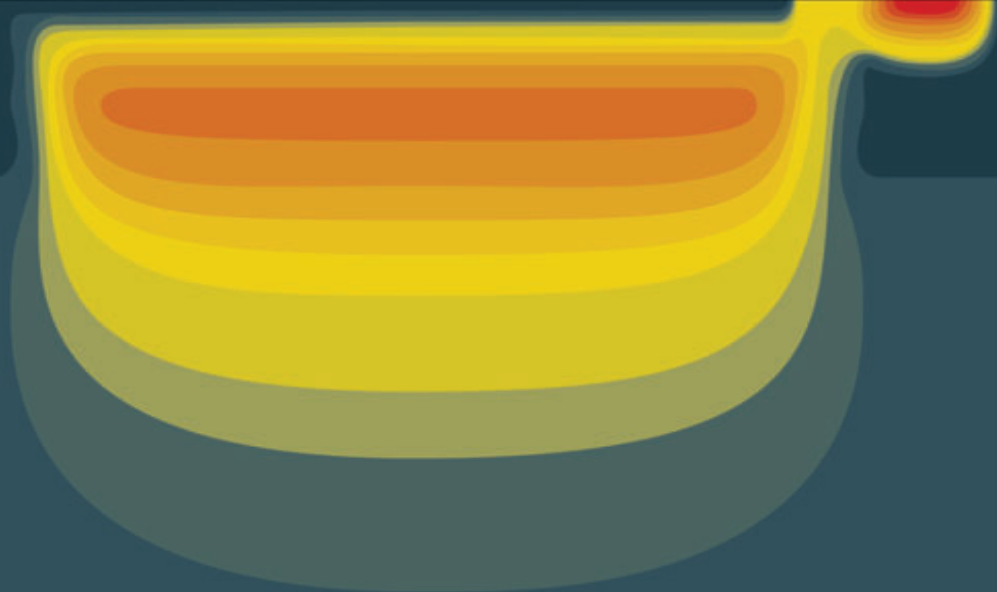


# CMOS Image Sensors

**Konstantin D Stefanov**



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# Chapter 5

## Characterisation

### 5.1 Introduction

Electro-optical (EO) characterisation is fundamental to image sensor operation and development. It aims to experimentally measure the parameters of the sensor under different operating conditions. The results are used to select the optimal settings for the best sensor performance, and for a comparison with the estimations calculated during the design phase. Despite the highly powerful simulations and electronic design automation (EDA) tools, there is still no substitute to sensor characterisation. High quality, detailed characterisation can offer a wealth of information that can help optimise the sensor's operation and identify unexpected behaviour or design flaws. It also provides feedback to the simulation tools used in the design.

Characterisation requires a great deal of investigative and problem-solving skills, logical thinking, solid technical knowledge, and ingenuity. It is highly skilled work taking years to master, and the people able to do this well are highly respected. No matter how experienced somebody is, there are always surprises, seemingly inexplicable behaviour and new things to learn; this is what makes it challenging but rewarding.

The number of experimental parameters to be measured can be very large, and the number of possible device settings is nearly infinite. Therefore, the characterisation has to be balanced so that it provides the desired information but is achievable within a limited time and budget. Certain parameters, such as the saturation signal, readout noise and dark current are of high importance and are invariably measured, while others may be of less or no interest and can be omitted. Publications such as the EMVA 1288 standard [1] and several ISO standards on electronic still-picture imaging [2] provide important information on measuring techniques.

The following is a non-exhaustive list of the main parameters to be determined, in order of their usual importance:

- Electrical characteristics for operation—readout rate, signal range, settling time, electrical transfer function (ETF), power dissipation;
- Responsivity, its linearity and uniformity, and saturation signal;
- System and conversion gain;
- Readout noise and dynamic range;
- Dark current and its uniformity;
- Image lag;
- Quantum efficiency (QE);
- Modulation transfer function (MTF).

