Applied Color Science Technical Note

High Resolution Image Sensors and Lens Performance-

The recent development of high quality multi-megapixel image sensors has revolutionized every aspect of image capture, processing and display. However, for many photographers, both amateur and professional, the transition from silver halide film to silicon-based sensor arrays has not been entirely seamless. One area where the differences between film-based and digital photography have been especially confusing is with regard to lens performance. After all, if I have a lens that gave me great images on my film SLR, it should work even better on my digital SLR, right? Not necessarily.

This article attempts to clarify some of the lens design and image sensor design issues that can be critical for digital camera performance. Hopefully after reading this, you will be able to better understand why some lenses work better with digital cameras and what to look for in a digital camera lens.

Pixel Design-

The basic imaging unit of a digital image sensor is the pixel. What is a pixel? It is nothing more than a tiny area of a silicon device that has been treated to be sensitive to light. (See Figure 1.)

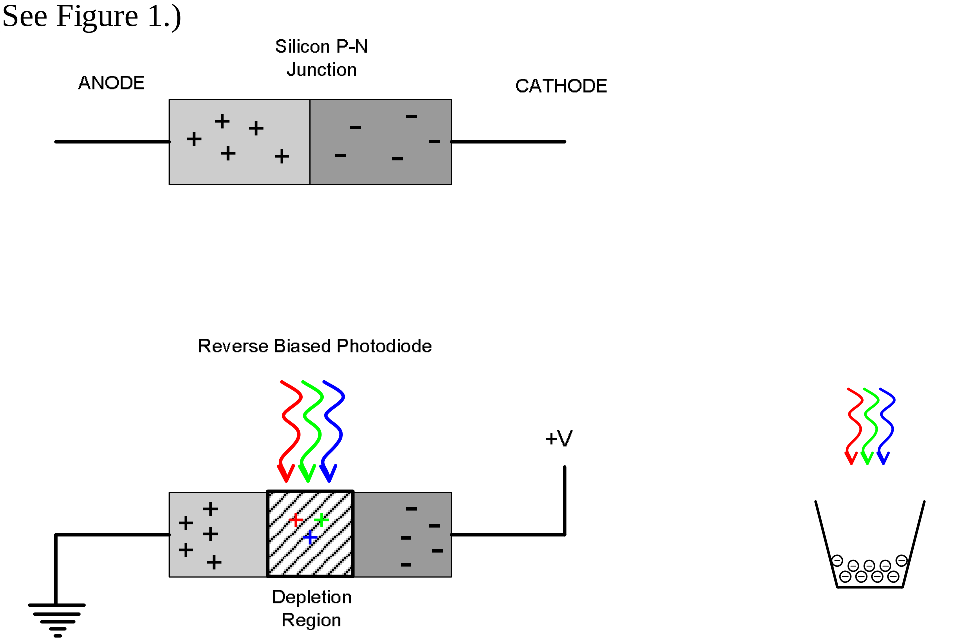


Figure 1 – Pixels = Photodiodes + Storage

When light hits the surface of an image sensor, the pixels react to that light by producing electrons. The brighter the light, the more electrons are produced. These electrons are then converted into an electrical signal that make up the image we see.

A modern image sensor used in digital photography is made up of millions of these pixels arranged into rows and columns (typically) for ease of readout and processing. (See Figure 2.)

