Are large pixels always more sensitive?

There is a common myth that larger pixel size image sensors are always more sensitive than smaller pixel size image sensors. This isn't always the case, though. To explain why this is more a myth than a fact, it is a good idea to look at how the pixel size of an image sensor has an impact on the image quality, especially for the overall sensitivity, which is determined by the quantum efficiency.

Quantum efficiency

The "quantum efficiency" (QE) of a photo detector or image sensor describes the ratio of incident photons to converted charge carriers which are read out as a signal from the device. In a CCD, CMOS, or sCMOS camera, it denotes how efficiently the camera converts light into electric charges, which makes it a very good parameter to compare the sensitivity of such a system. When light or photons fall onto a semiconductor - such as silicon - there are several loss mechanisms.

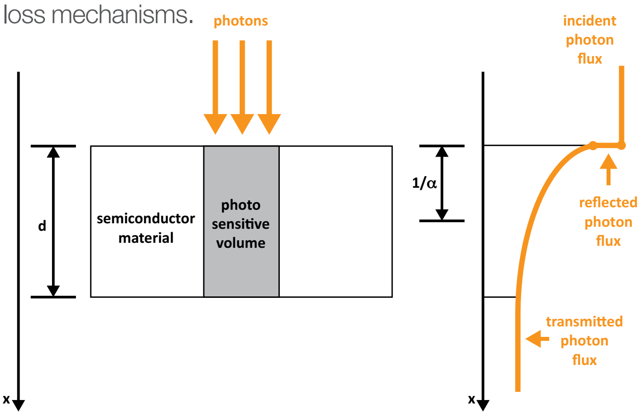

Figure 1: Semiconductor material with the thickness, d, and a light sensitive area or volume which converts photons into charge carriers. The graph shows what happens with the photon flux across the light penetration into the material[1].

Figure 1 shows the photons impinging on a semiconductor with a light-sensitive area. The figure also shows a curve, which represents the photon flux when the light hits the semiconductor and partially travels through it. As the orange curve of the photon flux shows, a part of it is lost at the surface via reflection, therefore a proper anti-reflective coating has a high impact on this loss contribution.

Following this, a part of the photon flux is converted into charge carriers in the light-sensitive part of the semiconductor, and a remaining part is transmitted. Using this illustration, the quantum efficiency can be defined as:

$$QE = (1 - \mathrm{R}) \cdot \zeta \cdot (1 - e^{-\alpha \cdot d})$$

with:

$(1 - \mathrm{R})$ Reflection at the surface, which can be minimized by appropriate coatings

ζ Part of the electron-hole pairs (charge carriers), which contribute to the photo current, and which did not recombine at the surface.

$(1 - e^{-\alpha \cdot d})$ Part of the photon flux, which is absorbed in the semiconductor. Therefore the thickness d should be sufficiently large, to increase that part.

Due to the different absorption characteristics of silicon, as a basic material for these image sensors, and due to the different structures of each image sensor, the QE is spectrally dependent.

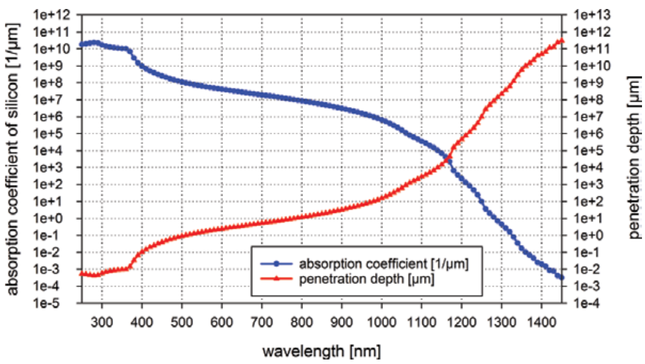

Figure 2: Measured absorption coefficients and penetration depth from silicon as material used in solar cells[2].

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This is illustrated in figure 2, which shows the spectrally dependent absorption coefficient (see fig. 2 – blue curve) of silicon as used in solar cells. The second curve (see fig. 2 – red curve) depicts the penetration depth of light in silicon and is the inverse of the blue curve. In this scenario, it is very likely that the material used had no AR-coating. This paper by Green and Keevers[2] also measured the spectrally dependent reflectivity of silicon. This is shown in figure 3. The curve represents the factor R in the above equation for the quantum efficiency.

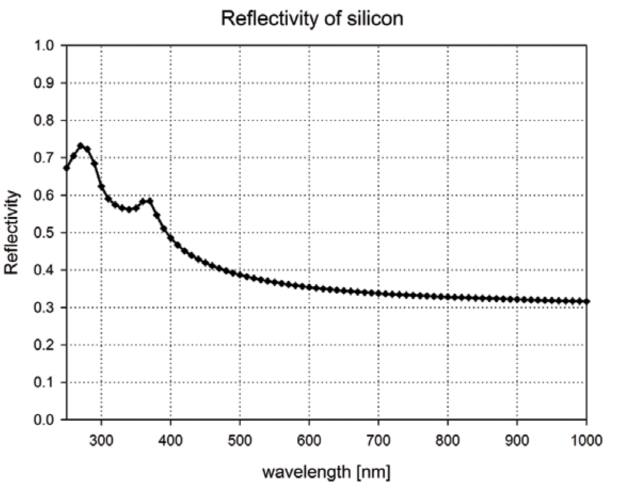

Figure 3: Measured reflectivity of silicon as material used in solar cells[3].

For camera systems, it is usually the QE of the whole camera system which is given. This includes non-material-related losses like fill factor and reflection of windows and cover glasses. In data sheets, this parameter is given as a percentage, such that a QE of 50 % means that on average two photons are required to generate one charge carrier (electron).

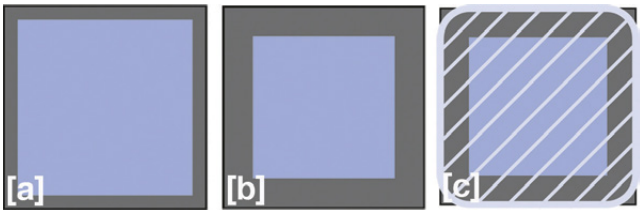

Figure 4: Pixels with different fill factors (blue area corresponds to light sensitive area): [a] pixel with 75 % fill factor, [b] pixel with 50 % fill factor and [c] pixel with 50 % fill factor plus micro lens on top.

Pixel size & fill factor

The fill factor (see figure 4) of a pixel describes the ratio of light sensitive area versus total area of a pixel, since a part of the area of an image sensor pixel is always used for transistors, wiring, capacitors, or registers, which belong to the structure of the pixel of the corresponding image sensor (CCD, CMOS, sCMOS). Only the light sensitive part might contribute to the light to charge carrier conversion which is detected.

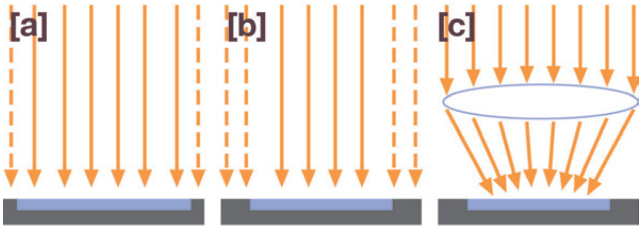

Figure 5: Cross sectional view of pixels with different fill factors (blue area corresponds to light sensitive area) and the light rays which impinge on them (orange arrows). Dashed light rays indicate that this light does not contribute to the signal: [a] pixel with 75 % fill factor, [b] pixel with 50 % fill factor and [c] pixel with 50 % fill factor plus micro lens on top.

In case the fill factor is too small[4], it is usually improved with the addition of micro lenses. The lens collects the light impinging onto the pixel and focuses the light to the light sensitive area of the pixel (see figure 5).

Fill factor	Light sensitive area	Quantum efficiency	Signal
large	large	high	large
small	small	small	small
small + micro lens	larger effective area	high	large

Table 1: Correspondences & relations

Although the application of micro lenses is always beneficial for pixels with fill factors below 100 %, there are some physical and technological limitations to consider. (See Table 2)

Pixel size & optical imaging

Figure 6 demonstrates optical imaging with a simple optical system based on a thin lens. In this situation, the Newtonian imaging equation is valid:

$$x_0 \cdot x_i = f$$

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Limitations	
Size limitation for micro lenses	Although micro lenses up to 20 µm pixel pitch can be manufactured, their efficiency gradually is decreased above 6-8 µm pixel pitch. The increased stack height, which is proprotional to the covered area, is not favorable as well.[5]
Front illuminated CMOS pixels have limited fill factor	Due to semi-conductor processing requirements for front-illuminated CMOS image sensors, there must always be a certain pixel area covered with metal, which reduces the maximum available fill factor.
Large light sensitive areas	Large areas are difficult to realize because the diffusion length (and therefore the probability for recombination) increases. Although image sensors for special applications have been realized with 100 µm pixel pitch.

Table 2: Some limitations

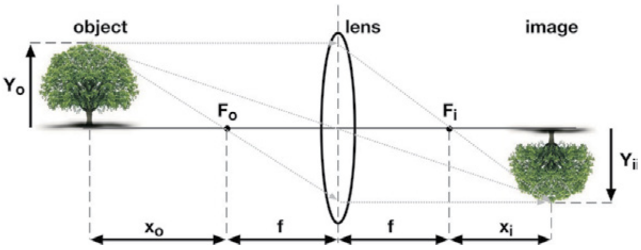

Figure 6: Optical imaging with a simple optical system based on a thin lens and characterized by some geometrical pa-rameters: f - focal length of lens, F_o - focal point of lens on object side, F_i - focal point of lens on image side, x_o - dis-tance between F_o and object = object distance, x_i - distance between F_i and image, Y_o - object size, Y_i - image size

Or the Gaussian lens equation:

$$\frac{1}{f} = \frac{1}{(x_0 + f)} + \frac{1}{(x_i + f)}$$

and the magnification, M, is given by the ratio of the image size Y_i to the object size Y_0:

$$M = \left|\frac{Y_i}{Y_0}\right| = \left|\frac{f}{x_0}\right| = \left|\frac{X_i}{f}\right|$$

Pixel size & depth of focus / depth of field[6]

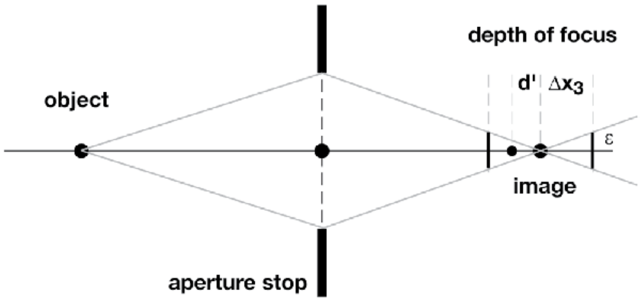

Figure 7: Illustration of the concept of depth of focus, which is the range of image distances in which the blurring of the image remains below a certain threshold.

The image equation (chapter 2) determines the relation between object and image distances. If the image plane is slightly shifted or the object is closer to the lens system, the image is not rendered useless. Rather, it gets more and more blurred the larger the deviation from the distances becomes, given by the image equation.

The concepts of depth of focus and depth of field are based on the fact that for any given application only a certain degree of sharpness is required. For digital image processing, it is naturally given by the size of the pixels of an image sensor. It makes no sense to resolve smaller structures but to allow a certain blurring. The blurring can be described using the image of a point object, as illustrated in figure 6. At the image plane, the point object is imaged to a point. It smears to a disk with the radius, e, (see figure 7) with increasing distance from the image plane.

Introducing the f-number $f_{/\#}$ of an optical system as the ratio of the focal length f_0 and diameter of lens aperture D_0:

$$f_{/\#} = \frac{f_0}{D_0}$$

the radius of the blur disk can be expressed:

$$\varepsilon = \frac{1}{f_{/\#}} \cdot \frac{f_0}{(f_0 + d')} \cdot \Delta x_3$$

where Δx_3 is the distance from the (focused) image plane. The range of positions of the image plane, [d' - Δx_3, d' +Δx_3], for which the radius of the blur disk is lower than ε,

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is known as depth of focus. The above equation can be solved for Δx_3 and yields:

$$\Delta x_3 = f_{/\#} \cdot \left(1 + \frac{d'}{f_0}\right) \cdot \varepsilon = f_{/\#} \cdot (1 + |M|) \cdot \varepsilon$$

where M is the magnification from chapter 2. This equation shows the critical role of the f-number for the depth of focus.

