Factors affecting Quantum Efficiency of High-Performance Cameras

Quantum Efficiency

The quantum efficiency (QE) of a sensor is a measure of its ability to convert photons into a useful output signal. This is obviously a critical parameter to consider when selecting which camera to use for a particular application, after all if a camera doesn't respond to the light you are trying to detect then there's not much point in looking at other specifications, such as array size, readout noise, cooling performance, etc...!

For imaging devices, the QE is defined as the percentage of photons incident per pixel producing a charge (usually electrons) which is successfully stored within the pixel. For example, if a sensor has 75% QE and was illuminated with 100 photons per pixel during an exposure, then in the absence of any noise sources, each pixel would contain a charge of 75 electrons due to 75 photons being absorbed and turned into charge (assuming each detected photon produces one electron within the device). The remaining 25 photons do not generate a measurable charge within the photosensitive volume of the device, possibly due to reflection losses, recombination effects, absorption in a non-photosensitive region or transmission through the device.

Determining whether or not a camera is going to be able to capture images of the quality required by your particular application, can be extremely difficult when looking at the datasheet alone, as not all manufacturers specify the cameras response to light in the same units or under the same conditions. Vendors may quote a detectors photosensitivity in radiometric units such as amps per watt while other may use photometric units, such as volts per lux-second. Historically the sensitivity of film and digital cameras were reported as an ISO number however for low light scientific cameras Raptor Photonics (and many other vendors) now choose to provide a graph of quantum efficiency as a function of wavelength, as shown in Figure 1.

This type of plot should make it possible to determine if a detectable signal will be produced within the sensor for a given set of illumination conditions.

However, this calculation must factor in multiple parameters including the size of the pixels in the detector array, the noise sources associated with the camera system (e.g. read noise and dark noise), the number of photons incident during the exposure time in addition to the wavelength of the illumination. When using QE plots to perform such calculations care must be taken to ensure the units of the quoted QE are understood. For example, is the graph showing relative QE, detective QE or an absolute QE figure? Also is it a fractional figure or a percentage?

In some instances, customers can find themselves looking at different cameras using the exact same image sensor and yet still see differences in the QE plots provided by the different vendors. How can this be the case?

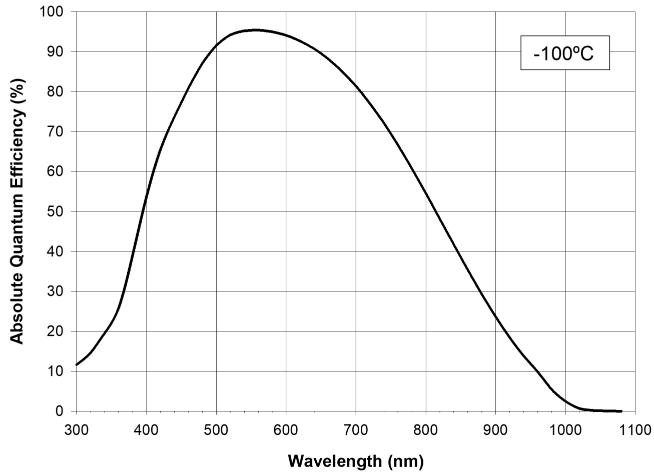

Figure 1: Absolute quantum efficiency for a back-illuminated, standard silicon, CCD with a 'Green' optimized AR coating (courtesy of Teledyne e2v).

Examples of factors affecting Sensor Quantum Efficiency

Sensor Material and Structure

QE is obviously going to be highly dependent upon the materials from which the image sensor is constructed. In order to produce a detectable signal from any photons, firstly the photons must make it to the photosensitive region of the sensor.

Secondly the photons (ideally all of them) should be absorbed within this photosensitive region, each producing a charge stored within the pixel where they were absorbed, before being read out to produce an image. In practice the ideal situation is not achievable as there are many loss mechanisms which limit a sensors ability to convert incident photons into charge.