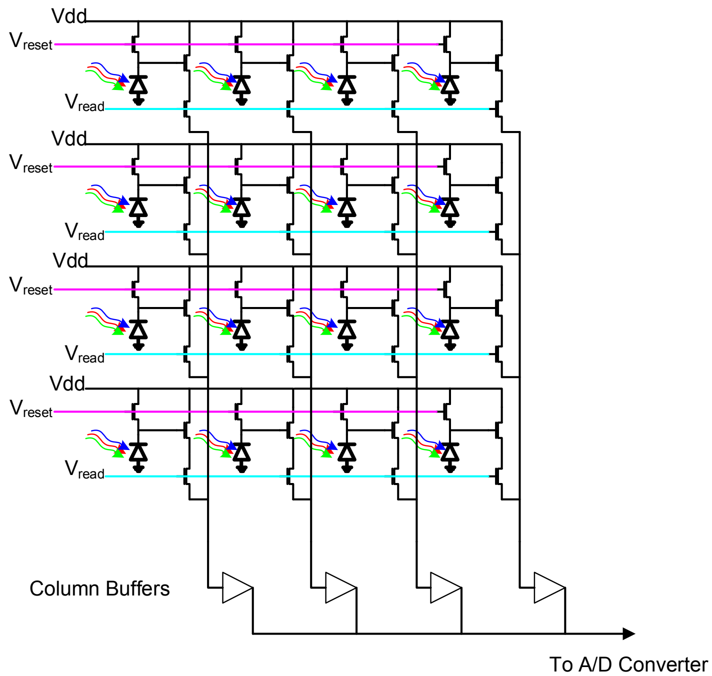


Figure 2 – An array of pixels forms an image sensor

This is one of the main structural differences between ‘conventional’ film and digital imaging devices. In a silver halide film emulsion, the light sensitive grains are ***randomly*** distributed over the light sensitive area, where in a digital camera the light sensing elements are ***uniformly spaced***.

If we dig a little deeper into the structure of a pixel, we can see that there is quite a bit more than ‘meets the eye’. Figure 3 is a cross-section diagram of the microscopic structure of a typical pixel in an image sensor.

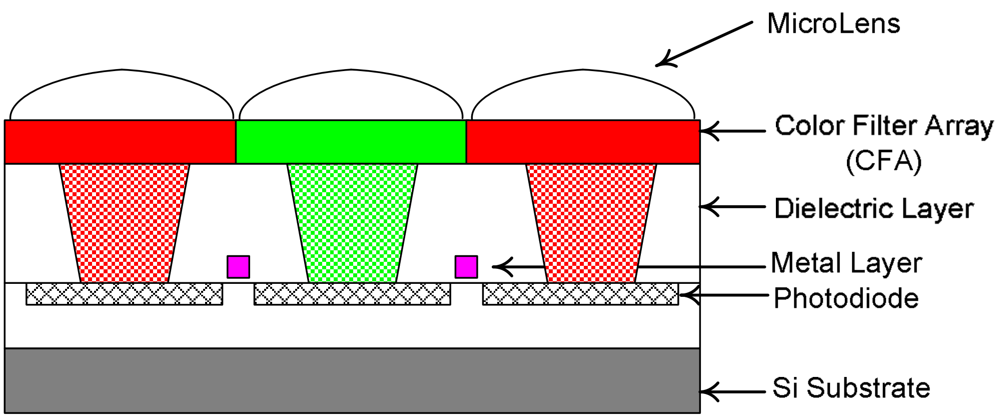


Figure 3 – pixel structure

Going from the bottom up, the layers of a pixel are:

1.) **Substrate:** This is the bottom silicon layer that is used to make the photodiodes and other microelectronic components that make up the image sensor circuits.

2.) **Photodiode:** This is the actual light-sensitive part of the pixel.

3.) **Dielectric Layer:** This is a layer of non-conducting material used in the image sensor fabrication process.

3.) **Metal Layer:** This is a layer of conducting material (Gold or Copper) used in the image sensor fabrication process.

4.) **Color Filter Array:** For single-chip color cameras, this is a microscopic layer of color filter material. The most common arrangement of these filters is known as a **Bayer pattern**, in which **Red, Green and Blue** filters are arranged in alternating rows and columns over the pixel array.

5.) **Microlens:** This is a top layer applied to pixel arrays to increase their light gathering efficiency. As we shall see below, these can have a pronounced effect on how well a camera lens works with an image sensor.

The cross-hatched areas in Figure 3 illustrate the ideal illumination condition where incident light on the image sensor is filtered so that only green light is detected by 'green' pixels and only red light is detected by 'red' pixels.

<u>Lens Design –</u>

Lenses for conventional film-based cameras are designed under the assumption that the image from the lens is formed on a set of photosensitive layers that are relatively insensitive to the ray angle of light from the lens. (See Figure 4.)