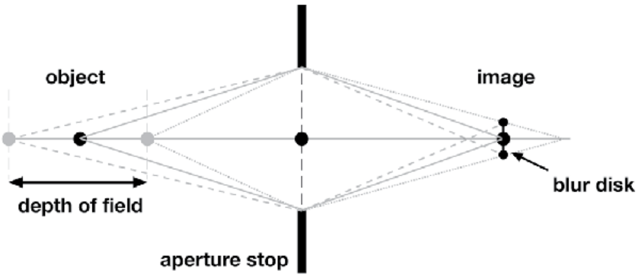

Figure 8: Illustration of the concept of depth of field. This gives the range of distances of the object in which the blurring of its image at a fixed image distance remains below a given threshold.

Of even more importance for practical usage than the depth of focus is the depth of field. The depth of field is the range of object positions for which the radius of the blur disk remains below a threshold ε at a fixed image plane.

$$d \pm \Delta x_3 = \frac{-f^2}{d' \mp f_{/\#} \cdot (1 + |M|) \cdot \varepsilon}$$

In the limit of $|\Delta x_3| \ll d$ we obtain:

$$|\Delta x_3| \approx f_{/\#} \cdot \frac{1 + |M|}{M^2} \cdot \varepsilon$$

If the depth of field includes infinite distance, the depth of field is given by:

$$d_{min} \approx \frac{{f_0}^2}{2 \cdot f_{/\#} \cdot \varepsilon}$$

Generally, the whole concept of depth of field and depth of focus is only valid for a perfect optical system. If the optical system shows any aberrations, the depth of field can only be used for blurring significantly larger than those caused by aberrations of the system.

Pixel size & comparison total area / resolution

If the influence of the pixel size on the sensitivity, dynamic, image quality of a camera should be investigated, there are various parameters that could be changed or kept constant. In this section, we'll follow different pathways to try to answer this question.

Constant Area

constant => image circle, aperture, focal length, object distance & irradiance,

variable => resolution & pixel size

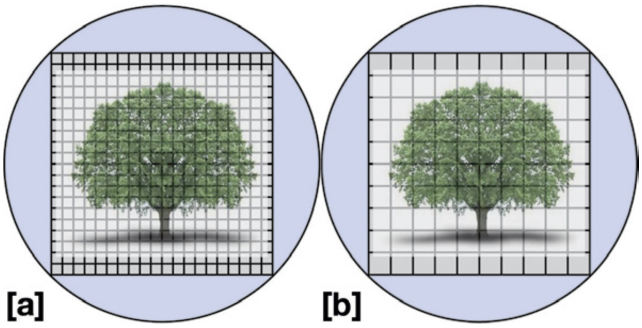

Figure 9: Illustration of two square shaped image sensors within the image circle of the same lens, which generates the image of a tree on the image sensors. Image sensor [a] has pixels a quarter the size area of the pixels of sensor [b].

For ease of comparison, we shall assume square shaped image sensors. These are fit into the image circle or imaging area of a lens. For comparison, a homogeneous illumination is assumed. Therefore, the radiant flux per unit area, also called irradiance E [W/m^2], is constant over the area of the image circle. Let us assume that the left image sensor (fig. 9, sensor [a]) has smaller pixels but higher resolution — e.g. 2000 x 2000 pixels at 10 µm pixel pitch — while the right image sensor (fig. 9, sensor [b]) subsequently has 1000 x 1000 pixels at 20 µm pixel pitch.

The question would be, which sensor has the brighter signal and which sensor has the better signal-to-noise-ratio (SNR)? To answer this question, it is possible to either look at a single pixel, which neglects the different resolution, or to compare the same resolution with the same lens, but this corresponds to comparing a single pixel with 4 pixels.

Generally, it is also assumed that both image sensors have the same fill factor of their pixels. The small pixel measures the signal, m, which has its own readout noise, r0, and therefore a signal-to-noise-ratio, s, could be determined for two important imaging situations:

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low light (s0), where the readout noise is dominant and bright light (s1), where the photon noise is dominant.

