Increasing CMOS Camera Sensitivity Through Back-Illumination

Introduction

Scientific camera sensitivity is determined by three main factors; quantum efficiency (QE), pixel size and noise characteristics. Quantum efficiency is the measure of the effectiveness of the camera to produce electronic charge (electrons) from incident photons, where a higher QE results in the conversion of more photons to electrons of signal. Electrons go on to be converted into a digital signal that can be read by a computer and visualized. Pixel size relates to the physical area of the pixel, where a larger pixel is able to collect more photons and therefore deliver more electrons of signal. Noise characteristics, particularly read noise at low-light levels, determine how much the electron signal can fluctuate per pixel. The higher the signal over the noise, the higher the signal-to-noise ratio and therefore image quality. There will be no sample detection if noise exceeds signal.

This technical note will focus on quantum efficiency and how it was made possible to increase sensitivity on CMOS cameras by increasing QE to an almost perfect, 95% through the process of back-illumination. An easily repeatable experiment is also outlined to evaluate camera sensitivity.

Quantum Efficiency

Quantum efficiency can be pretty well defined as the percentage of electrons produced from the number of incident photons. For example, if 100 photons hit a 95% quantum efficient sensor, 95 electrons would be theoretically generated. Likewise, if 100 photons hit a 65% quantum efficient sensor, 65 electrons would be theoretically generated.

This process is a property of the photovoltaic effect, where light energy (photons) incident on the silicon substrate of a pixel creates electron-hole pairs. These electrons are then read out by the device and converted into a digital signal that can be interpreted by a computer.

There are many conditions that affect the photovoltaic effect and thereby determine the number of electrons generated by a single photon. Of these, the two most important conditions are the absorption coefficient and the chemical and physical properties of the material on the sensor surface. As these conditions determine the number of electrons that can be generated by a single photon, they directly influence the quantum efficiency of the camera.

Absorption coefficient

The absorption of photons into the silicon substrate of the pixel is wavelength dependent. This is the reason why quantum efficiency is shown on camera datasheets as a curve, such as the curves shown in Figure 1.

