Case Study of a Global Shutter CIS—Part 2: Parasitic Light Sensitivity

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Abstract— This article focuses on the parasitic light sensitivity (PLS) of a commercially available CMOS camera with a global shutter (with a storage node in the charge domain) and shared pixel architecture. The PLS is characterized as a function of both the wavelength and the incident angle of the incoming light. The measurement results are linked to the layout of the pixels to understand and explain the obtained characterization data.

Index Terms— CMOS image sensor, global shutter, parasitic light sensitivity (PLS), shutter efficiency (SE), wavelength dependency.

I. INTRODUCTION

THE advantages of a CMOS image sensor over a charge-coupled device (CCD) imaging device require no explanation. It has been mentioned many times in the technical and scientific literature that a major drawback of a CCD is the presence of smear, an artifact that is not present in a CMOS image sensor [1]. Actually, this statement is only correct when comparing an interline-transfer CCD to a rolling shutter CMOS. In such a comparison, a major omission is made: comparing a global shutter (CCD) device with a rolling shutter (CMOS) device. A much better approach would be to compare global shutter devices of both technologies. In that case, one can state that a CCD suffers from a smear issue, while a CMOS global shutter sensor suffers from parasitic light sensitivity (PLS) or shutter inefficiency [2]. Both issues, smear and PLS, find their origin in a similar effect: while the information captured by the global shutter image sensor is stored in an in-pixel light-shielded storage node, this information is corrupted by further incoming light. Although the explanation of the effect is the same, its visibility in an image is different. In a CCD imager, the smear shows up as a column artifact running through a highlight, while in a CMOS image sensor, the PLS shows up as a kind of after-glow in the time domain [3].

This article focuses on the PLS of a commercially available global shutter CMOS image sensor. The storage node of the device under test (DUT) is based on an in-pixel, dedicated

MOS capacitor on which the information is temporarily stored in the charge domain [4]. To maintain the correlated-double sampling (CDS) capability, the floating diffusion node is not used for the global-shutter storage node. The PLS is characterized as a function of the wavelength as well as the angle of incidence of the incoming light.

II. SENSOR ARCHITECTURE

The device architecture and a few pixel details are described in the first part of this diptych.

If the device is operated in the global shutter mode, it is important to notice the following.

1) The beginning of the exposure time is the same for all pixels, as is the end of the exposure time. So, all pixels capture the information at exactly the same time.
2) The readout of the data takes place sequentially, that is, row after row, with the result that the information belonging to the first row is stored for a very short time in the memory nodes, while the information that belongs to the last row is stored for a very long time in the memory nodes.
3) If the storage or memory nodes are reset before the information from the photodiodes is transferred, then every artifact generated while the information is stored in the memory nodes will result in a shading (spatial low-frequency shift) from the first row until the last row. Issues that will show such a shading effect are as follows.
   a) Dark current generated in the storage nodes.
   b) Electrons generated in the storage nodes due to stray light that penetrate the storage node.
   c) Electrons generated deeper in the silicon substrate that are collected by the storage nodes instead of being collected by the photodiodes.

The latter two issues build up the PLS. The PLS is defined as the ratio of (the light signal rate generated in the storage/memory node) and (the light signal rate generated in the photodiode), usually expressed in dB. Another way of expressing this effect is the shutter efficiency (SE), that is, the ratio of (the light signal rate generated in the photodiode minus the light signal rate generated in the storage node) and (the light signal rate generated in the photodiode), mostly expressed as a percentage. The relation between the PLS and the SE is given by

$$PLS = S_{SN}/S_{PD}$$

$$SE = (S_{PD} - S_{SN})/S_{PD} = 1 - S_{SN}/S_{PD} = 1 - PLS$$

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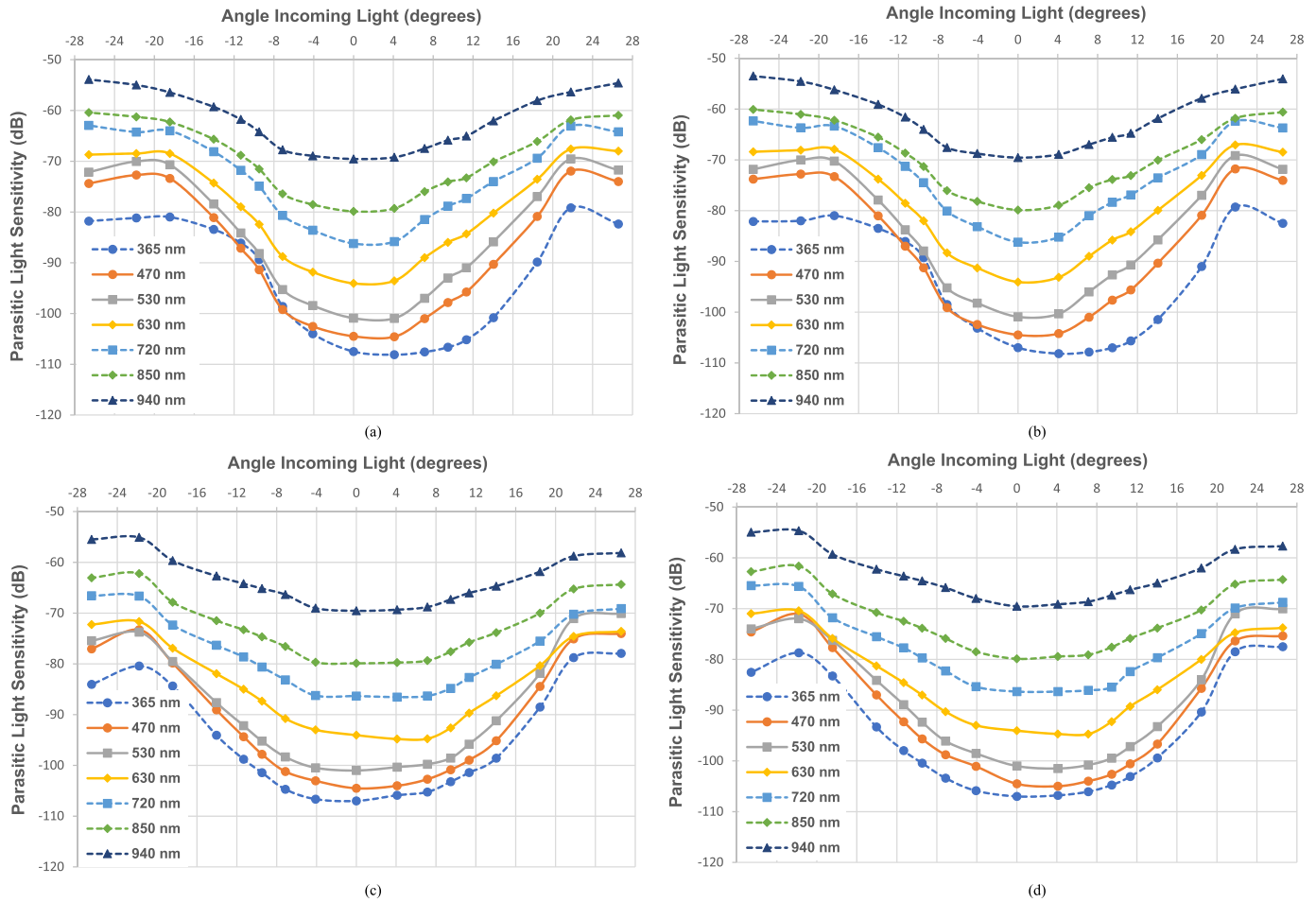
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Fig. 1. (a) PLS of the pixels belonging to the even rows as a function of the incoming angle (positive value: east direction; negative value: west direction), with the wavelength of the incoming light as a parameter. (b) PLS of the pixels belonging to the odd rows as a function of the incoming angle (positive value: east direction; negative value: west direction), with the wavelength of the incoming light as a parameter. (c) PLS of the pixels belonging to the even rows as a function of the incoming angle (positive value: north direction; negative value: south direction), with the wavelength of the incoming light as a parameter. (d) PLS of the pixels belonging to the odd rows as a function of the incoming angle (positive value: north direction; negative value: south direction), with the wavelength of the incoming light as a parameter.

where S_{SN} is the light signal generated in the storage node and S_{PD} is the light signal generated in the photodiode.

III. MEASUREMENT METHOD

The value of the PLS can be very low, for example, −100 dB, or equal to an SE of 99.999%. This means that the PLS signal is a factor of 100 000 times below the active signal retrieved from the photodiodes. To cope with these large ratios between the active signal and the signal from the artifact, the two parameters (active signal S_{PD} and parasitic light signal S_{SN}) are measured in two cycles, both with large amounts of light on the sensor and with differences in the timing.

A. Measurement of the Active Light Signal S_{PD}

For this measurement, the sensor is operated in the standard global shutter mode that is defined by the camera supplier. The exposure time during the capturing of the signal is adjusted so that the output signal of the sensor reaches about 75%

saturation. The exposure time (μs), light intensity (μW/cm^2), and output signal (DN) are recorded. From the obtained data, the output signal generated in the pixel per μW/cm^2 light input and per μs exposure time can be calculated (=active signal S_{PD}).

B. Measurement of the Parasitic Light Signal S_{SN}

The sensor under test is again operated in the normal global shutter readout sequence that is sketched above, with the same light intensity, but also with two exceptions compared to the previous timing as follows.

1) The exposure time is kept as short as possible (=1.52 μs) to keep the active signal S_{PD} as small as possible to allow the measurement of the PLS generated signal that is added to the signal coming from the photodiode (because external control of the storage node and/or transfer gate is not possible, the only way out to S_{PD} as small as possible is to work with a minimum exposure time).

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2) The row time is extended to the largest time possible in the available camera (=873 μs) to make the parasitic light signal as large as possible.

Parameters that are recorded are exposure time (μs), row time (μs), light intensity (μW/cm^2), and output signal (DN).

Under the above-mentioned conditions, the effect of the PLS is clearly visible as a shading signal from the top of the image (low S_{SN} signal) to the bottom of the image (large S_{SN} signal). From the obtained data (=slope of the S_{SN} signal), the parasitic light signal rate generated in the memory node per μW/cm^2 light input and per second can be calculated (=PLS signal S_{SN}).

All PLS measurements are done as follows.

1) A function of wavelength of the incoming signal. The light source used is based on multiple LEDs of various wavelengths: 365, 470, 530, 630, 720, 850, and 940 nm, of which the amount of light output can be digitally regulated. The full-width half-max (FWHM) values for the various LEDs are, respectively, 8.8, 18.9, 31.1, 13.1, 25.8, 20.7, and 70.8 nm.

2) A function of the angle of incidence of the incoming light (0°, 4.1°, 7.1°, 9.5°, 11.3°, 14.1°, 18.4°, 21.8°, 26.6°), from all four directions (north, south, east, west).

3) At room temperature (dark current collection at room temperature is small, but to make sure that the dark current is not effecting the PLS measurements, all data obtained with light are corrected by means of a dark frame subtraction).
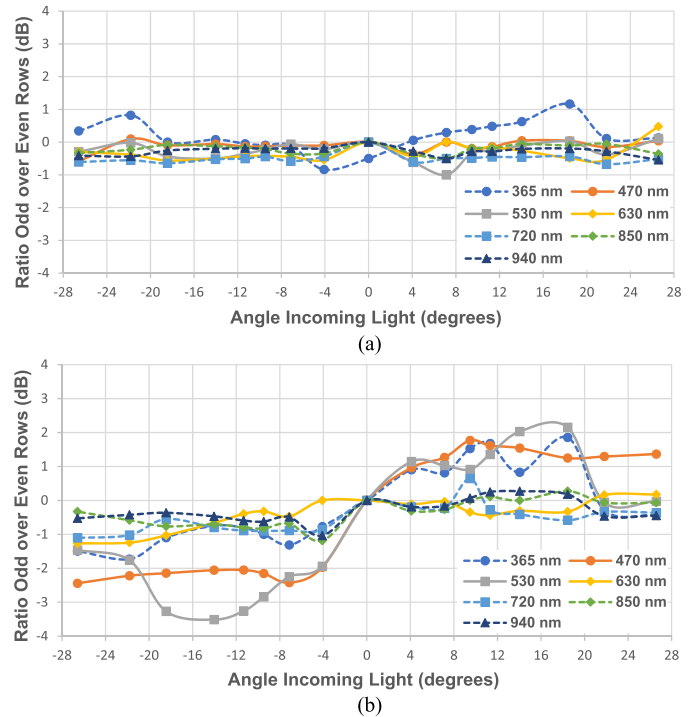

Fig. 2. (a) Ratio of the PLS of odd and even rows, as a function of the angle of incidence (positive value: east direction; negative value: west direction), with the wavelength of the incoming light as a parameter. (b) Ratio of the PLS of odd and even rows, as a function of the angle of incidence (positive value: north direction; negative value: south direction), with the wavelength of the incoming light as a parameter.

IV. PARASITIC LIGHT SENSITIVITY

All measurements reported here about PLS are obtained in a similar way as the angular dependency reported in the first part of the study: in the postprocessing of the obtained results, all data are normalized to 25 μW/cm^2 light power and an exposure time of 1 μs for the active light signal S_{PD}, with a total row/line time of 873 μs (standard line time + extended line blanking time). Besides the angular dependency, the PLS of the two pixel types is also measured, odd and even (due to the 2V × 1H shared pixel design), and for the four different directions of light input (north, south, east, west).

The results obtained for the PLS are shown in Fig. 1(a) (east–west, even rows), (b) (east–west, odd rows), (c) (north–south, even rows), and (d) (north–south, odd rows). Comparing Fig. 1(a) and (b) shows the PLS for east or west incoming light is very similar for pixels on odd rows and pixels on even rows. Because the pixels in the odd and even rows have the same left and right definition of the photodiodes, it can be expected that the curves do not shown much difference between east and west.

Notice that the PLS does not reach its minimum value for all wavelengths at an angle of 0°. This effect can be explained by the asymmetric layout of the pixels. To the right of the photodiode is where the memory node is situated, so light that enters the photodiode from the west has a greater chance of reaching the memory node compared to light coming from the east. In the latter case, the shadowing effect of the light shield is advantageous for the PLS. If the light comes from the west, the light shield above the photodiode can act as a light pipe which can deteriorate the PLS even further.

On a side note: at very large angles (20° or more), the PLS shows a slight improvement. This can be due to, or some effects in the calculation (because the active signal S_{PD} measured at these angles is very small as well), or a real slight increase in performance.

The shape of the curves in Fig. 1(c) and (d) is much more symmetric (around 0°) than it is in Fig. 1(a) and (b). The symmetry of the pixels along a horizontal line is much more "PLS-friendly" than it is along a vertical line, meaning that there will be no real great differences between the north and the south directions. It is not expected that the parasitic light signal S_{SN} will depend on the north–south direction of the incoming light. This theory is reflected in the shape of the curves in Fig. 1(c) and (d).

Calculating the differences between the results obtained in Fig. 1(a) and (b) shows also the PLS performance differences (if any) between even and odd pixels. The result of this calculation is given in Fig. 2(a) (shown is the ratio of two measurements, but when expressed in dB, it is the difference of the two data points). As already mentioned above, there is no real difference in pixel layout between the odd and even rows, when considering the east–west direction of the incoming light. This result is reflected in Fig. 2(a).

In Fig. 2(b), the same process illustrated in Fig. 2(a) is repeated, but now for the north–south direction. There seems to be a kind of symmetry in the curves: for negative angles of
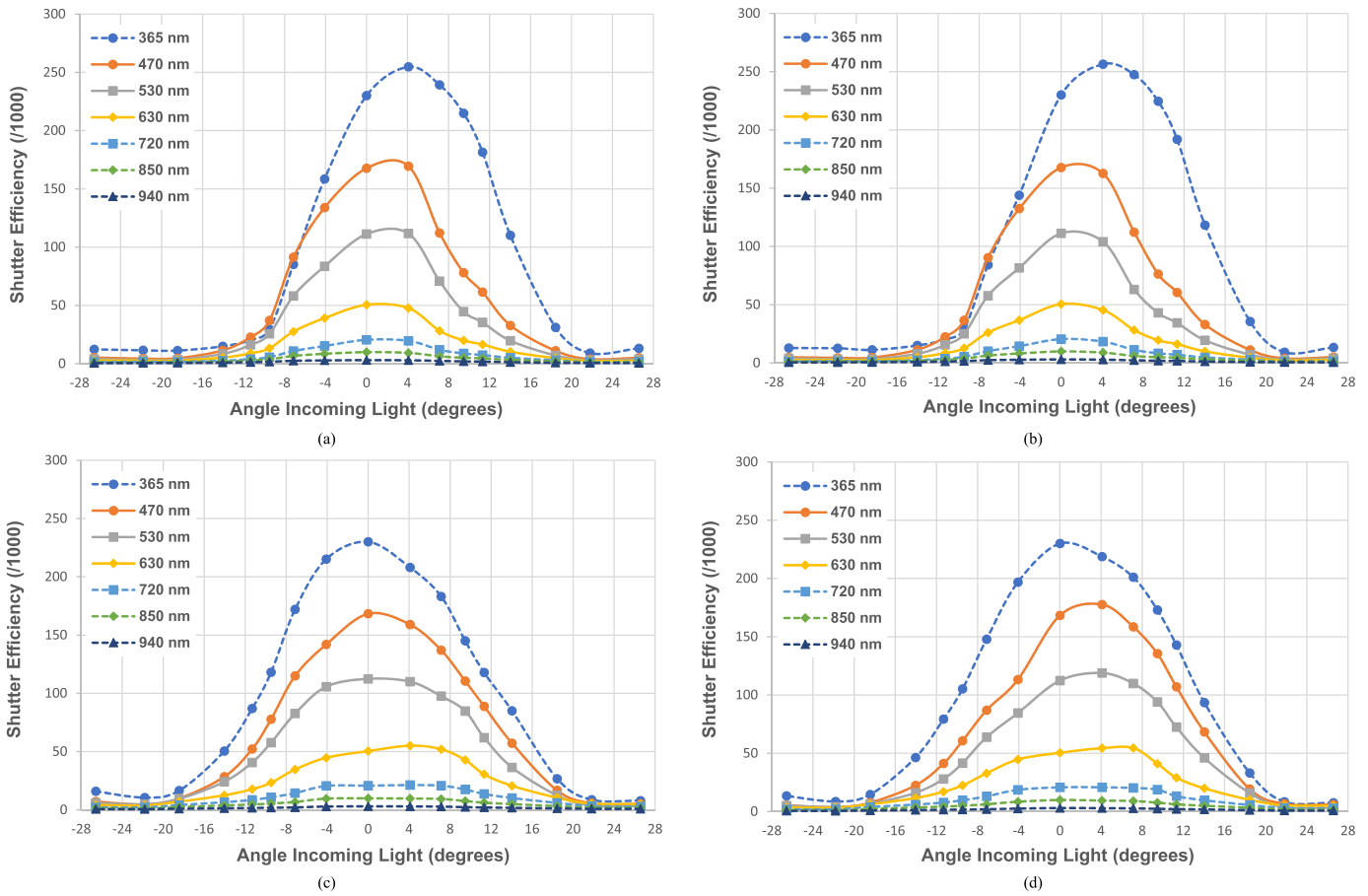
Fig. 3. (a) SE of the pixels belonging to the even rows as a function of the incoming angle (positive value: east direction; negative value: west direction), with the wavelength of the incoming light as a parameter. (b) SE of the pixels belonging to the odd rows as a function of the incoming angle (positive value: east direction; negative value: west direction), with the wavelength of the incoming light as a parameter. (c) SE of the pixels belonging to the even rows as a function of the incoming angle (positive value: north direction; negative value: south direction), with the wavelength of the incoming light as a parameter. (d) SE of the pixels belonging to the odd rows as a function of the incoming angle (positive value: north direction; negative value: south direction), with the wavelength of the incoming light as a parameter.

incidence, the curves show a result higher than 0, while for positive angles of incidence, the curves show a result lower than 0. Because the angle variation is north–south and the storage node is located to the right of the photodiode, the effect shown in Fig. 2(b) is not immediately expected. Ideally, all the curves should be straight horizontal lines through the vertical axis with a value of 0. But this can be explained by the angular dependency of the light sensitivity (PLS is the ratio of S_{SN} and S_{PD}).

Normally, the PLS is expressed in dB, but to obtain a better view of the strong relationship between the PLS and the wavelength as well as the angle of incidence, Fig. 3(a)–(d) are included, in which the SE is no longer expressed dB, but in a linear values [5].

Based on the data presented in Fig. 3 series [as well as Fig. 2(a) and (b)], the following statements can be formulated about the PLS.

1) The PLS depends strongly on the angle of incidence of the incoming light. As soon as the incoming light deviates from the normal, the photons will penetrate into the silicon at a certain angle. In this way, they can easily generate electron–hole pairs outside the depletion volume of the photodiode. Especially for the light coming from the west, these photons can finally land in the depletion volume of the storage node (unless the light shield above the storage node covers a large part of the photodiode close to the storage node as well). On the other hand, part of the light coming from the east will most probably not land in the photodiode, but instead will land into the device isolation region at the left side of the photodiode.

2) It is not by definition correct that the minimum PLS for all wavelengths will be reached at 0° incident light. It all depends on the layout of the pixel and especially the layout of the light shield.

3) The PLS depends strongly on the wavelength of the incoming light. Light with longer wavelengths has a lower absorption coefficient for silicon and can penetrate deeper into the material before being absorbed. As a result of this, light with a longer wavelength has a greater chance of generating an electron-hole pair where the electron will "diffuse" to a region different from that of the photodiode. The order of PLS values when it comes down to wavelength dependency is the same for

all situations: the shortest wavelength shows the best PLS, while the longest wavelength shows the worst PLS.

V. Summary

The best number obtained for the PLS in all measurements is 256 382 or –108.2 dB, corresponding to an SE of 99.9996%. The worst number found for the PLS in all measurements is 472 or –53.5 dB, corresponding to an SE of 99.97%. It should be clear that in the performance specification data sheets of an image sensor/camera, the PLS needs to be included with the angle of incidence and with the wavelength of the incoming light. Without knowing these two parameters, the specification of the PLS becomes meaningless and useless. Even knowing the PLS at a particular wavelength and a particular angle of incidence is no indication of the PLS at other wavelengths and/or other angles of incidence. The general trend is that shorter wavelengths achieve a better PLS performance, as well as smaller angles of incidence. But especially for the latter, even this is not always true!

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