Small is Beautiful !

Yes, But Also for Pixels of Digital Still Cameras ?

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In the rat race forever higher pixel counts for the digital still market, it is clear that if the chip size has to remain constant, then “more pixels” inherently means “smaller pixels”. The main driving force to keep the silicon area of the sensor as small as possible is the cost price of the sensor chip. Extra silicon costs quite a bit of money. A larger chip size also requires a larger and more costly lens, extra PCB area, and also a larger volume for the camera body. So, smaller pixels are the key words towards higher resolution sensors on the same silicon area, or towards a smaller chip size with the same resolution!

Unfortunately someone has to pay the bill for these improvements, and in this case it is the overall performance of the pixels. Irrespective of the sensor technology used, be it interline-transfer CCD (IL), frame-transfer CCD (FT), full-frame CCD (FF) or a CMOS imager with passive (PPS) or active pixels (APS), the performance of smaller pixels will deteriorate. Parameters such as light sensitivity, quantum efficiency, saturation level, dynamic range, signal-to-noise ratio and pixel non-uniformity will suffer from the trend towards ever smaller pixels. Very often a pixel of a solid-state imager with its electron packet is compared with a bucket containing water. This analogy helps very much not only in understanding the working principle of the pixels, but also in this discussion to explain the influence of smaller pixels on imaging performance.

Light Sensitivity

A bucket with a larger opening can collect more water faster than a bucket with a smaller opening. The same is true for pixels : the light sensitivity (expressed as the amount of generated electrons per lux incoming light) is directly proportional to the area of the pixels exposed to the incoming light. Changing the pixel size from 5.6 µm to 5.1 µm costs 17 % light sensitivity !

Quantum Efficiency

Every pixel in any kind of technology contains a certain area composed of a kind of dead zone which is not light sensitive. Most of the time this dead zone contains the isolation and separation structures between the pixels. In several technologies, this loss is counteracted by the use of micro-lenses, but never perfectly. In between two micro-lenses for example there will still be a dead space. Changing the pixel size from 5.6 µm to 5.1 µm in a technology with a 0.5 µm dead zone around the pixel (0.25 µm accounted to every adjacent pixel) costs 2 % in quantum efficiency.

Saturation Level

It is clear that the maximum content of water in a small bucket is less than the maximum content of a large bucket, especially if their height is equal. The same is true of course for the pixels of an image sensor. Very often the complete area of a pixel is not able to store charges. For example 90% of the area of FT, FF and PPS pixels can carry photo generated charge, 50% in IL pixels and about 30% in APS. This means that the saturation level deteriorates very quickly with shrinking pixel area. Changing the pixel size from 5.6 µm to 5.1 µm will decrease the saturation level by 17%.

Dynamic Range

The dynamic range, which varies directly with the saturation level, will therefore also shrink directly with the pixel area. Taking the same example as before, shrinking a pixel from 5.6 µm to 5.1 µm costs 17%, or about 1.6 dB of the dynamic range. It might seems that increasing the depth of the bucket will relieve the problem, unfortunately this is not always possible for ever smaller pixels.

This statement about dynamic range is true in the case that the noise floor is determined by thermal noise. In reality this is not always the situation: at elevated temperatures or at long integration times, the dark current noise becomes dominant. The dependency of the dark current noise on the shrinking pixel size is hard to predict: smaller pixels can lead to a smaller dark current, but increased electrical fields in the smaller pixel can give rise to the dark current and its noise.

Signal-to-Noise Level

Assuming equal noise levels in two types of pixels, the one with the lowest light sensitivity or with the lowest quantum efficiency will generate the lowest signal-to-noise level. In a uniform illumination level across the total area of the sensor, the signal of the smaller pixel will be lower by the product of light sensitivity decrease and the quantum efficiency decrease. Lowering the pixel pitch from 5.6 µm to 5.1 µm will cost 19 %, which is about 1.8 dB in signal-to-noise ratio.

Pixel Non-Uniformity

Pixel non-uniformities are caused by technological imperfections. These remain unaltered in absolute value if the pixel size is changed, but become relatively more important if the pixel is designed to smaller dimensions. As an example, the pixel non-uniformity will worsen by 19 % if the pixel size is shrunk from 5.6 µm to 5.1 µm.

Shrinking pixels to come to a higher resolution on the same chip size goes hand in hand with a major deterioration in pixel performance. An important remark must accompany this statement: shrinking pixels occur in parallel with further improvements in sensor technology. This means that the aforementioned examples are only valid if the various pixels are made in the same technology. Researchers are putting a lot of efforts into an improvement of the processing technology so that part of the negative aspects reported here are compensated by new technological developments. Examples for technological improvements are:

- increasing the quantum efficiency by making use of optimized micro-lens shapes or micro-lenses composed of two components,
- increasing the saturation levels by incorporating additional implantants during the production of the imagers,
- improving noise levels by means of technological steps as well as clever circuit design,
- switching to advanced processing techniques for the silicon diffusion.

Also new developments in camera lens design can compensate for losses in sensor performance.

Nevertheless, the smaller the bucket becomes, the less water it can hold!

Biography

Albert J.P. Theuwissen was born in Maaseik (Belgium) on December 20, 1954. He received the degree in electrical engineering and his Ph.D. from the Catholic University of Leuven (Belgium) respectively in 1977 and 1983.

In 1983, he joined the Micro-Circuits Division of the Philips Research Laboratories in Eindhoven (the Netherlands. In 1991 he became Department Head of the division Imaging Devices, including CCD as well as CMOS solid-state imaging activities.

In 1995, he authored a textbook "Solid-State Imaging with Charge-Coupled Devices". He is member of editorial board of the magazine “Photonics Spectra”, an IEEE Fellow and member of SPIE. In March 2001, he became part-time professor at the Delft University of Technology, the Netherlands.