The electrical characteristics are dealt with during the commissioning of the readout electronics. The starting point is the simulated performance of the on-chip readout, which is usually very reliable. Some adjustments may be needed to create correctly functioning imaging system, capable of powering and driving the sensor and supplying the appropriate optical signals. The system should be able to cope with the output readout rate, correctly capture the outputs of the sensor and have negligible noise. After all, we should be studying the sensor, not the quirks in the electronics and the bugs in the software.

A light source with controlled intensity, wavelength and timing is required for the determination of most characterisation parameters, except for the dark current. Very often the illumination must be synchronous to the sensor's drive signals, and in such cases, light emitting diodes (LED) can be used to provide light pulses with sub-microsecond duration.

A great deal of image sensor characterisation can be automated by software, and many parameters can be determined from the same data. Good software skills can be essential in analysing the data, especially when it involves processing a large number of recorded images.

## 5.2 Readout modes

There are two main modes of CIS readout—rolling shutter (RS) and global shutter (GS). The possible readout modes are tightly coupled to the pixel and sensor architecture.

The term ‘sensor readout’ is used to indicate the time when some part of the sensor is being read out. The term ‘integration time’ means the period when the sensor is *not* being read out but is integrating a light-generated signal. A sensor can be sensitive to light during both periods and the difference between them in terms of signal collection can be negligible. This definition of the readout and the integration time will be used for the image sensor characterisation.

Rolling shutter is the simplest readout mode and is the usual way to read 4T pixels because it uses CDS and delivers the best noise performance. RS can be continuous (shown in figure 5.1), which delivers the highest readout rate, or image integration over the whole sensor can be added between two consecutive readouts (figure 5.2). In both cases the pixels are continuously sensitive to light, except during the charge transfer from the PPD to the sense node. As we can see, in RS mode all rows are exposed to light for the same length of time, but *not at the same time*. This introduces distortions when imaging a moving scene and is a well-known effect.

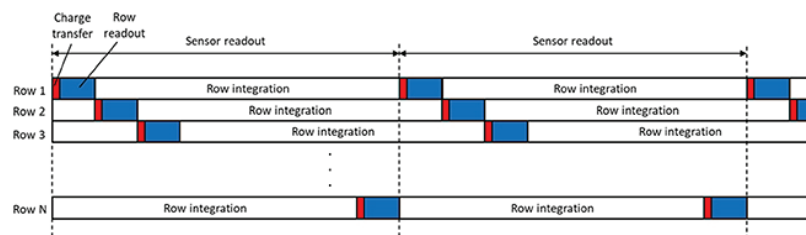


**Figure 5.1.** Rolling shutter, continuous 4T sensor readout.

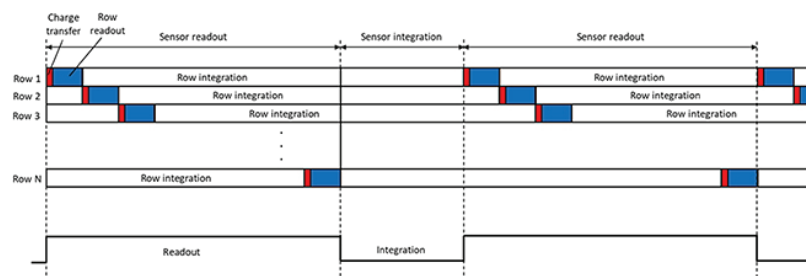


**Figure 5.2.** Rolling shutter readout with an additional sensor integration time.

To reduce motion distortions, a global reset is introduced with 5T pixels, but the readout is still in rolling shutter mode (figure 5.3). With global reset all pixels are emptied of charge at the beginning of the readout cycle, which helps reduce motion distortion but does not eliminate it. Global reset is

particularly effective when most of the signal is generated during integration, for example by using a flash illumination. Similar effect can be achieved with the RS readout in figure 5.2. As the integration time increases, the proportion of time during which all rows are simultaneously receiving signal increases too. If the integration time is much longer than the readout time, the overall effect becomes close to having a global reset.

