

# Infrared and ultraviolet imaging with a CMOS sensor having layered photodiodes

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## ABSTRACT

Recently introduced CMOS sensors using three layers of photodiodes for color separation<sup>1</sup> can also function well in the near ultraviolet and infrared bands. Ultraviolet sensitivity results from the close proximity of the top (blue) photodiode junctions to the surface of the silicon and the lack of any significant UV-absorbing materials above them. Infrared sensitivity extending nearly to the silicon band-gap cutoff results from depletion of the bottom (red) photodiodes into the substrate. Preliminary measurements indicate that the layered structure has high quantum efficiency over most of the 200-1100nm band covered by silicon photodiodes. Uniquely, these devices can be switched rapidly between narrowband monochrome imaging and full-color imaging in the visible band by the introduction of a visible pass filter. The response of the three photodiode layers is broad enough to permit stable false color encoding using two or three channels in conjunction with a redefinable 3 x 3 color transform matrix. Images have been acquired in the 300-400 nm UV band and for broad and narrow infrared bands out to 1064 nm. Thermal images of objects in the range of 600C have also been acquired demonstrating color-encoding of various UV, visible and IR bands and applications for particular encoding schemes.

Keywords: Image sensor, CMOS, CCD, color, multispectral, camera

## 1. INTRODUCTION

The development of a commercial color sensor incorporating layered photodiodes has brought a new technology to bear on the acquisition of color images. This sensor, the Foveon X3<sup>®</sup> Pro 10M, described by the authors in a previous paper<sup>1</sup>, consists of a two-dimensional array of three-photodiode stacks in which the junction depths of the three photodiodes are placed at depths that exploit the steep wavelength gradient in the optical absorption length of silicon to produce three color-separated signals.

Although this sensor is intended for use in color imaging, its response extends over the usual band of wavelengths detectable by silicon imaging devices – from about 340 nm to nearly 1100 nm. The three photodiodes in each pixel stack are accurately aligned, so that their output signals may be added together without generating misalignment artifacts. Since channel addition is just the selection of a set of values for the color space conversion that produces a monochrome signal, the sensor imaging characteristics outside the visible band can be readily displayed. In addition, other sets of values can be designed for use with the unfiltered sensor response or with various sorts of spectral shaping filters to map important spectral distribution information into the displayable color space.

Experiments in this have just begun and some early results are shown in this paper.

## 2. LAYERED PHOTODIODE COLOR SENSING

Semiconductor materials have characteristic photon absorption lengths that vary with the energy of the photons absorbed. Silicon, fortunately, has such a curve that varies by nearly two orders of magnitude over the visible range (Figure 1)<sup>2</sup>. This variation provides sufficient space to stack multiple diode junctions at depths that are both capable of separating photons of various wavelengths and amenable to fabrication using standard CMOS manufacturing processes.

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### 2.1 Junction depths

In practice, junctions at depths around 0.2  $\mu\text{m}$ , 0.8  $\mu\text{m}$  and 3.0  $\mu\text{m}$  provide workable spectral separation for true color imaging. With appropriate junction construction, the top diode can collect charge nearly to the surface of the silicon to extend response into the near ultraviolet and the bottom diode extended near-infrared response.

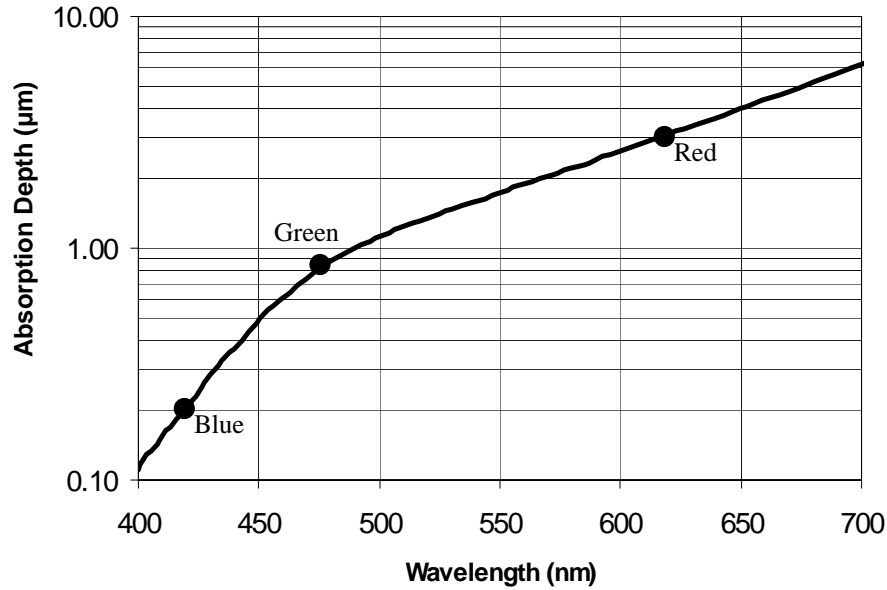


Figure 1 - Silicon photon absorption depth with practical junction depths indicated

### 2.2 Spectral characteristics

The large changes in absorption depth with wavelength provide sufficient separation red, green and blue signal signals to support accurate conversion of the acquired image data into conventional color spaces for processing and display. The curves in figure 2 show the relative response curves for the three channels including the effects of a filter with cutoffs at 400 and 660 nm normally used for true color imaging with this technology.

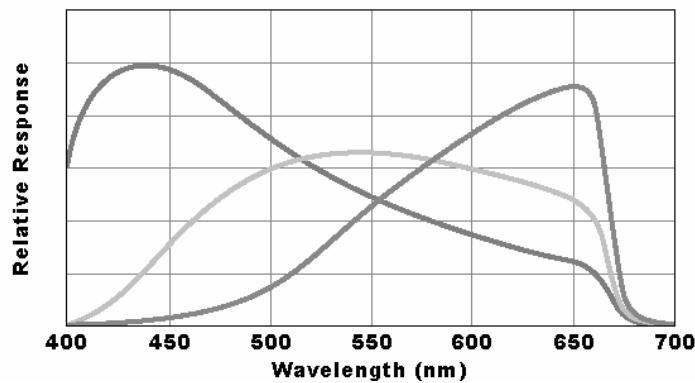
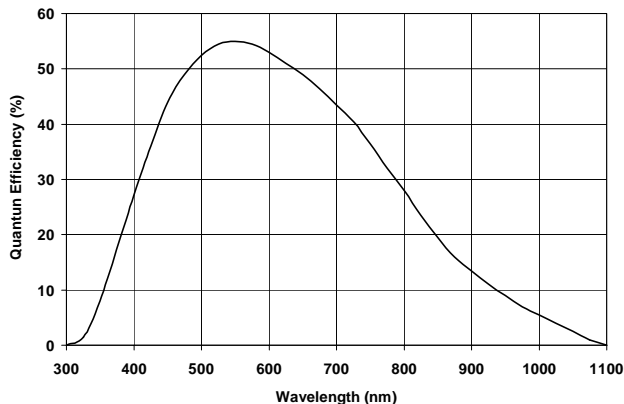


Figure 2 - Relative spectral response of three stacked junctions

### 2.3 Extended response

Even though the junction depths are tailored for best color operation, the three junctions together comprise a silicon photodiode with excellent total quantum efficiency. Figure 3 shows the total quantum efficiency for the three junctions

through the near UV, the visible and the near-IR. These figures include losses due to the 54% fill factor and gains from microlenses. Useful response extends from below 350 nm to nearly 1000 nm. This response curve is similar to curves from other silicon imaging devices with relatively thick active charge collection volumes.



**Figure 3 – Total net quantum efficiency**

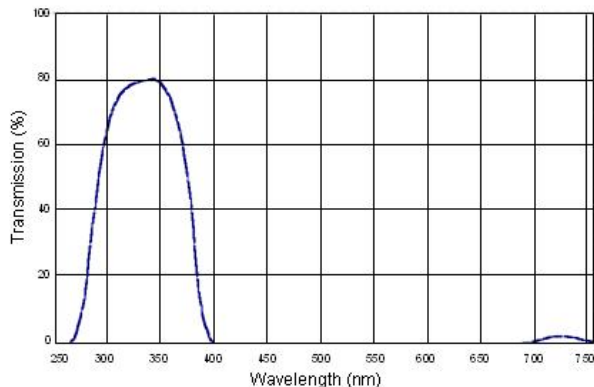
By comparing the total response curve with the individual channel curves in Figure 2, it can be seen that the blue channel will contain essentially all of the signal generated by ultraviolet photons. Signals generated by infrared photons are roughly proportional to the thicknesses of the collection zones for each of the three diodes.

**3. EXTENDED SPECTRUM IMAGING**

In true color imaging, the output from a color sensor is multiplied by a 3 x 3 matrix to convert the raw data into a standard color space. While “color space” has no meaning when some of the illumination to be included in the signal weighting is not visible, the matrix multiplication technique can be applied to any data set from a three-channel sensor to a visible color space. The output is, of course, not true color, but it effectively maps detected signals from desired bands into displayable colors. The results of such maps can make important illumination components readily visible in a variety of images.

**3.1 A UV-IR combination image**

A simple example of simultaneous detection combines the sensor with a Hoya U-340 UV pass filter. Figure 4 shows the transmission curve<sup>3</sup>.



**Figure 4 – Hoya U-340 transmission**

Combining this filter with the sensor produces significant signals in two channels – a blue signal from the transmission in the near UV and a signal in the red channel from the small transmission peak centered on 725 nm. In daylight, the

amount of illumination available is substantially higher in the red/IR range than in the UV so the signals are reasonably well balanced. The green channel provides a signal essentially redundant with the red. Viewing a scene of foliage and sky produces images like those in Figure 5.



**Figure 5 – Blue (left), Red (right) and combined color (center) images**

The images show clearly the strong UV component in the sky and the reduction in sky infrared with increasing angle. Conversely, the strong reflectance of foliage in the IR and high absorbance in the UV is clearly demonstrated.

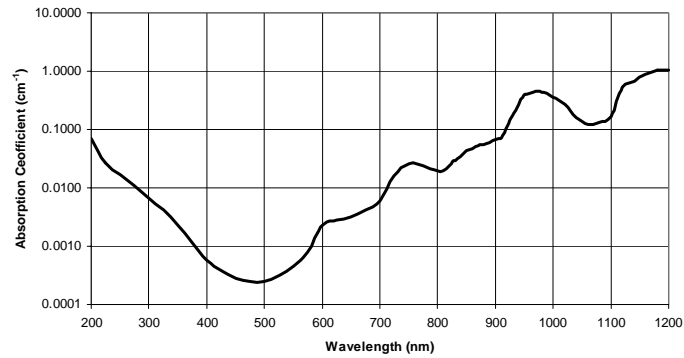
### 3.2 Imaging at 1064 nm

Narrowband imaging at any detected wavelength is also possible with this sensor. As an example, images were taken through a 1064 nm (20 nm FWHM) laser line filter. The sensor has sufficient sensitivity at this wavelength to easily take images in daylight. Figure 6 shows two examples. The bright spot to the right of center is an artifact of the optical setup.



**Figure 6 – 1064 nm images: “Bottle” and “Pool”**

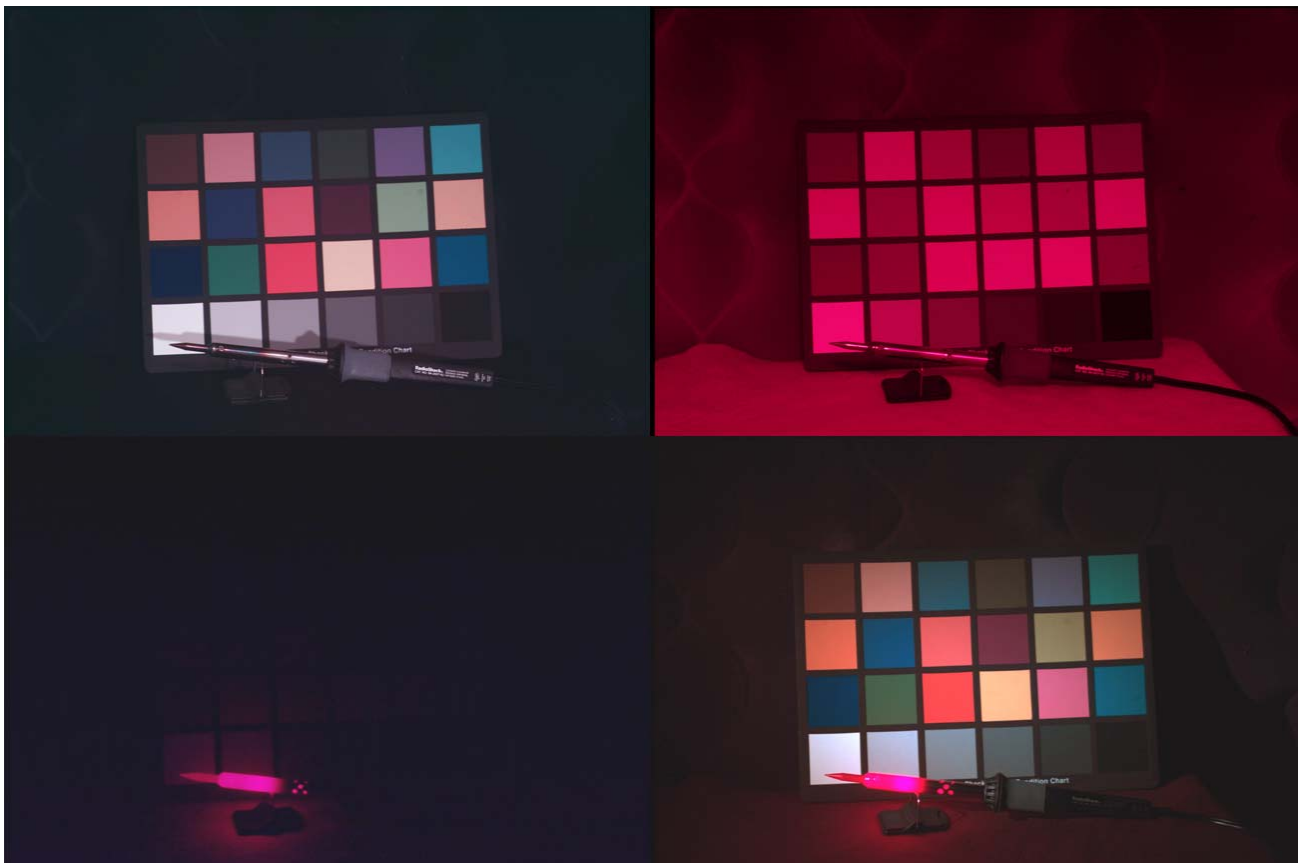
The high IR reflectance of foliage (and oranges) can be seen in these images, even in a reflection in the “Pool” image. The more interesting aspect is the water. The bottle on the table contains spring water. To the eye it is clear. As figure 7 shows, however, water has an absorption coefficient of about  $0.2 \text{ cm}^{-1}$  at  $1064 \text{ nm}^4$ . This produces about an 80% reduction in signal for radiation passing through the bottle. The effect is even more pronounced in the pool image. To the eye, this is a clean, blue pool in which the pool sweep at the other end of the hose can be clearly seen 2.5 meters down. However, even as little as 1 cm of water over the hose produces a visible attenuation at 1064 nm. As the hose descends, it rapidly disappears from view. The deepest visible extent is about 20 cm.



**Figure 7 – Spectral absorption of pure water.**

### 3.3 Simultaneous color and infrared imaging

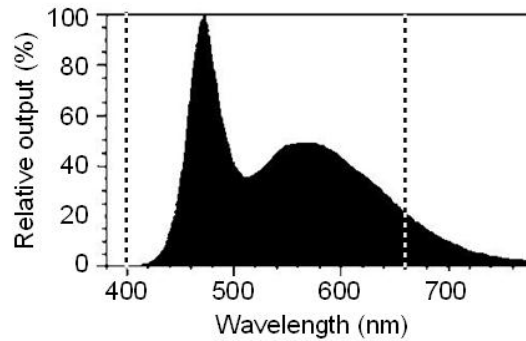
Since each pixel in the sensor has the ability to detect color whenever its illumination is restricted to the 400-660 nm spectral band, it is possible to arrange to have some pixels see color while other simultaneously see infrared. This could, of course, be done with a split filter to produce separated images but these images can also be made to overlap. The four images in figure 8 show one way to accomplish this.