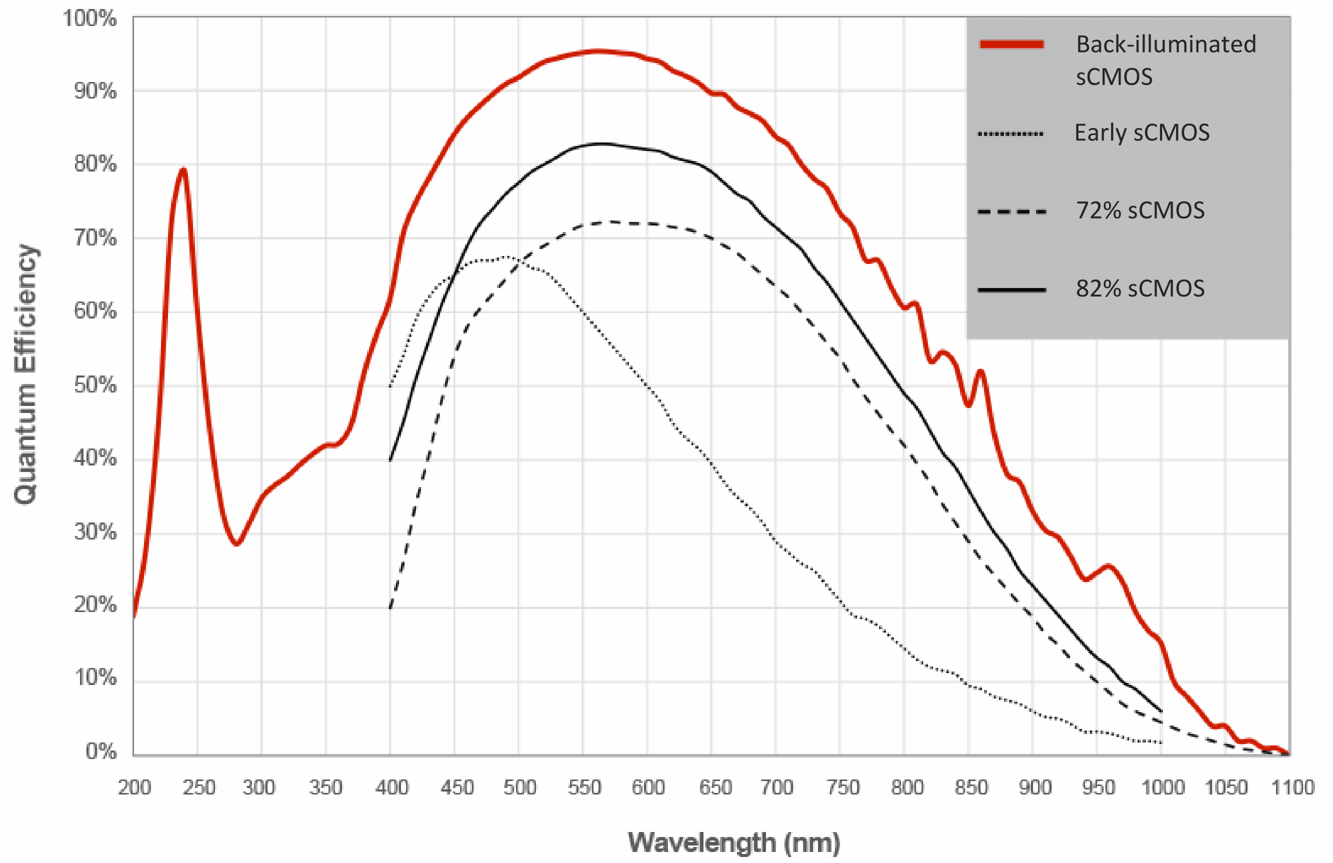

Figure 1: Comparison of quantum efficiency curves of some typical CMOS cameras.
Adapted from Princeton Instruments, Kuro sCMOS

Quantum efficiency is higher in the green and yellow region (500 nm – 600 nm) because these wavelengths penetrate well into the region of the silicon substrate of the pixel where the photovoltaic effect takes place (Figure 2).

Shorter wavelengths do not penetrate deep enough so many photons are lost before reaching the silicon substrate. At the other end of the spectrum, longer wavelengths penetrate too far so photons pass straight through the silicon substrate.

There is usually a quantum efficiency cut-off at around 400 nm where the majority of the photons are lost before they can reach the silicon substrate.

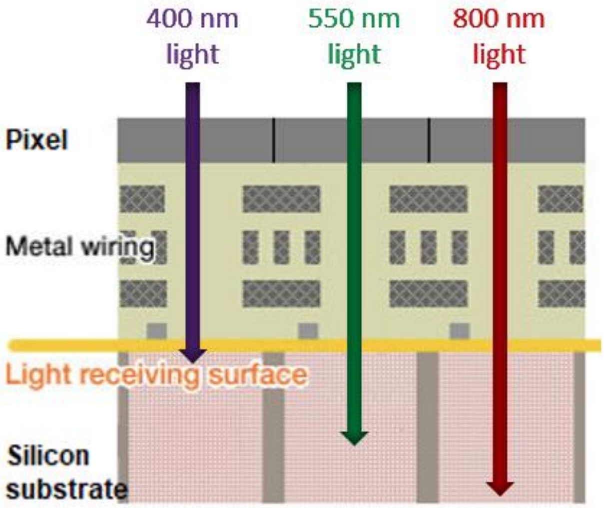

Figure 2: Light wavelength and silicon penetration. Adapted from Sony, back-illuminated CMOS image sensor

There is also a critical wavelength, usually at around 1100 nm, where incident photons have insufficient energy to produce an electron-hole pair so no signal can be generated.