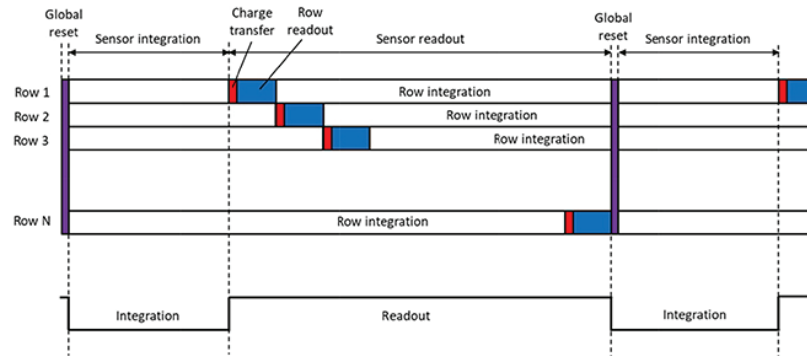


**Figure 5.3.** Rolling shutter with global reset using 5T pixels.

Global shutter is the preferred readout mode when imaging moving scenes because all pixels are sensitive to light simultaneously. This is accomplished by a sensor-wide, global signal capture from the photodiode to an in-pixel storage node (figure 5.4). The signal can be either charge or voltage and requires specialised pixel architecture. Following capture, the stored signals do not change under illumination and are read out row by row, simultaneously with the integration of the next image. Each pixel is photosensitive for the time duration between two applications of the global signal capture. Most GS sensors offer different readout schemes and can be read out in RS mode as well.

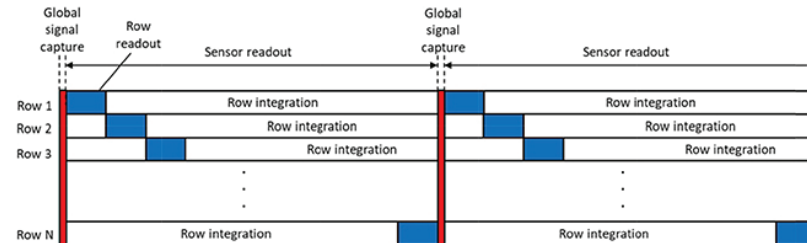


**Figure 5.4.** Global shutter readout mode.

The majority of scientific CIS are designed for RS operation, while GS mode is frequently needed for machine vision applications. RS readout with pulsed illumination during an added integration time as in figure 5.2 is the main mode used for the characterisation methods described further on.

### 5.3 Principles of EO characterisation

It is very useful to consider the general block diagram of a linear image system in figure 5.5. Regardless of the sensor's architecture and the manufacturing technology, the commonalities in the processes of converting photons into digital signal make such a diagram representative of a wide range of systems.

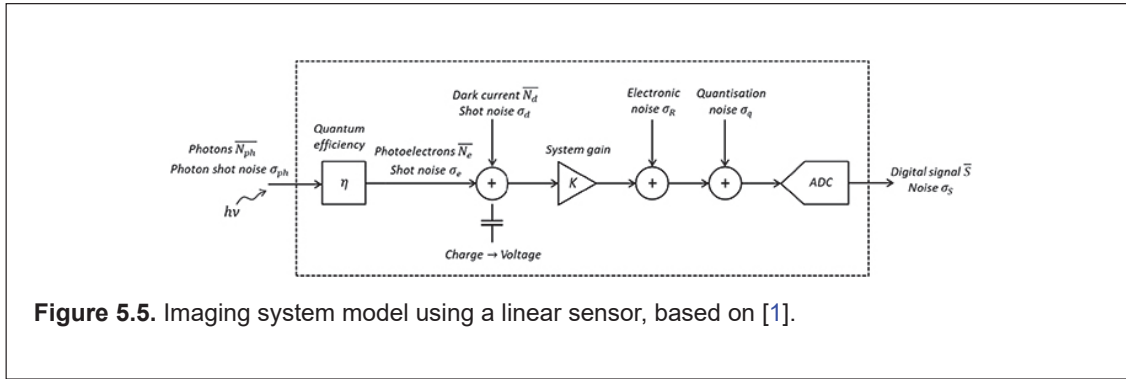


**Figure 5.5.** Imaging system model using a linear sensor, based on [1].

The signal path starts with incoming photons with mean number  $\overline{N}_{ph}$  received during the integration time, converted with quantum efficiency  $\eta$  to  $\overline{N}_e$  photoelectrons:

$$\overline{N}_e = \eta \overline{N}_{ph} \quad (5.1)$$

Electrons created by dark current during the same time interval, with mean  $\overline{N}_d$ , are added to the photogenerated signal before the conversion to voltage. The mean output signal  $\overline{S}$  is the digital code proportional to the total number of converted electrons:

$$\overline{S} = \frac{1}{K} (\overline{N}_e + \overline{N}_d) \quad (5.2)$$

The signal is in dimensionless analogue-to-digital units (ADU) corresponding to the generated ADC code, for example a 16-bit ADC can output code from 0 to 65535. Very often the equivalent notation 'digital number' (DN) is used instead of ADU.

The proportionality constant  $K$  is called *system gain* and is measured in the dimensionless units of  $e^-/\text{ADU}$ . The choice of units<sup>1</sup> is like this because we want to determine a physical value—the total number of electrons  $\overline{N}$ , from the output signal  $\overline{S}$ , which is just a digital code. From (5.2) this relationship is simply

$$\overline{N} = K \overline{S} \quad (5.3)$$

The system gain combines two very different, and virtually independent parts, into one:

- The *conversion gain* of the sensor, describing the voltage created by the charge-to-voltage conversion;
- Electronic gain in the system amplifying the voltage from the converted charge, and the digitisation by the ADC.

The conversion gain is a property of the conversion element, for example the sense node in the PPD, and is practically independent on the gain of the following electronic circuits. The conversion gain is a key design parameter and can be measured by knowing both the system and the electronic gain.

The digital output signal  $S$  is also called 'grey value' [1] which could be slightly confusing when applied to colour cameras, or with Gray code. To avoid this, the term 'signal value' meaning 'digital signal value' is used throughout this chapter.

Real-life systems exhibit some nonlinearity and therefore  $K$  is not a constant, but the model in figure 5.5 can still be used with due care. The system is not a 'black box' because we know its structure, although the exact physical implementation of the building blocks may be unknown. For the purposes of characterisation, it operates as a box where photons come in one end and ADC code comes out from the other.

The incoming photons have shot noise with standard deviation  $\sigma_{\text{ph}}$ , given by the Poisson statistics

$$\sigma_{\text{ph}} = \sqrt{N_{\text{ph}}} \quad (5.4)$$

If one interacting photon generates one photoelectron, which is the case for visible light in silicon, the standard deviation of the number of photoelectrons from (5.1) is

$$\sigma_e = \sqrt{\eta N_{\text{ph}}} \quad (5.5)$$

The dark current and signal electrons are treated in the same way by the charge-to-voltage conversion, and so is their shot noise. The readout noise with standard deviation  $\sigma_R$  represents all electronic noise in the system, generated in any part of the signal chain. The ADC quantisation noise has standard deviation  $\sigma_q = 1/\sqrt{12}$  ADU and should be negligible in a well-designed system. All noise sources are considered to be statistically independent, therefore the output noise variance is the quadrature sum of all of them.

$$\sigma_S^2 = \frac{1}{K^2} (\sigma_e^2 + \sigma_d^2) + \sigma_R^2 + \sigma_q^2 \quad (5.6)$$

In equation (5.6) all noise sources are dimensionless, however,  $\sigma_e$  and  $\sigma_d$  are expressed in electrons, while  $\sigma_S$ ,  $\sigma_R$  and  $\sigma_q$  are in ADU.