**Figure 8 – Simultaneous color and infrared imaging**

The first image is a typical color image made with tungsten illumination and the visible pass filter in place. The soldering iron is off. The next image, to the right, is the same scene with the visible pass filter removed. Everything is

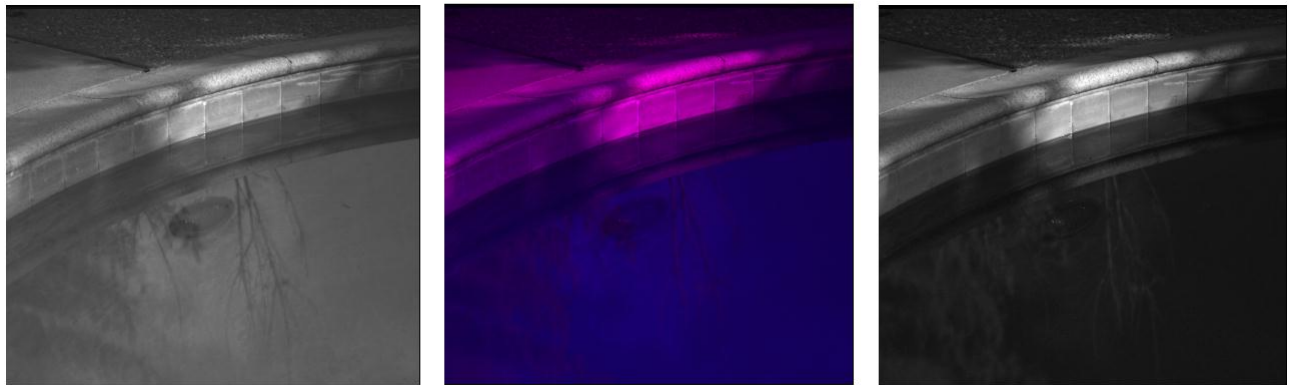
dominantly red because of the high IR content in incandescent lamps. In the third image at the lower left, the incandescent light is turned off and the iron is on. The tip temperature is about 400C and the hottest parts are not yet visible as red. The glow of the iron and the nearby objects it illuminates can be seen. In the final image, the scene is illuminated with a white LED flashlight, which has almost no infrared content. The chart can again be seen in color but the iron remains visible by its own radiation. It should be noted that the color rendering ability of white phosphor type LEDs is not very good because of their uneven spectral content (figure 9)<sup>5</sup>. The vertical lines indicate the nominal bandpass of the visible filter used with the sensor for normal color imaging.



**Figure 9 – White phosphor LED spectral output (typical)**

### 3.4 UV, IR and water

In this final image sequence shown in figure 10, the strong dependence of absorption in water on wavelength can be readily seen. This image uses the Hoya U-340 filter. The ratio of water absorption coefficients between the UV and red/IR bands passed by this filter is about 50.



**Figure 10 – Blue (left), Red (right) and combined (center) images**

The water is, of course, fairly transparent in the near UV and fairly opaque in the far red. The tile around the pool has a reflectance that is close to spectrally flat. In the center image, as a result, the pool water is a deep blue color while the tile and concrete are magenta. Notice also that the reflected sky image is bright only in the blue image. There are some other subtleties. The reflections of the illuminated foliage are also magenta as is a direct reflection of the sun off the underwater light, indicating that some of the red light will make it through the water.

## 4. CONCLUSIONS

Having three full-resolution parallel channels with wavelength separation in a single sensor offers some unique opportunities for direct imaging of up to three simultaneous bands without the need for multiple exposures or the generation of geometric artifacts. Straightforward application of standard color space conversion tools can map these signals into usable visible images with useful information coded in color.

## 5. FUTURE DEVELOPMENT

Additional experimentation will be undertaken to assess the accuracy of determining numerical data from three-channel images taken using the new three-band pass filters. In addition, work is underway to use two complementary filters of this type to obtain highly accurate color data from six-channel images in real time.

## 6. REFERENCES

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Note: Color images may be viewed at <http://www.alt-vision.com/publications>