5, which is set to be the minimum required to detect active light patterns against noise.

It is important to notice that we were not able to find any competing global shutter silicon imager with relevant QE at 940nm and a pixel size of 1.5μm to directly compare with this work, and we therefore compared the case of 3μm pixels for both CIS and QuantumFilm.

Although current levels of QuantumFilm sensor read noise are acceptable, there are several ways to reduce it by circuit techniques. One classic reduction scheme leverages the ability to design smaller than 1.5μm pixels, which might not be useful at longer wavelengths, like 940nm, as the diffraction spot size tends to be of the order of 2.5um even for the most aggressive lens F#s: by binning 4:1 all noise components are reduced by a factor 2 and still preserve a smaller than 3μm pixel size. Another possible noise reduction relies on active reset for kTC suppression: our preliminary test structures delivered a 3x reduction in reset noise when compared to hard reset operation.

Figure 5 shows an image from a commercial CMOS 3μm VGA sensor side-by-side with one from this work's sensor, under 940nm illumination. In this comparison we run the conventional 3μm NIR CMOS image sensor and the 3μm QuantumFilm NIR sensor at the same exposure, lens and equalized gains to match noise in the dark patch. We then compared signal and noise level in the bright patch and found that due to the higher QE and higher full well, the QuantumFilm based sensor can achieve a max SNR of 46dB vs 40dB of the conventional CMOS.

Figure 6 compares a commercial CMOS 3μm VGA sensor and the 1MP 1.5μm QuantumFilm sensor with exposures scaled to match pixel area to show the advantages in resolution, even under 940nm light.

III. AMBIENT LIGHT CANCELLATION

As already mentioned, ambient background light is an issue for many applications. For structured light or Lidar, laser dots need to be visible against background; for authentication, ambient light is usually non uniform and reduces the efficiency the ID matching algorithm significantly.

QuantumFilm allowed us to implement a novel way to cancel ambient light without using full frame subtraction, based on the unique ability of the material to electrically control the collection of either electrons or holes depending on the direction of the electric field applied between the electrodes. Figure 3 illustrates how two intra-frame adjacent global exposures, one with electron collection and the second with hole collection, impacts the voltage on the sense node. Width and voltage of each pulse can be tuned to match collection efficiency and cancel common mode signal (in this case background light). When the active light source is pulsed only during one of the collection phases, its signal is preserved while ambient background is cancelled. Moreover, to remove motion artifacts and increase dynamic range, multiple short pulses can be used.

IV. CONCLUSIONS

A 1.5um QuantumFilm based GS pixel with over 40% QE at 940nm has been leveraged to design a 1280x960 sensor for actively illuminated applications. The sensor is able to out-perform any currently available NIR sensor, in active illumination use cases. A novel way to cancel ambient light is also being presented which allows the QuantumFilm sensor to remove the contribution of background light without the need of a full frame subtraction.

REFERENCES

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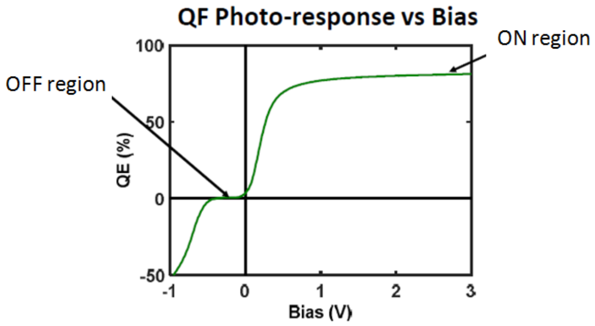


Figure 1: Quantum Efficiency as a function of electric potential across the QuantumFilm

Optical Format	1/7.5"
Pixel Size [um2]	1.5µm x 1.5µm
Frame rate [fps]	60 fps
Full Well [e]	12,000
Quantum Efficiency	40% @ 940nm
Dark Current	600 e/pix/s
Dark Noise 0dB gain	19 e-
Dark Noise [binned]	9.5 e-
Sensitivity	16,000 e/lux/s

Table 1

QFILM	Total Dark Noise	20	electrons
	940nm QE	40	%
	FullWell	10,000	electrons
CMOS	Total Dark Noise	5	electrons
	940nm QE	15	%
	FullWell	8,000	electrons