Front-Illuminated CMOS

On CMOS sensors, a certain fraction of the pixel surface is covered in the metal tracks, wiring and transistors (the circuitry) necessary to collect and transport charge (Figure 3). On front-illuminated sensors, this has the unfortunate side effect of making that area completely light insensitive.

The photons landing on this area can't reach the silicon substrate because they are physically impeded. These photons, therefore, won't be converted into electrons and so the quantum efficiency will be negatively affected.

The highest quantum efficiency sensors using this architecture was made possible through the addition of microlenses on the sensor surface (Figure 4). The microlenses are designed to focus the incident light away from the circuitry and onto the silicon substrate. This effectively increases the number of photons reaching the silicon substrate and therefore increases QE. CMOS Sensors using this architecture claim a QE of up to 82%.

A downside of microlenses, however, is that they are most effective when the incident angle of light is normal to the sensor surface. When light enters the sensor from any other angle, the effectiveness of the microlenses can become severely reduced. This means that the reported QE increase of a CMOS camera with microlenses may not accurately reflect the real QE increase.

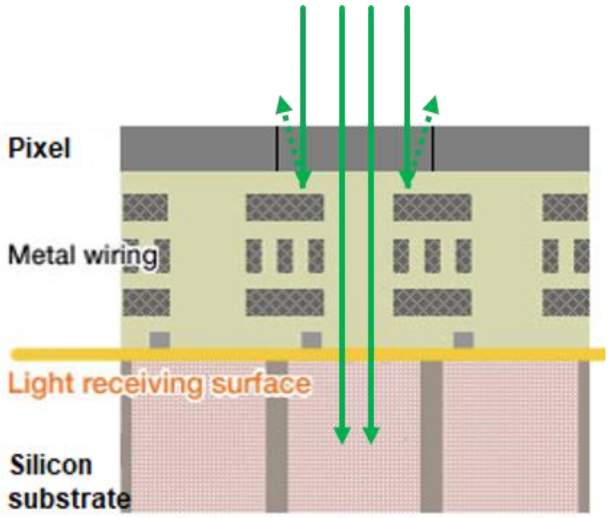

Figure 3: Photons unable to pass the metal tracks, wiring and transistors present in front of the CMOS sensor.

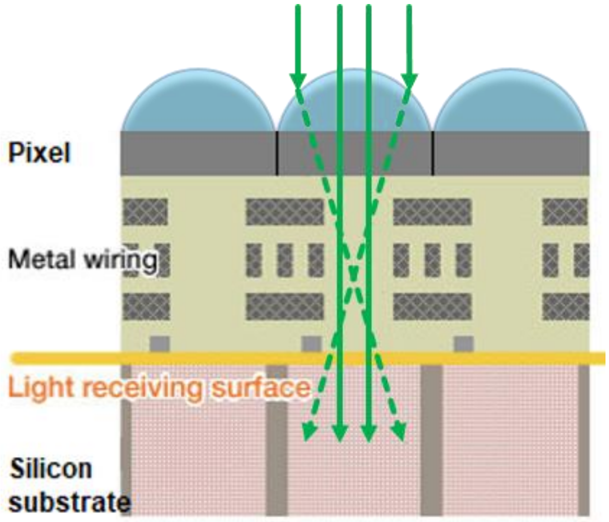

Figure 4: The use of microlenses to increase quantum efficiency of front-illuminated CMOS sensors.

Regardless of the issues with microlenses, the real problem to overcome is clearly the position of the circuitry. To address this, sensor manufacturers have recently started creating back-illuminated CMOS sensors. By inverting the sensor and bringing light in from the back, the circuitry can be avoided completely.

Back-Illumination

A back-illuminated sensor is one that has essentially been flipped over so light enters directly into the silicon substrate rather than having to pass through the circuitry (Figure 5). Any light loss due to objects on the sensor surface is thereby eliminated.

To allow the photons to penetrate deep enough into the silicon substrate to be converted into electrons, the silicon must also be thinned at the back. For this reason, a back-illuminated sensor may also be referred to as a back-thinned sensor.

The result is a sensor with an almost perfect, 95% quantum efficiency at its optimum wavelength. This can be seen in Figure 1, which shows the QE curve of a back-illuminated CMOS compared to front-illuminated CMOS devices, such as an 82% CMOS camera with microlenses.

Another advantage of back-illumination, highlighted in Figure 1, is the ability to achieve a high QE with shorter, UV wavelengths of light. It's possible to achieve UV light detection on other CMOS devices but, as stated earlier, the fill-factor becomes limiting. This problem is completely overcome with a back-illuminated sensor. Moving the circuitry below the silicon substrate allows the fill-factor to reach 100%, granting both a high UV response and a high QE over a wide spectral range.

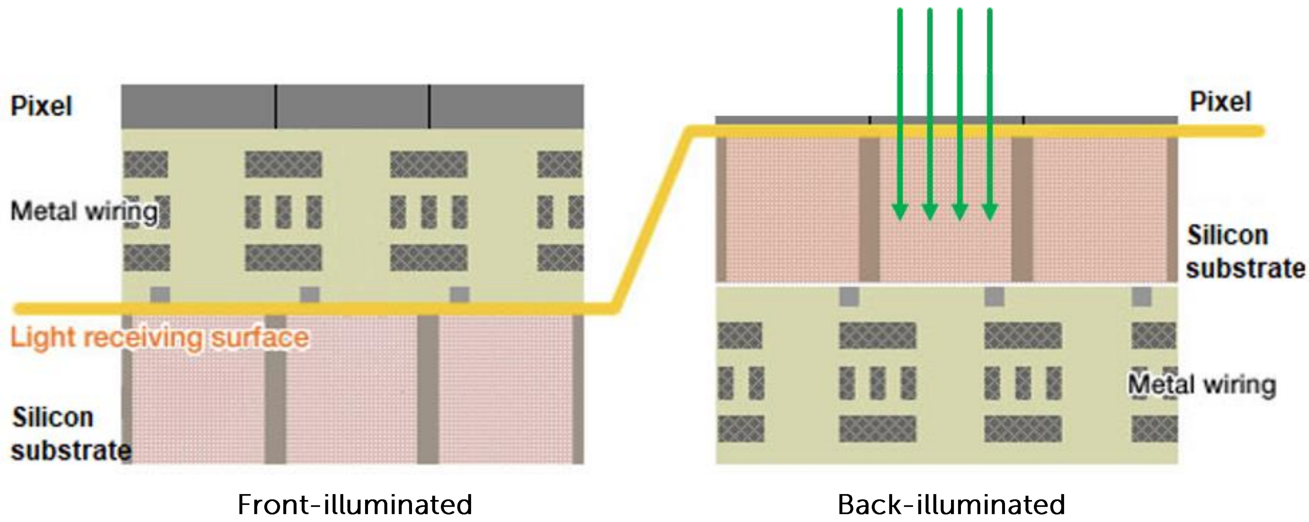

Figure 5: Comparison of front- and back-illuminated sensors.

To test the theoretical increase in quantum efficiency of a back-illuminated sensor over a front-illuminated sensor, we performed a simple experiment designed to compare the sensitivity of multiple cameras.

Summary

Scientific camera sensitivity is determined by quantum efficiency, pixel size and noise characteristics. Increasing pixel size comes with the disadvantage of reducing resolution so increasing quantum efficiency is a more attractive method of increasing camera sensitivity. Recently, back-illuminated CMOS sensors have been developed which allow quantum efficiency to reach up to 95%. An analysis of the back-illuminated Prime BSI CMOS camera compared to a typical front-illuminated CMOS camera was performed which confirmed the increase in sensitivity. We conclude that using the Prime BSI, which has an equal pixel size to typical front-illuminated CMOS cameras, would allow exposure times to be reduced by up to 25%.

References

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Cairn Research - https://www.cairn-research.co.uk/

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