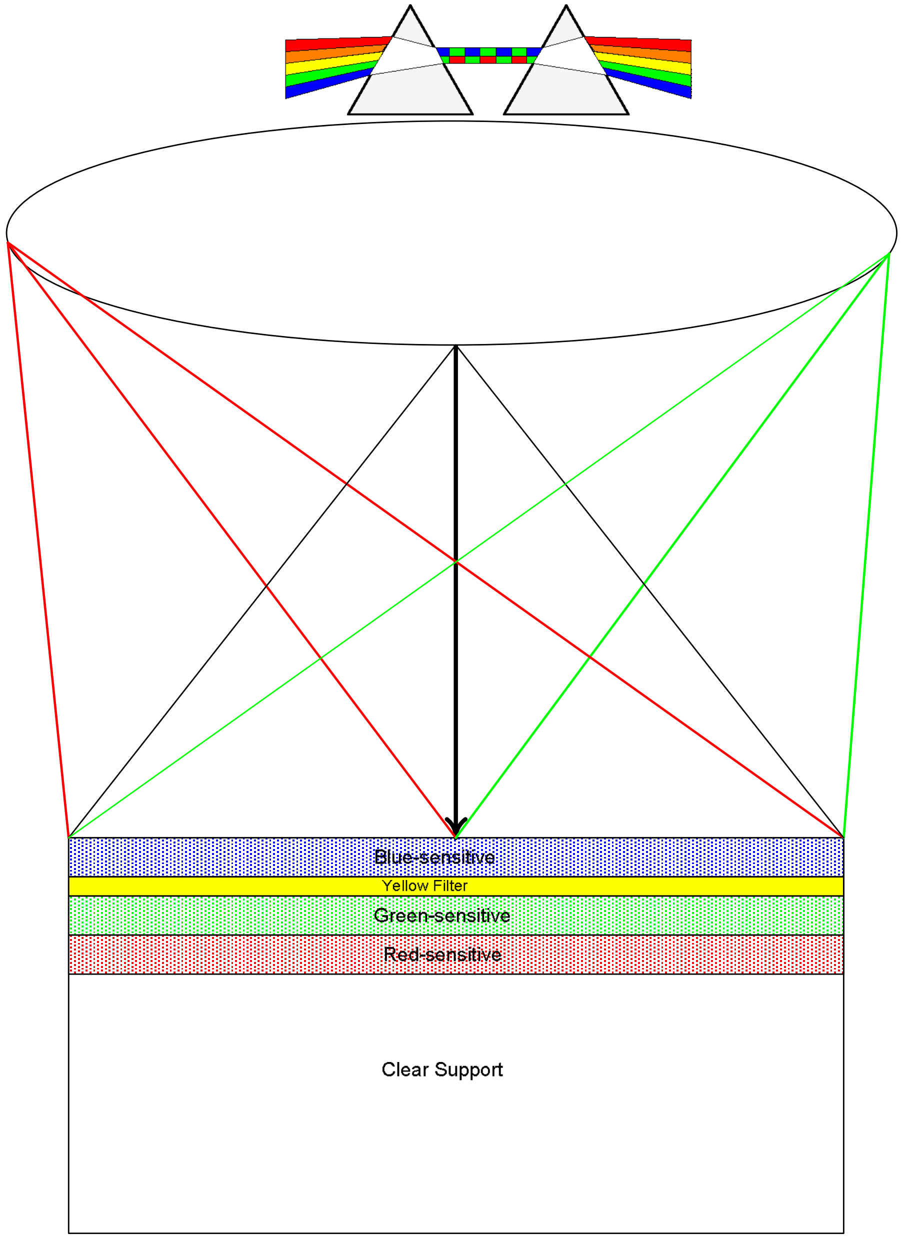


Figure 4. – Conventional film structure and lens ray angles

Using this assumption, image-forming lenses can produce fairly steep ray angles in the image plane without any penalty. To first order, the image formed by rays in the center of the film area and the image formed by rays at the edges of the film area are not affected by the structure of the film, since each image capture layer is composed of randomly oriented photo-sensitive grains.

However, if we apply the same lens design criteria to the image sensor of a digital camera, the results can be quite different. (See Figure 5.)