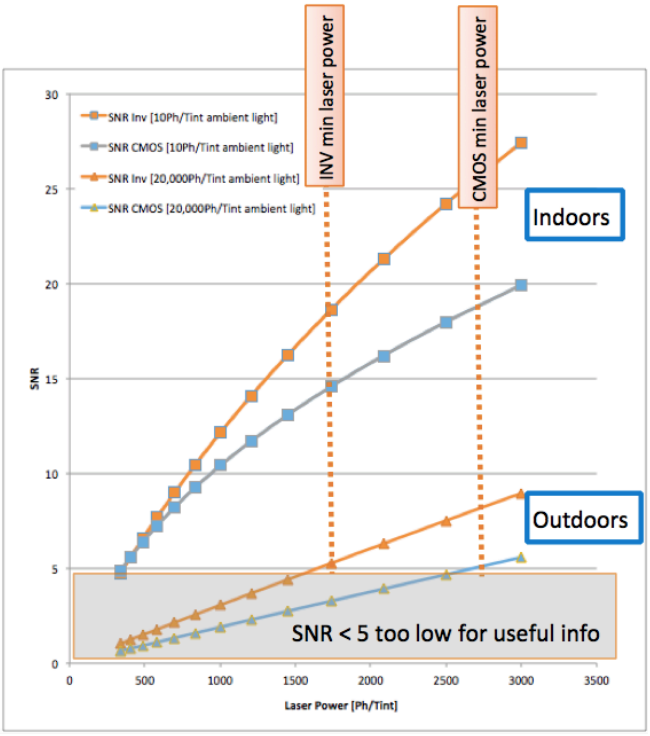


Figure 2: SNR in actively illuminated scenes

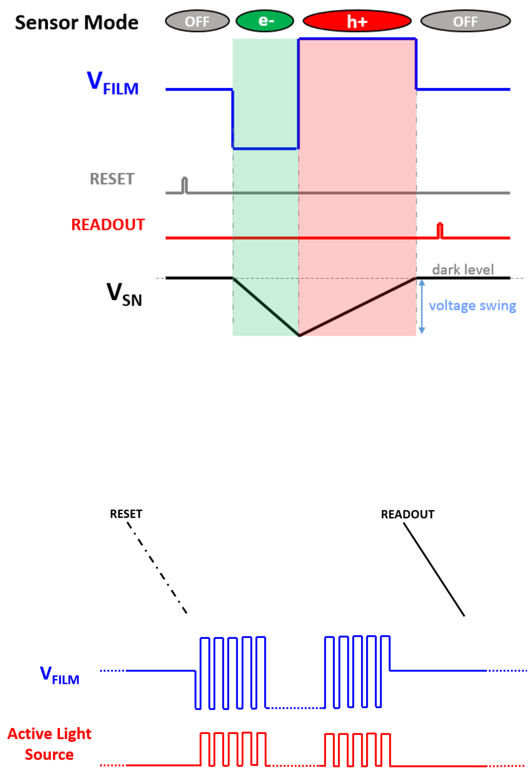


Figure 3: Ambient light cancellation

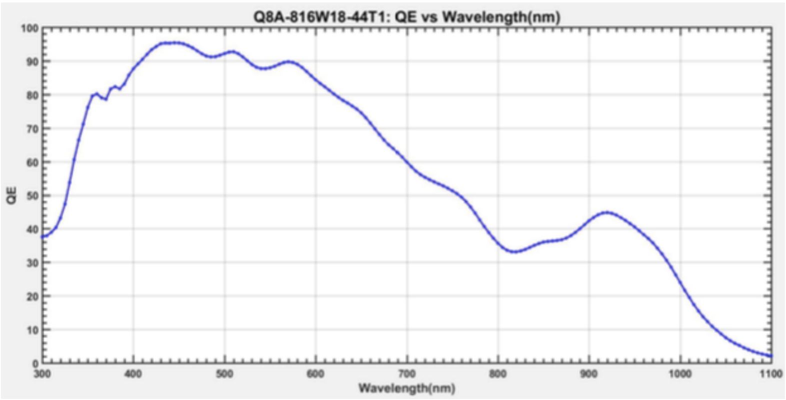
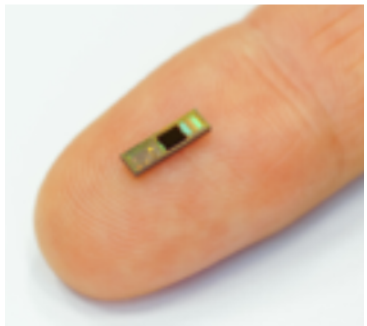


Figure 4: Sensor QE



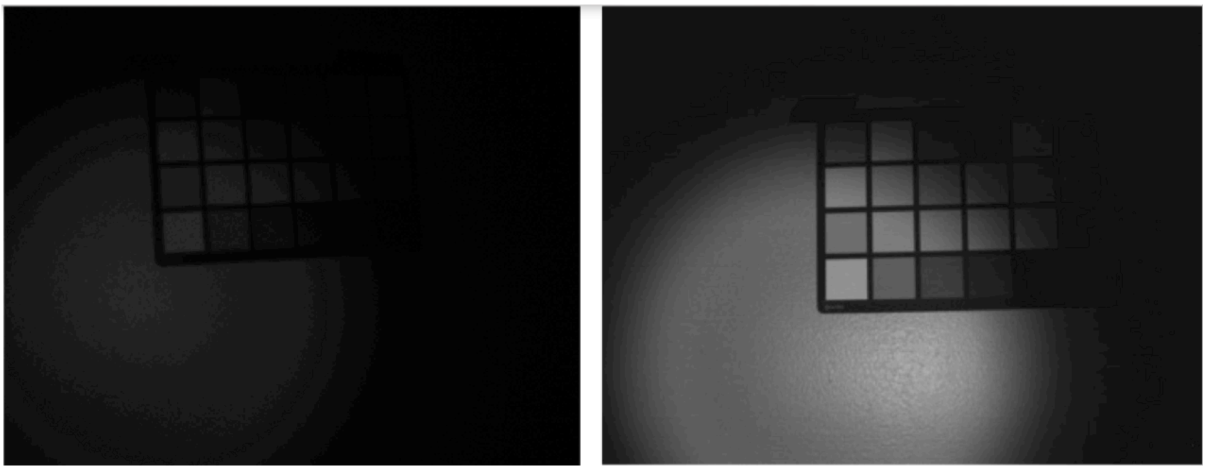


Figure 5: 940nm light scene. Conventional CMOS 3um (left) vs QuantumFilm CMOS 3um (right)

CMOS VGA image sensor (3 µm GS 1.25 ms)

QuantumFilm 1MP (1.5 µm GS, 5 ms)

Figure 6: CMOS VGA vs QuantumFilm 1MP