Characterising a sensor requires an experimental setup capable of providing light with controlled wavelength, intensity, uniformity and timing. Some measurements, for example the QE and the MTF are much more challenging than the 'easy ones' such as the linearity, and require sophisticated, and often expensive equipment. Many systems are not built to deal with a complete sensor characterisation. In its simplest form, a characterisation setup can comprise nothing more than a sensor and an LED in a light-tight box.

A full characterisation system (figure 5.6) would include a light source, monochromator, targets and optics, calibrated photodiodes, shutter, x-ray source and temperature control of the sensor.

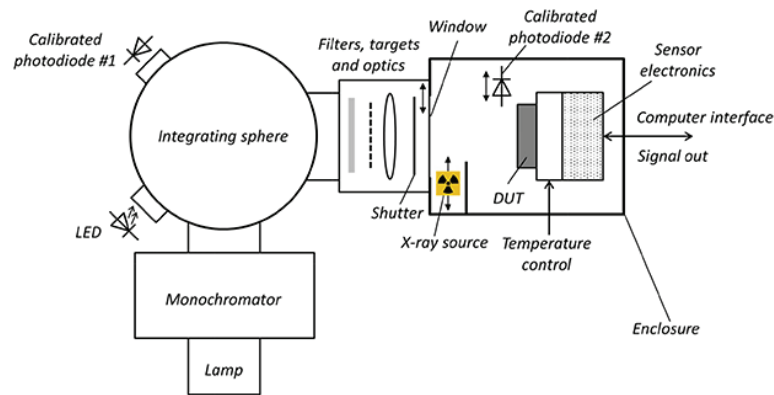


**Figure 5.6.** General diagram of a full optical characterisation setup.

The light source is usually a halogen lamp, but xenon arc or deuterium lamps can be used for UV wavelengths. The monochromator is used to select a narrow spectral line from the incoming broadband light for wavelength-dependent measurements such as the QE and the MTF. When narrowband light is not needed, LEDs with different dominant wavelengths can be used instead.

The integrating sphere provides a uniform output light beam from the source through multiple diffuse reflections off its inner wall. Various filters, targets (for MTF measurements) and focusing optics can then be used to project patterned or uniform light on the device under test (DUT). Sophisticated experimental apparatus covering wavelengths from vacuum UV to NIR, which is challenging to achieve with integrating spheres, has been developed [3] for demanding space-based imaging.

The first photodiode monitors the stability of the light source and provides a reference measurement. Diodes with well-known photoresponse are available with traceable calibration curve, for example referenced to the US National Institute of Standards and Technology (NIST) calibration sources. The second photodiode is used to determine the photon flux reaching the sensor, which can be calculated using the photodiode size and the geometry of the setup.

A low energy x-ray source, typically  $^{55}\text{Fe}$ , is often included in the setup to provide another method for system gain calibration. The x-ray source and the second calibrated photodiode can be moved in and out of the path of the optical beam. In its off-beam position the x-ray source is shielded and has no line of sight to the sensor. If a  $^{55}\text{Fe}$  source is used, the glass cover of the sensor must be removed because the low energy x-rays cannot penetrate it.

The shutter's function is to block any light and ensure a measurement in complete darkness. It can be within the light-tight enclosure too, and can be used to stop both light and x-rays. A normal photography shutter, made with thin steel blades, can easily stop the soft x-rays from a  $^{55}\text{Fe}$  source. A transparent plastic shutter can be used to stop x-rays but not visible light.

Temperature control is often required, or as a bare minimum at least a temperature measurement of the sensor's package. Knowing the sensor's temperature is paramount for dark current measurements. When operating below approximately 15 °C, water vapour could start to condense on the sensor. Therefore, at lower temperatures vacuum enclosures with a window for the incoming light beam must be used.

## 5.4 Photoresponse, non-uniformity and nonlinearity

Determining the photoresponse of a sensor is normally the first thing to do and is also one of the most straightforward. In simple terms, it is just recording the output signal versus the illumination level. There are two ways to do this, as illustrated in figure 5.7: