1051-465 Detectors Research Paper

Foveon X3 Detector: Real goodies or eyecandy?

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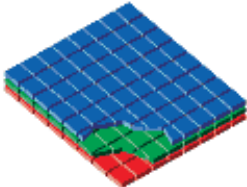
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Abstract

This paper investigates Foveons X3 sensor [6] , which vertically stacks three sensor layer that absorb light of different colors, talks about the operating principle of this type of sensors, and the advantages and disadvantages of such design.

1   Introduction

Color imaging is often done by taking images of the same scene in red, green and blue channel and combing them into one image. To reduce the amount shot taken, this process is commonly done using a mosaic color filter array (see Bayer pattern CFA as an example in next section) with R, G and B pixel aligned on the sensor plane alternately. However a major disadvantage of this method is that the formation of the color image is done through the interpolation of the R, G and B pixels, therefore 2/3 of information are made up. Also, the using of filter reduces the intensity of incident light, therefore decreases the absorption efficiency.

2 Prior work

2.1 Bayer pattern color filter array

There have been many ways to acquire color images using photodiode array prior to the invention of Foveon sensor. Among them, Bayer pattern color filter array [1] is the most widely used one. As figure 2 shows[1], this type of color sensors use a color filter mosaic to select colors at different pixel location. To be specific, in a unit mosaic region, there are 50% of green pixels and the remaining are red and blue pixels, 25% each.

2.2 Visible/infrared imaging device with stacked cell structure

Besides the Bayer pattern design, there are also design [5] that applies layers of thin-film photosensitive material upon the photo diodes [Figure 1], therefore the sensor is able to detect photons of different wavelength bands.

Figure 1: Visible/infrared imaging device with stacked cell structure
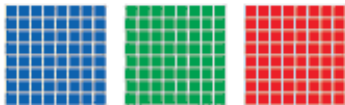
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[1]http://www.foveon.com/article.php?a=69

Foveon X3® Capture

A Foveon X3 direct image sensor features three separate layers of pixel sensors embedded in silicon.
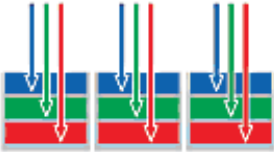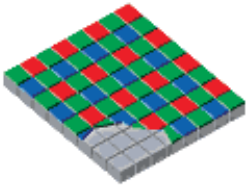
Since silicon absorbs different wavelengths of light at different depths, each layer records a different color. Because the layers are stacked together, all three colors are captured.
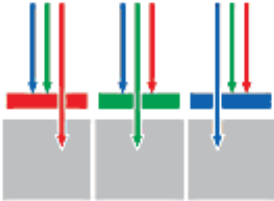
As a result, only Foveon X3 direct image sensors capture red, green, and blue light at every pixel location.

Mosaic Capture

In conventional systems, color filters are applied to a single layer of pixel sensors in a tiled mosaic pattern.

The filters let only one wavelength of light–red, green, or blue–pass through to any given pixel location, allowing it to record only one color.

As a result, mosaic sensors capture only 25% of the red and blue light, and just 50% of the green.

Figure 2: A comparison between Foveon X3 sensor and traditional Bayer pattern color filter array sensor

3 Foveon X3 Sensor

Foveon X3 detectors have a triple-well structure that utilizing dependency of the absorption length on the wavelength of incident photons to sense and output three colors at each pixel, thus solving the spatial color crosstalk caused by color demosaicking process required by conventional CFA-based detectors. [2]
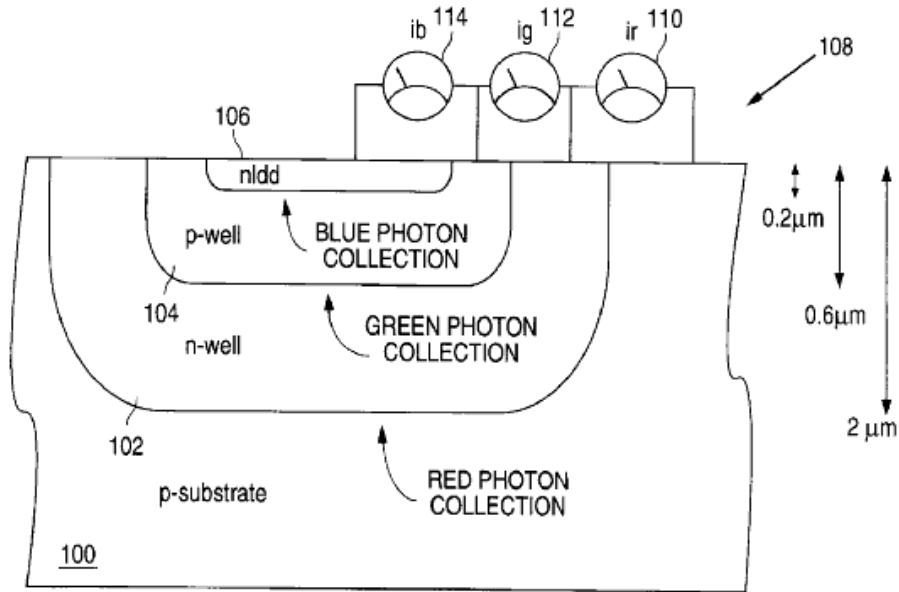
3.1 Triple-well structure

Figure 3: Triple-well structure of each pixel on Foveon X3 sensor

As figure 3 shows, to separately detect color in each pixel of the MOS imaging array, the photosensor structure has a deep-doped N region on the P-doped silicon substrate, so that the p-n junction between the substrate and the N-region will be able to detect red light. And upon the N-doped region, a P-doped region is applied so that the P-N junction between these two layers are sensitive to green light. There is finally an N-region on the top of that P-region to make the P-N junction in-between be able to detect blue light.

3.2 Absorption length

The reason different color light can be absorbed at different depth is that the penetration depth of the incident photons into a material depends on the wavelength, whereas longer wavelength has a greater absorption length. This is shown [2] in Figure 4.
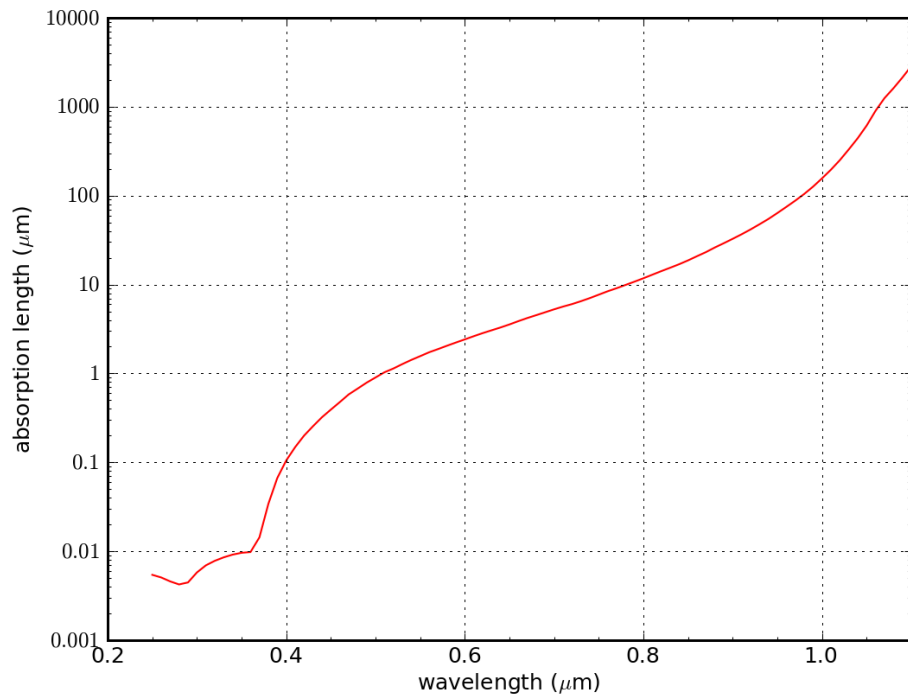

Figure 4: Absorption length of silicon

3.3 Calculating the response curve at each color sensitive depth

If the incident light at certain wavelength of intensity I_0 enter a material, the intensity of that light at depth x can be describe as

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[2]http://physics.ucsd.edu/do-the-math/2011/09/dont-be-a-pv-efficiency-snob/

$$I = I_0 \cdot P(x, \delta) \tag{1}$$

where $P(x, \delta)$ is the probability of the incident photons have not been absorbed, which can be calculated [3] by Beer-Lamber law:

$$P(x, \delta) = e^{-x/\delta \cos \theta} \tag{2}$$

where θ is the incident angle and attenuation distance δ is given by

$$\delta = 1/\beta, \tag{3}$$

and β is defined as

$$\beta = \omega \sqrt{\frac{\mu \epsilon}{2}} \left[\sqrt{1 + \left(\frac{\sigma}{\omega \epsilon} \right)^2} - 1 \right]^{1/2}, \tag{4}$$

where ω is the angular frequency of the light in silicon solid and is given by

$$\omega = 2\pi f = \frac{2\pi / \sqrt{\mu \epsilon}}{\lambda} \tag{5}$$

For the semi-conduction material, silicon, used in Foveon sensor, the permeability μ and the permittivity ϵ can be calculated by:

$$\sqrt{\mu \epsilon} = \sqrt{\mu_0 \epsilon_0} \cdot n, \tag{6}$$

where the index of refraction of silicon $n = 3.96$, permeability of vacum $\mu_0 = 4\pi \times 10^{-7}$ V $\cdot$ s/(A $\cdot$ m), permittivity of vacum $\epsilon_0 = 8.85 \times 10^{-12}$ F/m and σ, the conductivity of silicon is 4.2×10^2 S/m

Given the sensor plane depth for each of the RGB channels in Table 1, I calculated the theoretical silicon absorption at different wavelength and plotted the absorption ratio (absorbed/incident) vs. incident photon wavelength in Figure 5.

Gamal [2] gave the comparison of measured RGB spectral response of the Foveon sensor and standard CFA sensor, shown in Figure 6.

3.4   Potential problems

As Figure 5 and Figure 6 shows, due to the physical limit of the Foveon sensor design, the vertical color leakage is really severe: There is large overlap
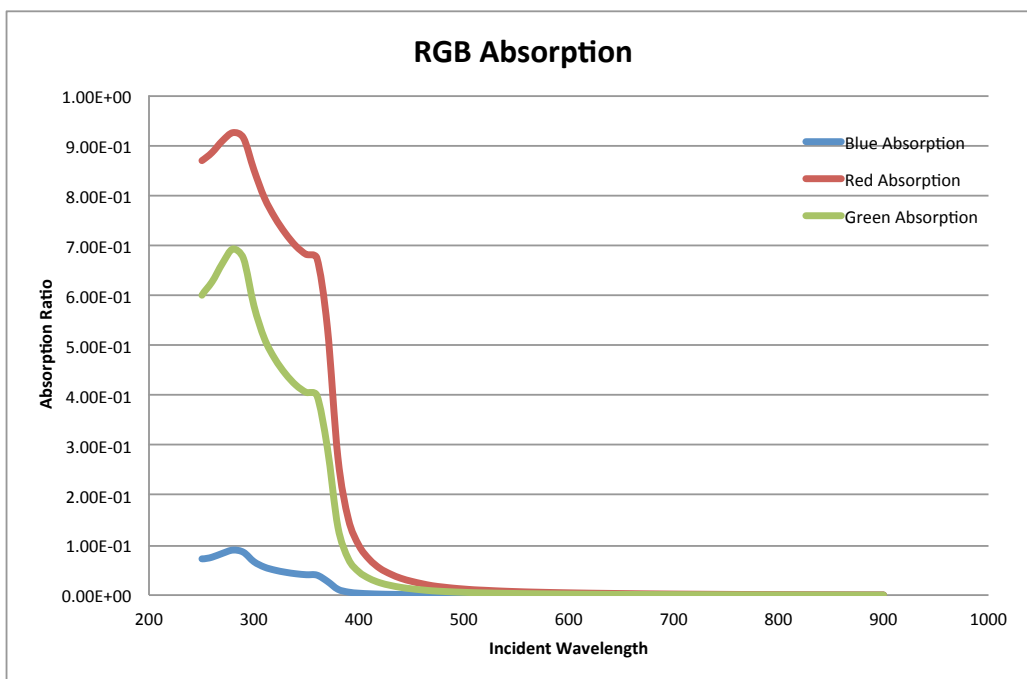
Figure 5: Theoretical absorption at different depths at depth of 0.15 (Blue plane), 0.5 (Green plane) and 1.1 (Red plane)μm
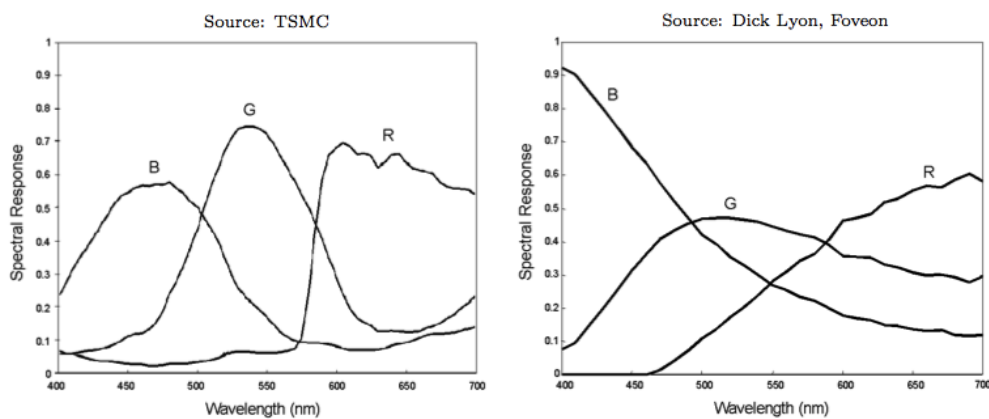

Figure 6: Measured RGB spectral response for (left) standard CFA and (right) Foveon sensor.

Table 1: Junction deption for R, G and B color

Color	Wavelength (nm)	Optional junction depth (μm)	Foveon Triple-well (μm)	Foveon improved (μm)
Blue	450	0.1-0.4	0.15	0.1-0.4
Green	550	0.8-1.2	0.5	0.8-1.2
Red	650	1.5-3.5	1.1	1.5-3.5

between the RGB channels, therefore causing trouble to separate them. As a result, at the "blue" junction, not only blue will be absorbed but also red and green, likewise, at each junction, the absorption is not solely done for that specific color, but accompanied by other colors. Therefore, Foveon claimed to have an algorithm to deal with this problem, but the details about it is less documented. Moreover, amplification may be required to perform the separation algorithm, which may introduce extra noise into the system.

In 2004, Foveon Inc. [7] came up with a improved design (Figure 7) to solve this problem. Instead of the triple well, there are now six alternately aligned P and N layers, sampling each color twice at different depth. This might help them to get a higher flexibility in the design of the algorithm, but still cannot solve the problem caused by the fundamental physics law.

4   Conclusion

Though the Foveon X3 is a smart design that exploits the dependency of the absorption coefficient on wavelength to output three colors at each pixel, there are still many problems to overcome, among which the color inaccuracy is the most severe one. However, Foveon successfully dodged this problem and