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INTELLIGENT OPTO SENSOR

DESIGNER'S NOTEBOOK

TEXAS ADVANCED OPTOELECTRONIC SOLUTIONS®

TAOS Photo Sensor Response Part II: Sensitivity to Temperature

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ABSTRACT
Silicon photodiode response to light is dependent on the wavelength of light incident upon it as well as the temperature of the sensor. This paper will explain this dependence and discuss how to calculate the change in response at a given temperature. Note that this paper is intended to be a continuation of the Application Note "DN23: TAOS Photo Sensor Response Part I: Sensitivity to Wavelength", which discusses methods to calculate the photodiode response for light sources with different spectral power distributions.

INTRODUCTION

The responsivity of a silicon photodiode is dependent on the temperature of the silicon. The change in a photodiode's sensitivity due to temperature is expressed as a Temperature Coefficient (tempco) in ppm (parts per million) per degree Celsius. The temperature coefficient can be factored into the response calculation for any given light input.

RESPONSIVITY DEPENDENCE ON WAVELENGTH

To better understand how the sensitivity of a silicon photodiode is affected by temperature, it is best to first revisit the photodiode response's dependence on wavelength in a little more detail.

Silicon's response is wavelength dependent because the energy at different wavelengths of light is absorbed by silicon at different rates. For example, imagine that a light with a peak wavelength at 450nm and a light with a peak wavelength at 650nm strike a Silicon photodiode. For simplicity, these two sources will henceforth be referred to as the blue light and the red light, respectively, although it is not completely accurate to describe them so. Since there is an inverse relationship between the wavelength of light and the energy contained in a photon of that light, the blue light will contain more energy than the red light. According to Equation 1, the 450nm light delivers 2.76eV while the 650nm light delivers only 1.91eV of energy to the silicon.

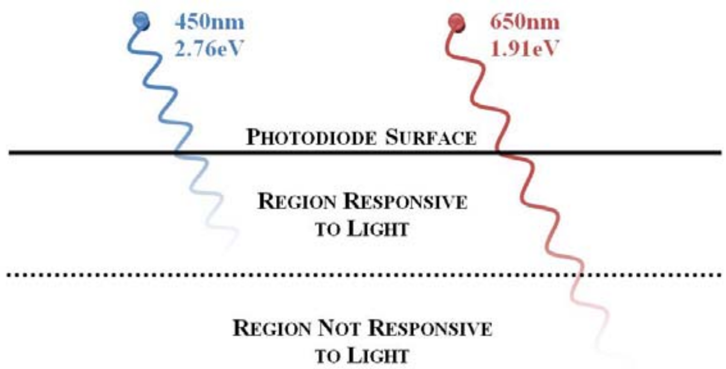

Figure 1. Absorption of different wavelengths of light in silicon

The higher energy of the blue light will be absorbed by the photodiode more quickly than the energy of the red light, for a given silicon thickness. In other words, the red light will penetrate into the silicon deeper than the blue light before it is completely absorbed. Since the absorbed energy can only induce an electric response within the active diode region, the amount of energy absorbed will be dependent on the depth of the active diode region. If the effective light responding region of the photodiode is not deep enough, some of the red light will not be absorbed and the response will be less sensitive to red light. If, however, the effective region depth is sufficiently large, more of the energy in the red light will be absorbed. Figure 1 shows a simplified cross-section of a silicon photodiode. In this figure, some of the red light is not being absorbed within the light responding region while all of the blue light is.

$$E = \frac{hc}{\lambda} \qquad \text{(Eq. 1)}$$

E is the Energy of a photon (eV)
h is Planck's constant: 4.14×10^{-15} (eV sec)
c is the speed of light: 3×10^{17} (nm/s)
λ is the wavelength of light (nm)

The upper limit of the silicon responsivity curve is determined by the smallest amount of energy that will elicit a response from silicon. This amount of energy is the bandgap voltage, and for silicon, it is approximately 1.12eV at 25°C. Using Equation 1, it can be seen that this corresponds to a wavelength of 1109nm, which is the general upper limit of silicon's spectral response to long wavelengths.

Responsivity Dependence on Temperature

An additional variable is introduced when the temperature of the Silicon changes. At higher temperatures, the absorption rate increases so that all wavelengths of light are absorbed in a shorter distance. This could alter the sensor's response if it causes wavelengths to be absorbed differently than they were at a reference temperature. For instance, in the example above, if our red light was absorbed more efficiently at 70°C than at 25°C, the response would increase. Alternatively, colder temperatures would result in a decreased absorption rate, causing a decreased response to the red light.

This can be seen in Figures 2 and 3. Figure 2 shows the depth in Silicon at which ~95% of the energy at a given wavelength is absorbed. Note that as the temperature is increased beyond 27°C, the absorption rate increases causing the absorption depth to decrease. This makes the sensor more sensitive to light at longer wavelengths. As the temperature is lowered, the absorption depth increases, making the sensor less sensitive to light at longer wavelengths. If, for example, the light responding region is 1µm deep, then according to Figure 2, at 27°C, about 95% of light with a wavelength of 450nm is absorbed. In this example, more than 95% of the light with wavelengths shorter than 450nm will be absorbed and less than 95% of light with wavelengths longer than 450nm will be absorbed.

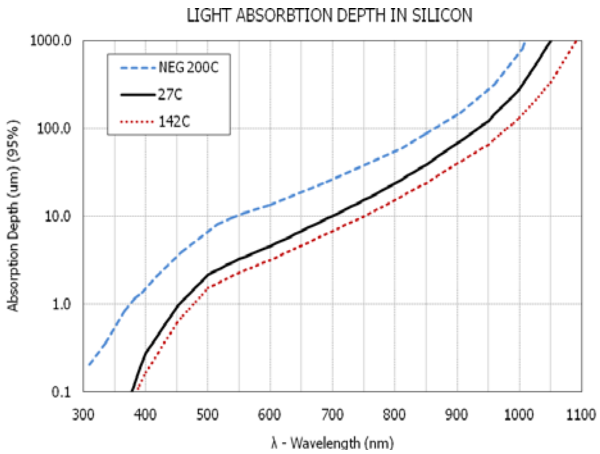

Figure 2. Absorption Depth vs. Temperature

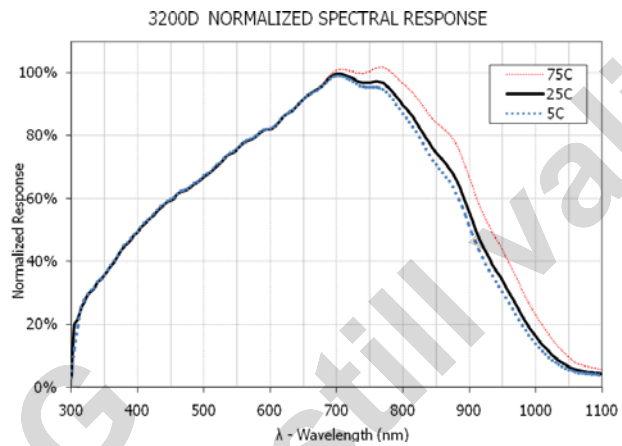

Figure 3. TCS3200D Normalized Response Dependence on Temperature

Figure 3 shows the absolute response of the TCS3200D at different operating temperatures. Note that temperature has little effect on the response of the shorter wavelengths. This is because most of the energy in the light with shorter wavelengths is being absorbed regardless of the silicon's temperature, with the photodiode process that is used by TAOS. With an increase in temperature, more of the longer wavelength light's energy is absorbed within the effective p-n junction depth. Because of this increased absorption, the response to the light with longer wavelengths increases and the response curve is extended with each hotter temperature.

The upper limit of the spectral response curve is also affected by temperature. There is an inverse relationship between the bandgap voltage and the temperature for silicon. This means that as the temperature is increased, the bandgap voltage decreases and the upper limit of the spectral response curve increases. The bandgap voltage of silicon is approximately 1.12eV at 25°C and approximately 1.11eV at 70°C [1]. Using equation 1, a change in temperature from 25°C to 70°C, would result in a change in silicon's spectral response limit from 1109nm to 1119nm.

TEMPERATURE COEFFICIENT

A temperature coefficient or tempco is a measurement of how sensitive the photo sensor response is to temperature changes. TAOS datasheets typically report this measurement in datasheets in terms of ppm per °C for some specific interval of wavelength (10,000 ppm or parts per million = 1%). For example, between -25°C and 70°C, the TCS3200D is rated at having ±200 ppm/°C tempco for wavelengths less than 700nm. This is equivalent to 0.02% per °C.

This can be seen in Figure 4, which shows the tempco between 300 and 1000nm. Here again, it can be seen that the tempco for shorter wavelengths is averaging near zero.

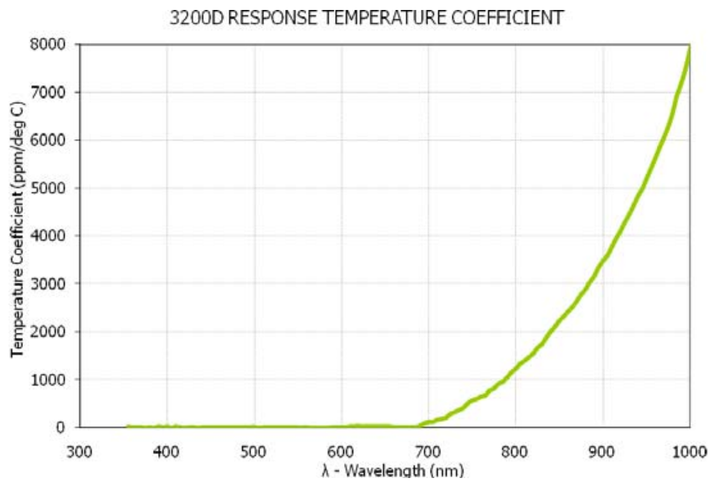

Figure 4. TCS3200D Temperature Coefficient versus Wavelength

DARK SIGNAL

When no optical input is present, silicon photodiodes will still produce a small electric response. This response is the dark response, and it is temperature dependent. The dark response roughly doubles with every ~8-10°C increase in silicon temperature. This relationship is shown in Figure 5.

TAOS datasheets will specify the dark response at a particular temperature. For example, at 25°C the TCS3200D has a typical clear channel dark frequency of 2Hz. Thus, it would be reasonable to expect ~4Hz response at 35°C.

The dark response is present in dark as well as light conditions; however in a well lit environment the effects of the dark response are insignificant. For example, a typical dimly lit environment (~100 lx) might produce a response of 100 Hz. At 25°C, the dark response would constitute 2% of the total response. A typical well lit environment (~1000 lx) could elicit a response of 100 kHz. In this case, at 25°C, the dark response would only account for 0.002% of the total response.

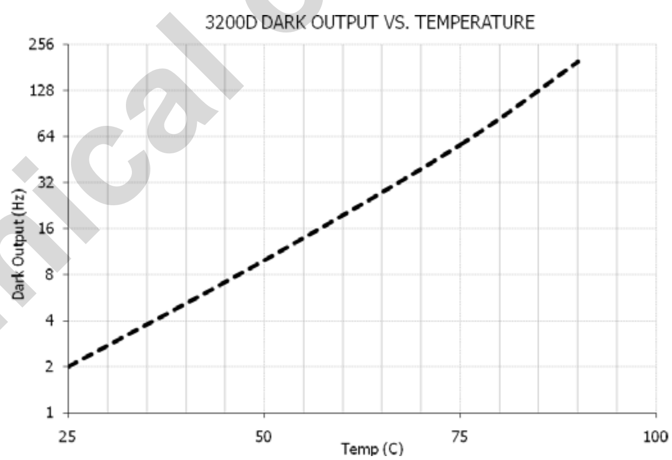

Figure 5. TCS3200D Dark Response Dependence on Temperature

EXAMPLE

The following example will help to better understand the photo sensor's sensitivity change to temperature. This example will focus on two broadband light sources and how the response to those sources changes from 25°C to 75°C. The two light sources used are a cool white LED and a 3000K blackbody radiator. Spectral Power Distribution curves (SPD's) are shown for these light sources in Figure 6.

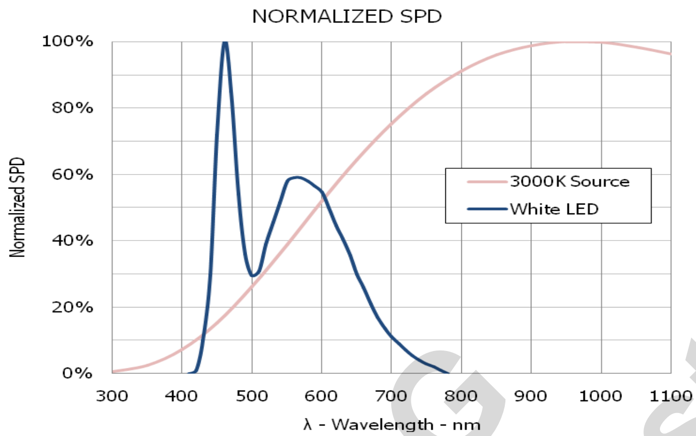

Figure 6. Normalized SPD for 3000K source and white LED

When the normalized SPD of the source (Figure 6) is weighted with the normalized response of the sensor (Figure 3), the result is a normalized response for the given source. This is shown in Figure 7 for each of the two sources at 25°C and 75°C.

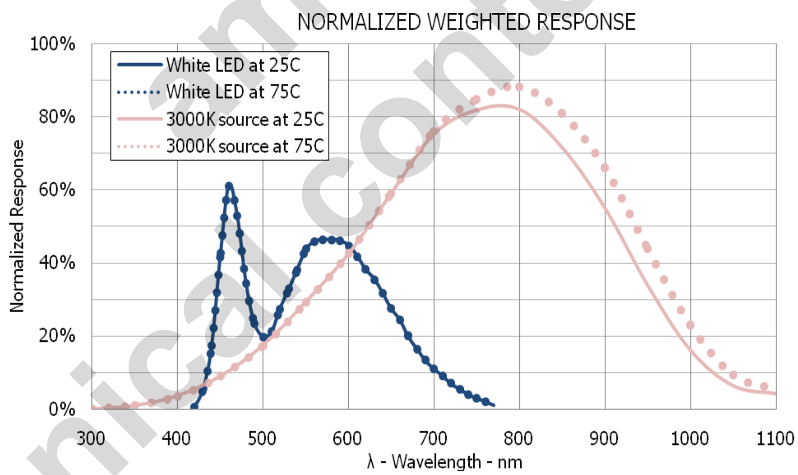

Figure 7. Normalized photo sensor response to white LED and 3000K source at 25°C and 75°C

From Figure 8, it can be seen that the response to the 3000K source is much more sensitive to temperature changes than the response to the white LED is. This is due to the 3000K sources' SPD having a higher concentration of light with longer wavelengths. Numerically, the response of the photo sensor to the white LED at 75°C was 99.8% of its response at 25°C. The response to the 3000K source at 75°C, however, was 108.6% of its response at 25°C.

A user can calculate the change in response to a particular light source at a particular temperature, by using the tempco data provided in TAOS datasheets. For example, the tempco for the TCS3200D at 750 nm is approximately 600 ppm/°C or 0.06%/°C (Figure 4). Thus, at 50°C, the responsivity at 750 nm equals the responsivity at 25°C plus 1.5%. At 800 nm, the tempco is approximately 1200 ppm/°C or 0.12%/°C. So at 50°C the responsivity at 800 nm would increase by a factor of 3.0% compared to the response at 25°C. This can be repeated to create a new spectral responsivity chart at 50°C. The absolute response can then be calculated using the numerical method discussed in part I of this application note, DN23: TAOS Photo Sensor Response Part I: Sensitivity to Wavelength.

MINIMIZING SENSITIVITY TO TEMPERATURE CHANGE

For certain applications, it may be necessary to minimize the sensitivity of the photo sensor to changes in temperature. As long as the area of concern is within the visible spectrum, an IR blocking filter may be used to attenuate the wavelengths of light that correspond to the greatest temperature coefficients. Figure 8 shows the response of a photo sensor with and without an IR filter. The IR filter used in this example, limits the response of light with wavelengths greater than 700nm. The use of this IR blocking filter would diminish the temperature coefficient on the TCS3200D to approximately ±200 ppm/°C under any light source (see Figure 2).

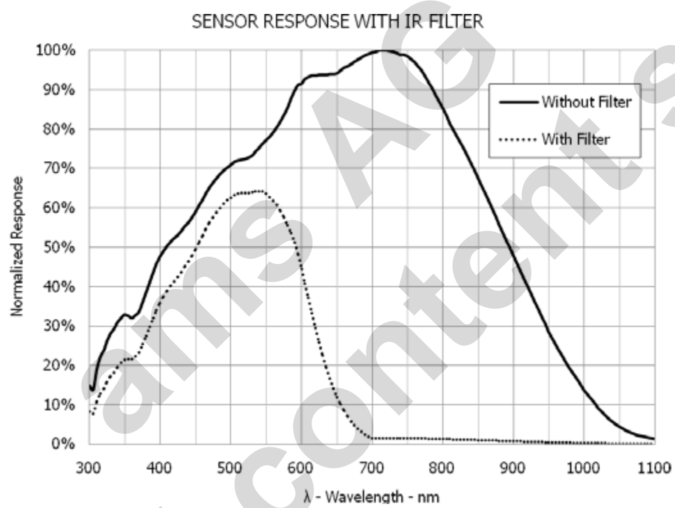

Figure 8. TCS3200D response with and without a BG-39 1mm thick glass IR filter

CONCLUSION

The sensitivity of silicon photo sensors to changes in temperature varies across wavelengths of light. The temperature coefficient describes this sensitivity change. TAOS photosensors, such as the TCS3200D, have low temperature coefficients (±200 ppm/°C) for the wavelengths of light below 700nm. The increased temperature coefficient for wavelengths of light greater than 700nm can be limited with the use of an IR filter. For more information on TAOS optical sensors, please visit http://www.taosinc.com/.

REFERENCES

1. University of Colorado, "Principals of Semiconductor Devices", B. Van Zeghbroeck, 2007, Internet http://ece-www.colorado.edu/~bart/book/eband5.htm.