The majority of scientific sensors used for the detection of visible wavelengths are made from doped silicon. The interaction of light with the silicon material determines the limits of the useful detection range in such devices. As the photon wavelength increases the absorption length also increases, meaning that typically photons will travel further into the silicon before being absorbed (and generating charge). This is OK until the absorption length is so long that most of the absorption occurs outside of the photosensitive region of the device, i.e the detector is becoming increasingly transparent to the longer wavelength photons. Under these conditions most absorbed photons no longer produce a charge which is stored in the pixels of the device and as a result the QE plot for silicon detectors falls off at longer wavelengths. Increasing the depth of the photosensitive region (such as using deep depletion or red enhanced silicon as the base material for the device) can increase QE in the near-IR part of the spectrum for silicon-based sensors, however increasing the photon wavelength beyond ~1150nm means that the photon energy becomes smaller than the band gap of silicon. At these wavelengths absorption of a photon does not provide enough energy to produce charge within the pixel and so the QE falls towards zero. Detection of these wavelengths is possible using a different sensor material, such as InGaAs which has an excellent response for wavelengths up to approximately 1700nm.

At the blue end of the visible spectrum (and into the UV) the absorption length in silicon decreases and so most photons will be absorbed near the surface on which they are incident. Front illuminated CCDs have polysilicon gates on the illuminated surface and this electrode structure prevents the photons from reaching the photosensitive region, resulting in the characteristic fall off in QE at shorter wavelengths. Back-illuminated sensors avoid this issue as the illumination does not have to pass through any electrode structure before reaching the photosensitive region, however the back thinning process must be done well to minimize any oxide layer and 'dead-region' near the surface of the device to provide high QE in both the UV and soft x-ray regions.

Anti Reflection Coatings

As described above, using back-illumination can minimize absorption of photons before they reach the photosensitive region of the image sensor. However, silicon is a high refractive index material and therefore reflection at the detector surface can prevent a large fraction of incident photons from being detected, as they never reach the photosensitive region of the sensor. One way to mitigate this effect is to apply an anti-reflection (AR) coating to the surface of the sensor thereby minimizing reflection losses and allowing transmission of more photons into the device. AR coatings can be tuned (by the sensor manufacturer) to optimize the sensor QE for different regions of the UV-visible-NIR spectrum on silicon devices. Single layer coatings can provide a dramatic increase in sensor QE across a wide range of wavelengths but generally have a peak at a certain region of the spectrum. Multi-layer AR coatings can also be applied to give a broader 'top-hat' shape to the sensor QE curve.

In some applications, such as direct detection of soft x-rays, uncoated devices may be preferred / required, as the AR coating can prevent some photon energies reaching the photosensitive region of the detector.

Detectors fabricated from other materials, such as InGaAs, also benefit from the use of AR coatings to minimize reflections.

Cover Glass / micro-lenses

Many sensor packages and camera systems will protect the sensor from dust / foreign object debris with a transmissive glass cover. In the case of cooled sensors, the window material forms part of the sensor enclosure used to prevent condensation forming on the sensor surface. The optical properties of the material used for the cover glass or entrance window will obviously affect the QE of the overall camera system as all photons must pass through it before reaching the detector, so reflection and absorption losses at this stage must be minimized. A range of materials are used for this purpose including BK7 glass, fused silica and sapphire, again AR coated components are typically used to minimize reflection losses.

Most scientific CCD sensors (excluding interline devices) have close to 100% fill factors. This means virtually 100% of the pixel area has a response to light intrinsic to the material from which the sensor is made. However, CMOS pixel designs typically have a small photosensitive area in each pixel surrounded by on-chip circuitry / components which are not sensitive to light. This produces pixels which have a small fill factor and a device with a poor response to light, as the number of photons detected per pixel area would be a small fraction of the total number incident per pixel.

Thankfully micro-lens arrays can be used to steer a high fraction of the light incident on the pixel into the photosensitive region and in some cases achieve peak QE values of ~80%. Typically micro-lens materials have poor transmission in the UV region and must be designed carefully to maximize the wavelength range over which they effectively steer light into the photosensitive area. Attempting to couple another optical component directly onto a micro-lens array, eg. by using coupling gel or adhesive will negate the effectiveness of the micro-lenses and revert the sensor to a poor response / low fill factor state.

Micro-lens arrays are also used on interline CCD devices, again to steer light away from the on-chip structures which are not sensitive to light, in this case the vertical shift registers, and achieve high fill factor pixel performance.

Temperature

Temperature is another parameter that will alter the QE of an imaging device. Many cameras are designed to operate with the image sensors cooled to relatively low temperatures <-80°C. Such cooling can be necessary to reduce the thermally generated dark signal produced within the pixels of the imaging device in the absence of any light. This dark signal could otherwise limit the usable dynamic range of the sensor and introduce a large dark noise component resulting in reduced image quality. The downside to cooling the sensor is that the QE of the device actually decreases the more the image sensor is cooled, this is particularly evident in the NIR response of silicon-based detectors as shown in Figure 2. There are many factors contributing to this QE change, however a primary cause is that the band gap increases slightly at lower temperatures, reducing the probability of a photon being absorbed and creating an electron-hole pair. Many camera vendors provide QE plots for the image sensors used within their cameras which represent the device performance at room temperature, however they neglect to mention that this is not the response the customer will obtain when the sensor is cooled to the operating temperature within the camera. When comparing QE graphs from different datasheets it is very important to confirm that the plot illustrates the performance of the device at the actual operating temperature used.

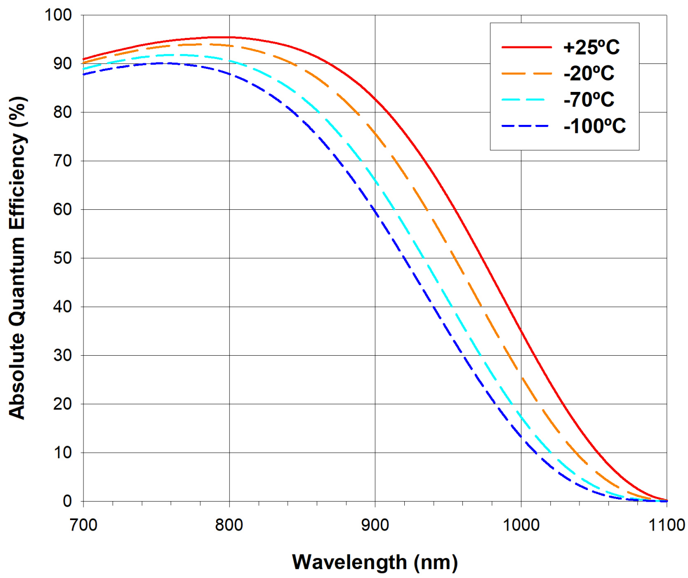

Figure 2: Temperature variation of the absolute quantum efficiency for a back-illuminated, deep depletion CCD with a 'NIR' optimized AR coating (courtesy of Teledyne e2v).

Conclusion

It can be very tricky to evaluate and compare different camera sensitivities based solely on the manufacturers datasheets. When attempting such calculations it is important to ensure like for like comparisons are being made, this requires the units for the various camera performance parameters to be identical and unambiguous. In addition care should be taken to check that the quoted parameters, such as QE, are actually applicable to the device under the operating conditions intended to be used. It may be worthwhile also evaluating which operating conditions are best suited to your application, for example in some NIR detection applications, if short exposures are to be used (i.e. dark signal will have a minimal impact on the acquired images) it may be advantageous to maintain the sensor at a slightly warmer temperature than the headline cooling figure on the camera datasheet, so that you can utilize the higher QE values and still not suffer from dark signal effects.

Determining the best selection of camera for your application can be a challenging and complex decision to make, our experienced engineering team at Raptor Photonics would welcome the opportunity to assist camera users in making this choice, please contact us directly at sales@raptorphotonics.com

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