even made it a major selling of this sensor in consumer market. On the other hand, Foveon sensor does have advantages in color aliasing [4] compared to CFA sensor that requires color demosaiking (Figure 8). Also, currently the size of each pixel on the Foveon sensor is larger compared to the conventional CFA ones, this can bring a better dynamic range, but at the same time limits the number of pixels in unit area.
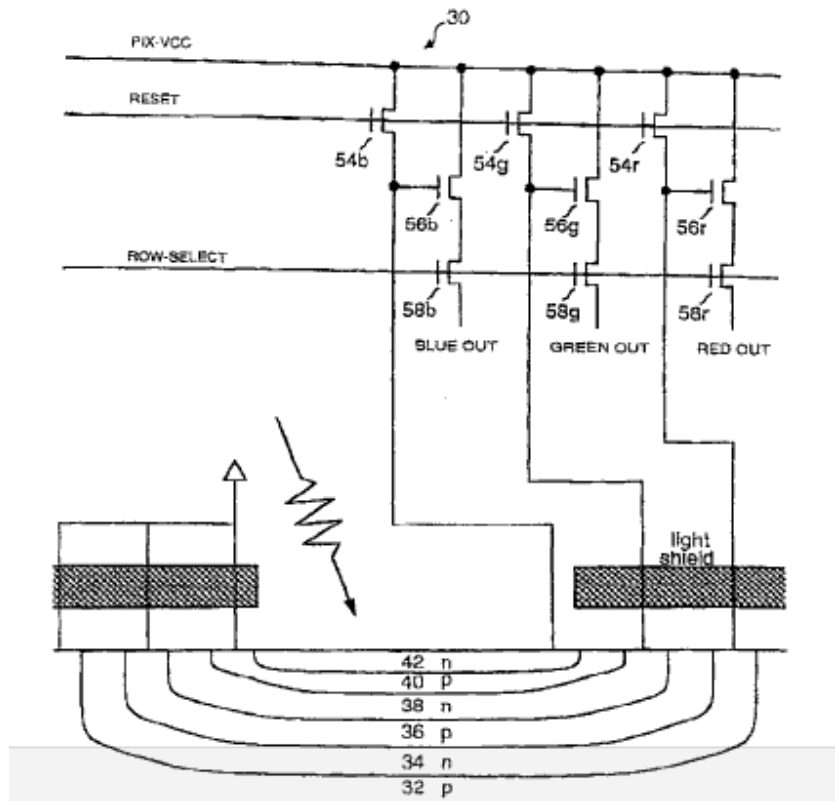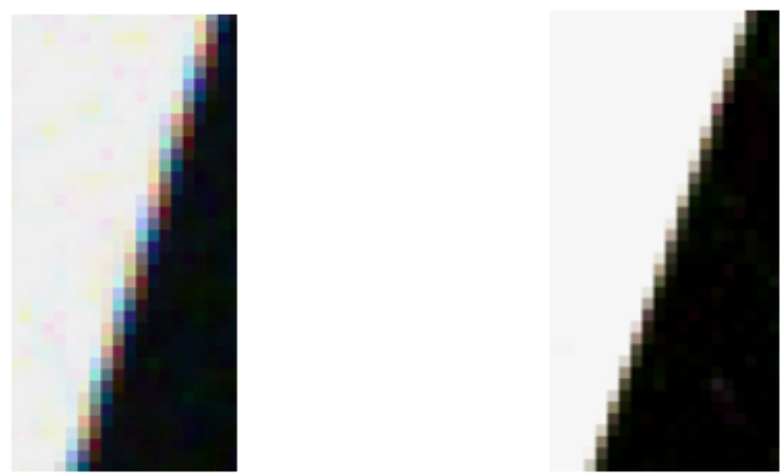
Figure 7: A improved Foveon sensor design

Figure 8: Color aliasing of CFA sensor (left) and Foveon sensor (right)

References

[1] B.E. Bayer. Color imaging array, July 20 1976. US Patent 3,971,065.

[2] A. El Gamal. Trends in cmos image sensor technology and design. In *Electron Devices Meeting, 2002. IEDM'02. Digest. International*, pages 805–808. IEEE, 2002.

[3] D.J. Griffiths and Reed College. *Introduction to electrodynamics*, volume 3. prentice Hall New Jersey, 1999.

[4] R.J. Guttosch. Investigation of color aliasing of high spatial frequencies and edges for bayer-pattern sensors and foveon x3® direct image sensors. Technical report, tech. rep., Foveon, 2002.

[5] N. Harada and O. Yoshida. Visible/infrared imaging device with stacked cell structure, March 17 1987. US Patent 4,651,001.

[6] R.B. Merrill. Color separation in an active pixel cell imaging array using a triple-well structure, October 12 1999. US Patent 5,965,875.

[7] R.B. Merrill. Vertical color filter detector group and array, April 27 2004. US Patent 6,727,521.