Pixel type	Signal	Readout noise	SNR low light	SNR bright light
Small pixel	m	r_0	s_0	s_1
Large pixel	4 x m	> r_0	> s_0	> s_1
4 small pixel	4 x m	2 x r_0^7	2 x s_0	2 x s_1

Table 3: consideration on signal and SNR for different pixel sizes same total area

Still, the proportionality of SNR to pixel area at a constant irradiance is valid, meaning the larger the pixel size and therefore the area, the better the SNR will be. However, this ultimately means that one pixel with a total area that fits into the image circle has the best SNR:

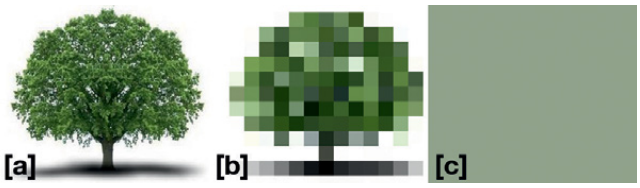

Figure 10: Illustration of three resulting images which were recorded at different resolutions: a) high resolution, b) low resolution and c) 1 pixel resolution

Assume three image sensors with the same total area, which all fit into the image circle of a lens, but all three have different resolutions. As seen in figure 10, a) shows the clearest image but has the worst SNR per pixel. Figure 10 b), the SNR / pixel is better, but due to the smaller resolution, the image quality is worse compared to a). Finally, figure 10 c) with a super large single pixel shows the maximum SNR per pixel but unfortunately the image content is lost.

Constant Resolution

constant => aperture & object distance,

variable => pixel size, focal length, area & irradiance

Another possibility to compare is whether the number of pixels should be the same at the same object distance. To test this, it would be necessary to change the focal length of the lens in front of the image sensor with the small pixels. Since the information (energy),

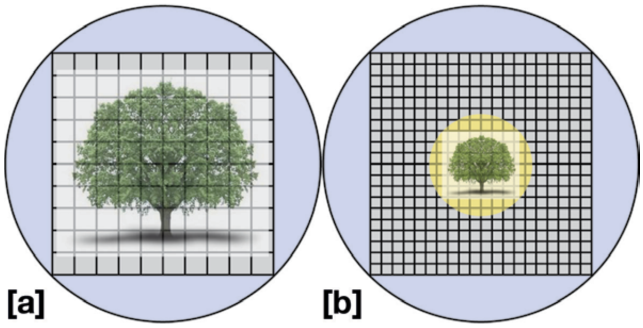

Figure 11: Illustration of two square shaped image sensors within the image circle of the same lens type (e.g. f-mount). The tree is imaged to the same number of pixels which require lenses with different focal lengths: Image sensor [a] has pixels with 4 times the area of the pixels of sensor [b].

which before was spread to a larger image area, now has to be "concentrated" to a smaller area (see figure 11 and 12).

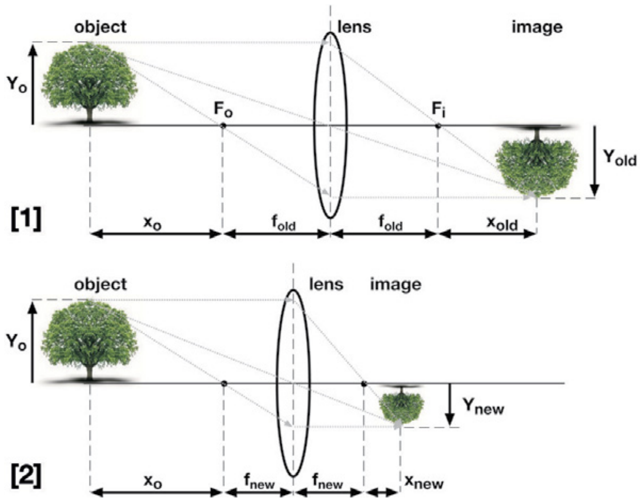

Figure 12: Illustration of two imaging situations, which are required for comparison: [1] this is the original lens which images completely to the large pixel sensor - [2] this is the lens with the changed focal length, which images to the smaller pixel size sensor

