Temperature Dependence of the EUV Responsivity of Silicon Photodiode Detectors

Benjawan Kjornrattanawanich, Raj Korde, Craig N. Boyer, Glenn E. Holland, and John F. Seely

***Abstract*—Responsivity of silicon photodiodes was measured from -100 C to $+50$ C in the 3 to 250 nm wavelength range using synchrotron and laboratory radiation sources. Two types of silicon photodiodes were studied, the AXUV series having a thin nitrided silicon dioxide surface layer and the SXUV series having a thin metal silicide surface layer. Depending on the wavelength, the responsivity increases with temperature with the rates 0.013%/C to 0.053%/C for the AXUV photodiode and 0.020%/C to 0.084%/C for the SXUV photodiode. The increase in responsivity is consistent with the decrease in the silicon bandgap energy which causes a decrease in the pair creation energy. These results are particularly important for dose measurement in extreme ultraviolet (EUV) lithography steppers and sources since the detector temperature often increases because of the high EUV intensities involved.**

***Index Terms*—Extreme ultraviolet (EUV) photodiodes, silicon radiation detectors, ultraviolet detectors.**

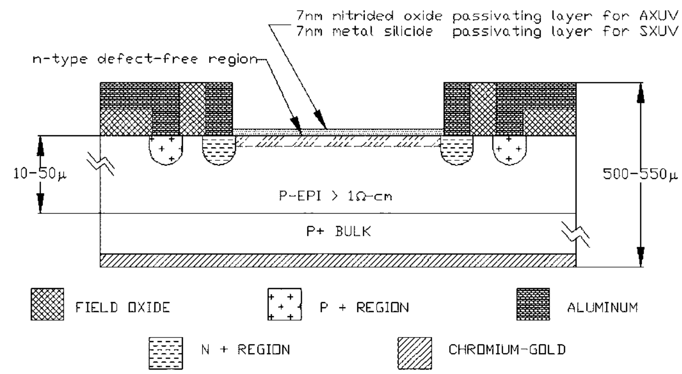

Fig. 1. Schematic of the AXUV and SXUV photodiodes.

I. Introduction

SILICON photodiode detectors are widely used over a broad wavelength range extending from the X-ray to the visible regions [1]. Silicon photodiodes with good stability and radiation hardness have been adopted as absolute calibration standards in the extreme ultraviolet (EUV) region [2]. The responsivity, defined as the ratio of the current appearing in the photodiode's external circuit and the incident radiation power (A/W), of several types of silicon photodiodes have been accurately measured in the EUV region and at room temperature [3]–[5]. Nevertheless, the change in responsivity with temperature has not been measured in the EUV region. There have been some analytical models proposed and measurements made for the temperature dependence of the spectral responsivity of silicon-based devices, but these models and the results were generally applied and tested at ultraviolet and visible wavelengths [6]–[8]. The change in responsivity with temperature is crucial for applications where the detector is used in a harsh environment such as synchrotron facilities, in spacecraft instruments, and in EUV lithography steppers and sources. The responsivity change is particularly important as the investigated photodiodes are being used as absolute calibration standards by laboratories worldwide. In addition, the photodiode detectors are often cooled (typically to -70 °C or lower) for the purpose of reducing the noise level, and the responsivity can vary considerably from the room temperature value.

Two types of silicon photodiodes, AXUV and SXUV, from International Radiation Detector Inc., were studied. Fig. 1 shows the cross section structure of the investigated n-on-p type AXUV and SXUV photodiodes, both have 10×10 mm active area. The AXUV photodiode has a thin nitrided SiO_2 surface layer (approximately 7 nm thick) and 100% internal quantum efficiency [9]. The silicon dioxide layer is known to have a fixed positive charge which repels minority carrier holes generated at the surface by strongly absorbing EUV radiation [10]. This results in nearly ideal theoretical responsivity in the EUV region. The SXUV photodiode has a metal silicide surface layer which replaces the oxide layer on the AXUV photodiode and improves the radiation hardness. However, the absence of the oxide layer causes significant surface recombination in the SXUV photodiodes and reduces the internal quantum efficiency below the 100% value that is characteristic of the AXUV photodiodes.

The changes in responsivity of AXUV and SXUV photodiodes with temperature were measured using synchrotron radiation in the 3- to 88-nm wavelength range and using laboratory radiation sources in the 120 to 250 nm wavelength range. AXUV and SXUV photodiodes were investigated because these are universally used by all the EUV stepper and source manufacturers. These devices are also used or are planned for use in satellite instruments such as SOHO, GOES, EOS, SDO, and CORONAS-PHOTON.