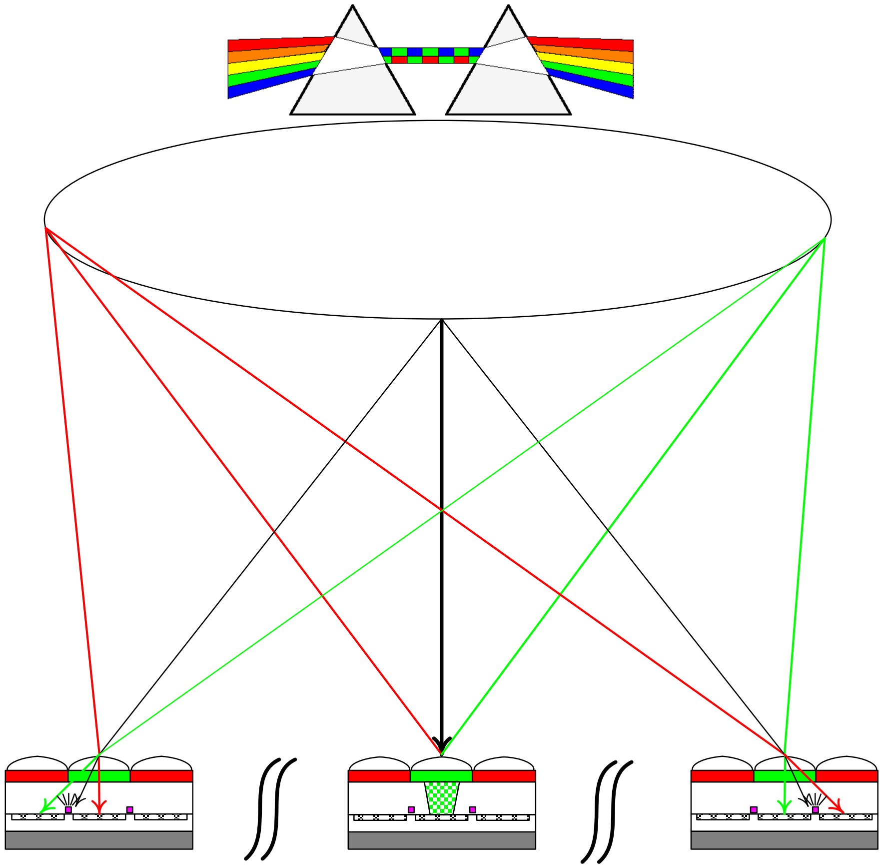


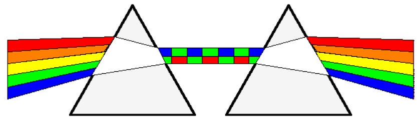
Figure 5 – Pixel structure and image formation

Because of the discrete nature of pixel arrays in image sensors and the presence of microlenses on top of the imaging array, light at the edges of the image sensor array that is incident at too steep a ray angle can actually be detected by a neighboring pixel. The result is that red-filtered light is mixed in with the signal from a green pixel and green-filtered light is mixed in with a red pixel. Additionally, mis-directed light can scatter from metal layers between pixels. These effects are collectively known as “pixel cross-talk” and can produce one or more unwanted image artifacts listed below:

1.) **Reduction in color saturation** – As pixel signals of different colors begin to mix, the ‘purity’ of color response from the color filter array is reduced and images tend to look ‘pastel’ or faded.

2.) **Color fringes on sharp edges** – Portions of an image that contain sharp transitions tend to look ‘softer’ or even have colored fringes around them.

3.) **Colored rings** – Depending on the lens and the type of microlenses on the image sensor, colored rings can appear around the edges of the image where steep ray angles tend to dominate the image.



Pixel Crosstalk Solutions-

Several solutions have been proposed to reduce pixel cross talk caused by lens effects. One technique introduces a **spatial shift of the microlenses** over pixels near the edges of an array so that the principal rays from the lens are shifted back toward the correct photodiode. While this approach may reduce pixel cross talk, the fixed shift in microlens position places a limit on the types of lenses that produce the desired effect. In some cases, using the wrong type of lens with a shifted microlens may actually *increase* the cross talk.

A more reasonable approach is to use lenses in which the ray angles at the edges of the image sensor array don't exceed the acceptance angle of the microlens. One example of this solution is a **telecentric lens.** In a telecentric lens, the chief rays (oblique rays which pass through the center of the aperture stop) are parallel to the optical axis in front of or behind the system, respectively. By ensuring that the chief rays in the image plane are parallel to the image axis, the steep ray angles are eliminated and pixel crosstalk effects are greatly reduced or completely eliminated as shown in Figure 6.

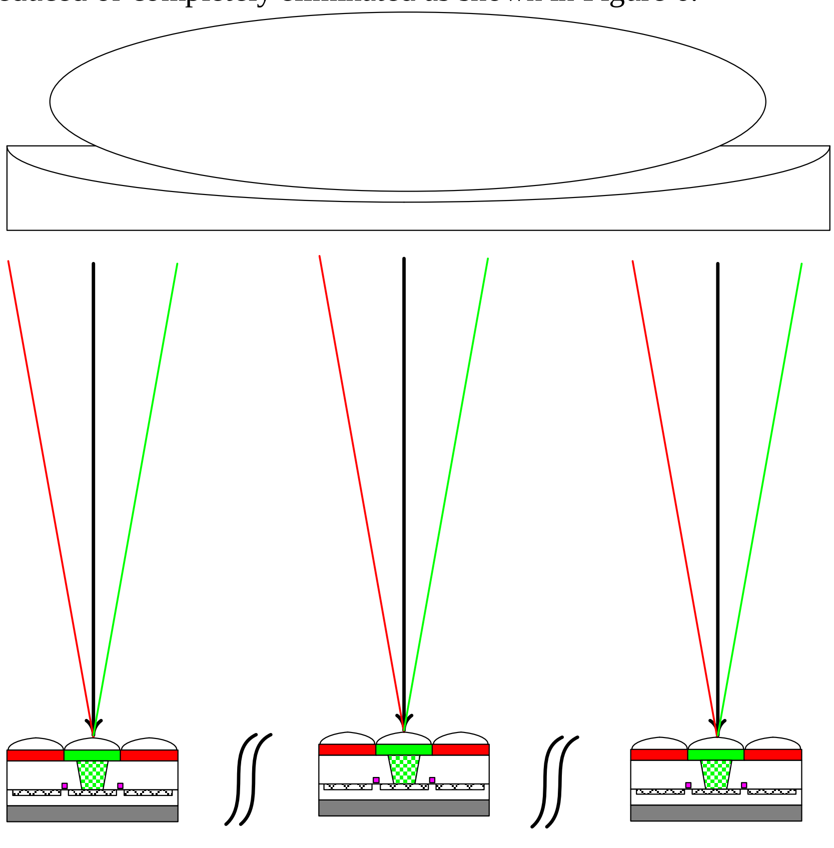


Figure 6 – Pixel structure and image formation – **Telecentric lens**

However, restricting lens choices to strictly telecentric designs may limit the available lens formats and range of lens performance characteristics.

A third alternative for minimizing pixel cross talk is to use lenses which are **near-telecentric,** i.e. – those that limit the chief ray angles in the image plane without requiring them to be parallel. The advantage of this approach is that there is still considerable lens design latitude to produce optical systems with various focal lengths and *f*- numbers, but the pixel cross talk effects are held in check by maintaining a limit on the chief ray angles at the edges of the image sensor. From a lens design perspective, this can be achieved by effectively increasing the image circle of the lens, as shown in Figure 7.

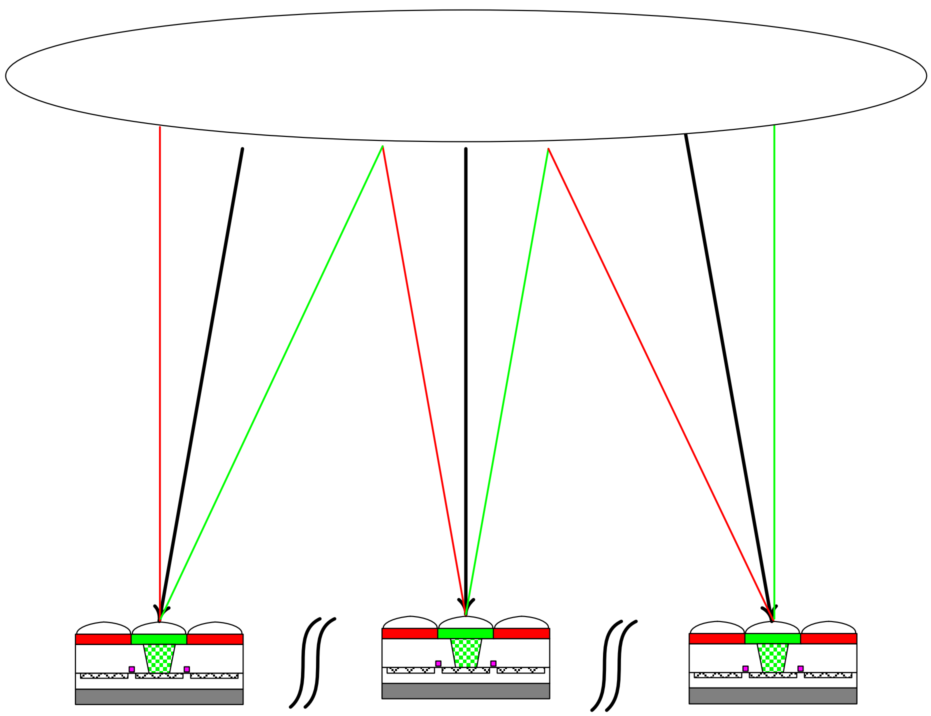


Figure 7. – Image formation – **Near-telecentric lens**

Conclusion –

When choosing lenses for digital photography, the criterion of "it works well with film" does not always apply. If the quality of the captured image is critical (and when isn't it?) then it's best to choose a lens whose design takes into account the properties of today's high resolution image sensors.