If, for example the resolution of the image sensor is 1000 x 1000 pixels, and the sensor with the smaller pixels has a pixel pitch of half the dimension of the larger pixel sensor, the image circle diameter d_{old} of the larger pixel sensor amounts to $\sqrt{2}\cdot$ with c = width or height of the image sensor. Since the smaller pixel sensor has half the pitch, it also has half the width and

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height and half the diagonal of the "old" image circle, which gives:

$$d_{new} = \frac{\sqrt{2}}{2} \cdot c = \frac{1}{\sqrt{2}} \cdot c$$

To get an idea of the required focal length, it is possible to determine the new magnification M_{new} and subsequently the required focal length f_{new} of the lens (see chapter 2 and figure 9), since the object size, Y_0, remains the same:

$$M_{new} = \frac{|Y_{new}|}{Y_0} = \frac{\frac{|Y_{old}|}{2}}{Y_0} = \frac{1}{2} \cdot M_{old} \; with \; \frac{Y_{new}}{Y_{old}} = \frac{\frac{1}{\sqrt{2}} \cdot c}{\sqrt{2} \cdot c}$$

Since the photon flux, Φ_0, coming from the object or a light source is constant due to the same aperture of the lens (NOT the same f-number!), the new lens with the changed focal length achieves to spread the same energy over a smaller area, which results in a higher irradiance. To get an idea of the new irradiance, we need to know the new area, A_{new}:

$$\frac{A_{new}}{A_{old}} = \frac{\pi \cdot \left(\frac{\frac{1}{\sqrt{2}} \cdot c}{2}\right)^2}{\pi \cdot \left(\frac{\sqrt{2} \cdot c}{2}\right)^2} = \frac{1}{4}$$

With this new area it is possible to calculate how much higher the new irradiance, I_{new}, will be.

$$I_{new} = \frac{\Phi_0}{A_{new}} = \frac{\Phi_0}{\frac{1}{4} \cdot A_{old}} = 4 \cdot \frac{\Phi_0}{A_{old}} = 4 \cdot I_{old}$$

The reason for that discrepancy between the argumentation and the results is within the definition of the f-number $f_{/\#}$:

$$f_{/\#} = \frac{f}{D}$$

Figure 13: Images of the same test chart with the same resolution, same object distance, and same fill factor but different pixel size, and different lens settings (all images have the same scaling for display):

[a] pixel size 14.8 µm x 14.8 µm, f = 100 mm, f-number = 16
[b] pixel size 7.4 µm x 7.4 µm, f = 50 mm, f-number = 16
[c] pixel size 7.4 µm x 7.4 µm, f = 5 0mm, f-number = 8

The lenses are constructed such that the same f-number always generates the same irradiance in the same image circle area. Therefore, the attempt to focus the energy on a smaller area for the comparison is not accomplished by keeping the f-number constant. It is the real diameter of the aperture, D, which has to be kept constant. Therefore, the new f-number would be, if the old f-number was f/#=16 (see example in figure 13):

$$f_{/\#new} = \frac{f_{new}}{D_0} = \frac{f_{new}}{\left(f_{old} / f_{/\#old}\right)} = \frac{f_{new}}{f_{old}} \cdot f_{/\#old} = \frac{50}{100} \cdot 16 = 8$$

Again the question would be which sensor has the brighter signal and which sensor has the better signal-to-noise-ratio (SNR)? This time we look at the same number of pixels but with different size, but due to the different lens at the same aperture, the irradiance for the smaller pixels is higher. Still, it is assumed that both image sensors have the same fill factor of their pixels.

Pixel type	Signal	Readout noise	SNR low light	SNR bright light
Small pixel	m	r_0	s_0	s_1
Large pixel	m	$> r_0$	$< s_0$	s_1

Table 4: consideration on signal and SNR for different pixel sizes same resolution

If now the argument would be that the larger f-number will cause a different depth of field, which will in turn change the sharpness of the image and therefore the quality, the equation from chapter 3 can be used to look at the consequences.

From the above example we have the focal lengths f_{old} = 100 mm and f_{new} = 50 mm, and we are looking for the right f-number to have the same depth of field. Therefore:

$$\frac{f_{old}^2}{2 \cdot f_{/\#old} \cdot \varepsilon} = \frac{f_{newold}^2}{2 \cdot f_{/\#new} \cdot \varepsilon} <=> f_{/\#new} \frac{f_{new}^2}{f_{old}^2} \cdot f_{/\#old} = \frac{50^2}{100^2} \cdot 16 = 4$$

From the above example we have the focal lengths fold = 100 mm and fnew = 50 mm, and we are looking for the right f-number to have the same depth of field. Therefore:

Since we have calculated a f-number = 8 for the correct comparison, the depth of field for the image sensor with the smaller pixels is even better.

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Pixel size & fullwell capacity, readout noise, dark current

The fullwell capacity of a pixel of an image sensor is an important parameter which determines the general dynamic of the image sensor and therefore also for the camera system. Although the fullwell capacity is influenced by various parameters like pixel architecture, layer structure, and well depth, there is a general correspondence also to the light sensitive area. This is also true for the electrical capacity of the pixel and the dark current, which is thermally generated. Both, dark current and capacity[8] , add to the noise behavior, and therefore larger pixels also show larger readout noise.

Pixel type	Light sensitive area	Fullwell capacity	Dark current	Capacity	Readout noise
Small pixel	small	small	small	small	small
Large pixel	large	large	large	large	large

Table 5: consideration on fullwell capacity, readout noise, dark current

How to compare cameras with respect to pixel size & sensitivity

Generally, it is a good idea to image the same scene to each camera, which means:

- Keep the object distance and the illumination constant!

If the cameras should be compared, they should use the same resolution, which either means analogue binning or mathematical summation or averaging, or usage of a region/area of interest.

- Keep or adjust the same resolution for all cameras!

Then select a proper focal length for each camera, whereas each camera should see the same image on the active image sensor area.

- Select corresponding lens with the appropriate focal length for each camera!
- Adjust the lens with the largest focal length with the largest useful f-number!

For a proper comparison, use the equation for the f-number on page 6, keep the aperture D constant, and calculate the corresponding f-number for the other lenses and adjust them as good as possible - then compare the images!

- Adjust the f-numbers of the other lenses in such a way that the aperture of all lenses is equal (similar)!
- Compare for sensitivity!

Are image sensors with larger pixels more sensitive than smaller pixels?

No, because the sensitivity has nothing to do with the size of the pixel. In a given optical set-up, the image sensor with the larger pixels will give a larger signal at a lower resolution due to the larger collection area. But the parameter to look at, in case a more sensitive image sensor is required, is the quantum efficiency, and it is spectrally dependent. Therefore, the application defines which image sensor is the most sensitive.

END NOTES

1 Graphic has been inspired by figure 17.1-1 from “Fundamentals of Photonics”, B.E.A. Saleh and M.C. Teich, John Wiley & Sons, Inc., 1991.

2 Data are taken from Green, M.A. and Keevers, M. “Optical properties of intrinsic silicon at 300 K”, Progress in Photovoltaics, p.189-92, vol.3, no.3; (1995).

3 Data are taken from Green, M.A. and Keevers, M. “Optical properties of intrinsic silicon at 300 K”, Progress in Photovoltaics, p.189-92, vol.3, no.3; (1995).

4 The fill factor can be small for example: the pixel of an interline transfer CCD image sensor, where 35 % of the pixel area is used for the shift register or the global shutter 5 or 6T pixel of a CMOS sensor, where the transistors and electrical leads cause a 40 % fill factor.

5 For some large pixels it still might be useful to use a less efficient micro lens if, for example, the lens prevents too much light falling onto the periphery of the pixel.

6 This chapter comes from the book “Practical Handbook on Image Processing for Scientific and Technical Applications” by Prof. B. Jähne, CRC Press, chapter 4. Image Formation Concepts, pp. 131 - 132.

7 Since it is allowed to add the power of the readout noise, the resulting noise equals the square root of (4 x r_0^2).

8 The correspondence between pixel area, capacity and therefore kTC-noise is a little bit simplified, because there are newer techniques from CMOS manufacturers like Cypress, which overcome that problem. Nevertheless, the increasing dark current is correct, whereas the sum still follows the area size. Further in CCDs and newer CMOS image sensors most of the noise comes from the transfer nodes, which is cancelled out by correlated double sampling (CDS).

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