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II. Synchrotron Measurements

For the 3–88-nm wavelength measurements, the test silicon photodiodes were mounted in a vacuum chamber at the Naval Research Laboratory beamline X24C at the National Synchrotron Light Source. The photodiode under study was custom packaged to include an integrated temperature sensor to measure the photodiode temperature during the EUV measurements. The photodiode package was mounted on a support fixture that included a temperature controller consisting of a 50-W heater and a separate temperature sensor. Cooling was achieved by flowing liquid nitrogen through a vacuum feedthrough coupled by a flexible copper strap to the photodiode support fixture. This arrangement made it possible to cool the photodiode to approximately -100 °C. The photodiode temperature was adjusted to a selected higher temperature using the heater associated with the temperature controller. All the reported measurements were performed with no bias on the photodiode.

The experimental procedure was to allow the photodiode to stabilize at a number of selected temperatures and to scan the wavelength of the incident radiation beam over a number of wavelength ranges at each selected temperature. The 1×3 mm radiation beam was incident approximately at the center of the 10×10 mm active area of the photodiode. At each discrete wavelength step, the photodiode current was measured by a precision electrometer.

The wavelength scans were performed by a computer-controlled monochromator consisting of two optical elements, a 600-groove/mm diffraction grating, and a gold mirror. The monochromator's grating and mirror were rotated and translated while maintaining fixed entrance and exit slits. The spectral resolution was approximately 600. For each wavelength scan range, a thin metallic filter was inserted into the radiation beam to transmit the desired wavelength range and attenuate the higher harmonic radiation from the monochromator. Previous studies using transmission gratings indicated that the contamination of the beam by higher harmonics was at the 1% or lower level in each wavelength scan range.

The intensity of the radiation beam decayed slowly over a period of hours as electrons were lost from the storage ring. The beam intensity was proportional to the electron current circulating in the storage ring. The effect of the decreasing beam intensity was removed by normalizing the photodiode currents with respect to the ring current. The subtraction of dark current from the illuminated current was also performed. This step is important especially for measurements at high temperatures where the photodiode dark current increases with increasing temperature.

The change in the photodiode responsivity was measured in the first eight wavelength ranges listed in Table I using synchrotron radiation. An example of wavelength scans obtained from the AXUV photodiode in the 17.1–19.0-nm range are shown in Fig. 2. In this wavelength range, a 300-nm-thick aluminum filter was used to transmit the 17.1–19.0-nm wavelengths and to attenuate higher harmonics (shorter wavelengths). The currents were measured at eight photodiode temperatures from -91.5 °C to $+40.7$ °C and normalized to the current measured near room temperature (+26.3 °C). The normalized currents are essentially a measure of the change in the responsivity of the photodiode with temperature.

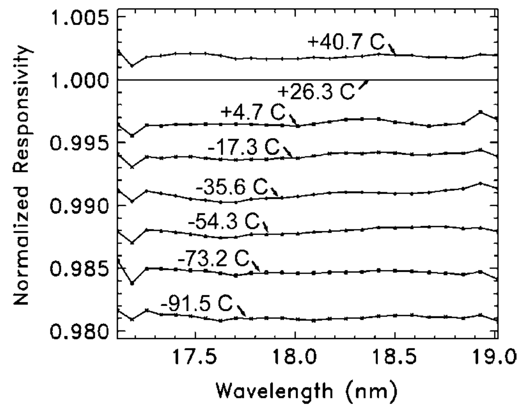

Fig. 2. Normalized responsivity of the AXUV photodiode (currents from the AXUV photodiode at the indicated temperatures normalized to the current at 26.3 °C) in the 17.1- to 19.0-nm wavelength range.

TABLE I
Measurement Wavelengths and Change in Responsivity at 22 °C. The Radiation Source Is Indicated (SR Is Synchrotron Radiation, and the D_2 Lamp Was a Laboratory Source)

Wavelength Range (nm)	Average Wavelength (nm)	Radiation Source	Change in Responsivity at 22 C (%/C) AXUV	SXUV
2.8-3.2	3.0	SR[a]	0.018	0.039
4.5-5.5	5.0	SR[a]	0.017	0.049
8.2-10.2	9.2	SR[a]	0.048	0.047
12.5-15.3	13.9	SR[a]	0.024	0.020
17.1-18.9	18.0	SR[a]	0.013	0.036
25.2-27.4	26.3	SR[a]	0.038	0.024
52.8-60.8	56.8	SR[a]	0.027	0.063
75.2-101.2	88.2	SR[a]	0.046	0.084
115-125	120	D_2 lamp[b]	0.053	c
150-170	160	D_2 lamp[b]	0.021	c
250	240 - 260	D_2 lamp[b]	0.036	0.028

[a]Vacuum measurement. [b]Air measurement. [c]Signal too low.

As seen in Fig. 2, the normalized responsivity (equal to the normalized current) of the AXUV photodiode tends to increase with temperature. At each photodiode temperature, the normalized responsivity was averaged for each wavelength range and represents the normalized responsivity at each average wavelength value. The average wavelength of each of the eight wavelength ranges, extending from 3.0 to 88.2 nm, is listed in Table I. The average normalized responsivity values of the AXUV photodiode as functions of temperature at the indicated wavelengths are shown by the data points in Fig. 3(a), with the error bars representing the standard deviations from the average values. The curves in Fig. 3(a) represent the best fits to the

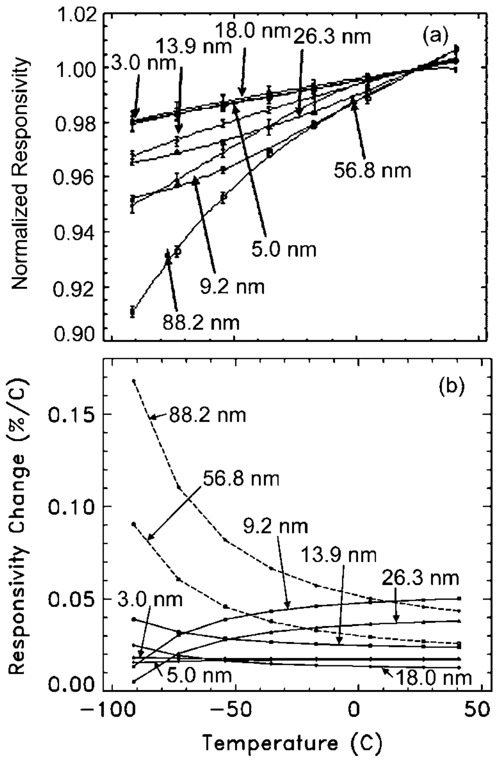

Fig. 3. (a) Normalized responsivity of the AXUV photodiode at the indicated wavelengths as a function of temperature. (b) Change in the current from the AXUV photodiode with temperature, in units of percentage change per degree Centigrade (%/C), at the indicated wavelengths.

data points by the least squares method. The derivatives of the curves represent the responsivity change with temperature, and these values in units of percent change per degrees Centigrade (%/C) are shown in Fig. 3(b).

The change in responsivity values shown in Fig. 3(b) for the AXUV photodiode are typically in the 0.015%/C to 0.05%/C range except for the two wavelengths 56.8 and 88.2 nm which have higher values at the lower temperatures. These anomalously high values can be attributed to the accumulation of moisture on the photodiode surface that has relatively low transmittance at 56.8 and 88.2 nm as described below.

The transmittances of water films with thicknesses in the 0.1–4-nm range are calculated as shown in Fig. 4 [11]. It can be realized that the condensation of a water film as thin as 0.1 nm on the photodiode surface can significantly absorb the incident radiation beam and affect the change in responsivity values, particularly at the 56.8- and 88.2-nm measurement wavelengths. While the pressure was 10^{-7} torr or lower in the vacuum chamber, it is entirely possible that thin moisture films could accumulate on the photodiode surfaces at low temperatures and affect the responsivity change values at these wavelengths.

To show the trends in the change in responsivity values with wavelength, the AXUV responsivity change values derived from Fig. 3(b) at two selected temperatures, (a) −80 °C and (b) +22 °C, are shown in Fig. 5. Similar values for the SXUV photodiode are shown in Fig. 6. The apparent scatter in the responsivity change average values at 56.8 and 88.2 nm wavelengths, measured at −80 °C, is believed to result from water

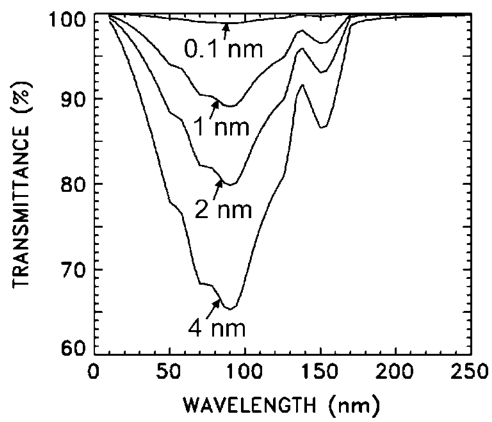

Fig. 4. Calculated transmittance of water films with thicknesses in the 0.1 nm to 4 nm range.

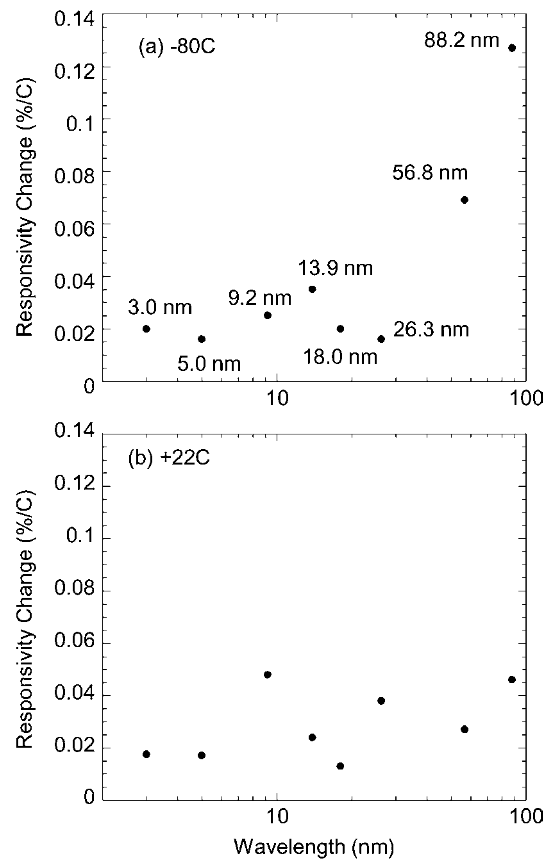

Fig. 5. Responsivity change as a function of wavelength for the AXUV photodiode at temperatures of (a) −80 ° C and (b) +22 ° C.

condensation on the surface for the case of AXUV photodiode when operating at low temperature. However, the remaining scatter in the responsivity change values with wavelength (apart from the above reason) indicates that the wavelength dependence of the responsivity change values is quite significant.

For the SXUV photodiode, the scatter in the responsivity change values is somewhat higher than for the AXUV photodiode. This could be a result of surface contamination as well as oxidation of the SXUV metal silicide surface, in addition to the water condensation effect at low temperature. Moreover, the signal currents from the SXUV photodiode were lower than

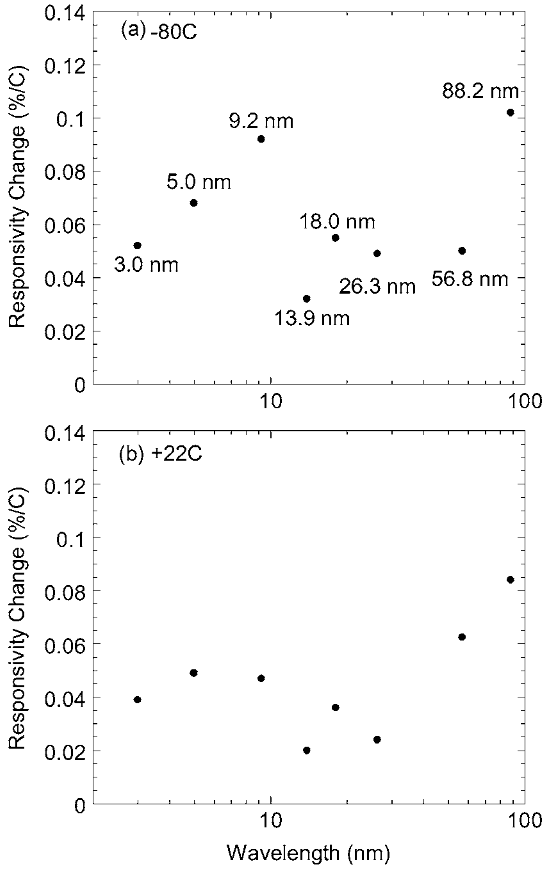

Fig. 6. Responsivity change as a function of wavelength for the SXUV photodiode at temperatures of (a) -80 °C and (b) $+22$ °C.

from the AXUV photodiode and could contribute to the considerable variations in the SXUV data.

III. Laboratory Measurements

In order to investigate the possibility of moisture condensation during the synchrotron measurements, additional measurements were performed at the wavelengths 120, 160, and 250 nm using available laboratory radiation sources and bandpass filters. A number of procedural techniques were implemented to reduce the effect of moisture condensation. The vacuum chamber was much smaller than the chamber used for the synchrotron radiation measurements. The chamber was evacuated by a turbomolecular pump, and the pressure was further reduced by a large plate that was cooled by liquid nitrogen. The pressure was typically $<10^{-7}$ torr for the measurements at temperatures <0 °C. The reference photodiode was thermally isolated and was at room temperature throughout the measurements.

The radiation source was a deuterium discharge lamp with a MgF_2 window. The lamp interfaced to a vacuum chamber that housed the same test photodiode support fixture and temperature control system that were used for the synchrotron measurements. The vacuum chamber had several mechanical vacuum feedthroughs which were used to move the bandpass filters, a soda-glass filter, and a room-temperature reference AXUV photodiode into the beam. Similar to the synchrotron measurements, the test photodiode was cooled by a copper strap attached to a liquid nitrogen reservoir. The room-temperature reference AXUV photodiode monitored the lamp intensity.

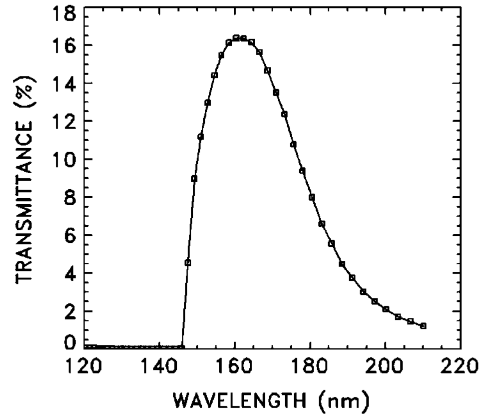

Fig. 7. Transmittance of the 160-nm bandpass filter measured by synchrotron radiation.

One of three thin-film interference bandpass filters could be inserted into the radiation beam between the lamp and the photodiodes. The filters had peak transmittances at wavelengths of 120, 160, and 250 nm. The filters had low transmittances at wavelengths much shorter than the peak wavelengths, because of low substrate transmittance, but could have significant transmittances at longer wavelengths. For example, the transmittance of the 160-nm filter, measured using synchrotron radiation, is shown in Fig. 7. While the filter has relatively high transmittance in the 150–170-nm wavelength range and negligible transmittance shorter than 145 nm, the filter has significant transmittance at wavelengths longer than 200 nm.

The effects of longer wavelengths were accounted for by performing measurements with and without a soda-glass filter that had low transmittance for wavelengths <250 nm. The measured quantities were (TD-TG)/(RD-RG) where TD was the test (temperature controlled) photodiode current with the bandpass filter and without the glass filter, TG was the test photodiode current with the bandpass filter and the glass filter, RD was the reference (room temperature) photodiode current with the bandpass filter and without the glass filter, and RG was the reference photodiode current with the bandpass filter and the glass filter. Thus, the quantity (TD-TG)/(RD-RG) is essentially the in-band current measured by the temperature controlled test photodiode divided by the in-band current measured by the room temperature reference photodiode.

The (TD-TG)/(RD-RG) values, normalized to the values at 22 °C, are shown in Fig. 8 for the AXUV test photodiode. The data points are the average values of five measurements performed at each temperature, and the error bars are the standard deviations of the five measurements. The dashed lines are the best fits (linear in this case) to the average values using the least squares method. The slopes of the dashed lines are the responsivity change with temperature. For the wavelengths 120 and 160 nm, the responsivity change values of the AXUV photodiode are 0.053%/C and 0.021%/C, respectively. The responsivity change value at 120 nm is rather high, and this may imply that our method of preventing water condensation might not be as efficient. Since the current from the SXUV test photodiode

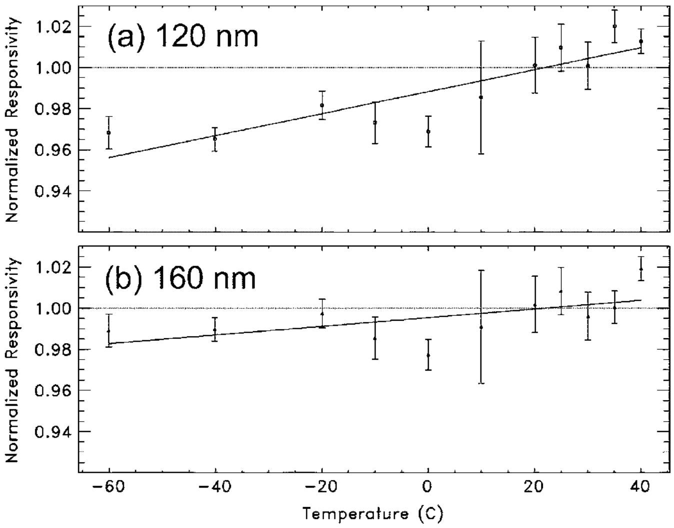

Fig. 8. Normalized responsivity of the AXUV photodiode at wavelengths of (a) 120 and (b) 160 nm.

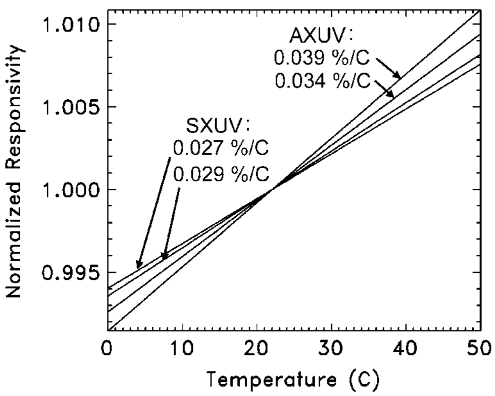

Fig. 9. Normalized responsivity of AXUV and SXUV photodiodes at a wavelength of 250 nm.

was a factor of ten lower than the current from the AXUV photodiode, the SXUV data were not sufficiency accurate to determine the change in responsivity.

Because water is essentially transparent at 250-nm wavelength (see Fig. 4), the laboratory measurements were performed at this wavelength using a brighter deuterium lamp. In this case, the test photodiode was not housed in a vacuum chamber and was cooled by thermoelectric coolers with a dry nitrogen gas purge over the photodiode surface. The test photodiode currents were only measured over the 0 °C to 50 °C temperature range and were normalized to the room temperature values. The current change was linear over this temperature range, and straight lines were fitted to the data by the least squares method. The normalized responsivities of two AXUV and two SXUV photodiodes are shown in Fig. 9. The change in responsivities of the two AXUV photodiodes are 0.034%/C and 0.039%/C, and the corresponding SXUV values are 0.027%/C and 0.029%/C.

IV. Discussion

The AXUV and SXUV photodiodes both have positive temperature dependence meaning that their responsivity increases with increasing temperature. Except for the anomalously high responsivity change values at low temperatures where water condensation is feasible and at wavelengths where water absorption is high, the average responsivity change values (in %/C) of the AXUV photodiodes are relatively insensitive to temperature and can be represented at room temperature (22 °C) as summarized in Table I. The values for the change in responsivity of the AXUV photodiode range from a low of 0.013%/C at 18.0 nm wavelength to a high of 0.053%/C at 120-nm wavelength. In comparison, the SXUV values at 22 °C range from 0.020%/C at 13.9 nm to 0.084%/C at 88.2 nm.

Since the AXUV photodiodes have essentially 100% internal quantum efficiency and the surface reflection is negligible at the EUV wavelengths, the parameter that can change with temperature is the silicon pair creation energy which is related to the silicon bandgap [12] and is known to decrease with temperature [13]. The temperature dependence is given by

$$E_g(T) = E_g(0) - \alpha T^2/(T+\beta) \quad (1)$$

where $\alpha = 4.73 \times 10^{-4}$ eV/K and $\beta = 636$ K. The percentage decrease in the bandgap energy with temperature varies from 0.018%/C at -100 C to 0.027%/C at $+50$ ° C, and these values represent a decrease in the pair creation energy (also known as ionization energy) and a corresponding increase in the responsivity with temperature. The change in the silicon bandgap energy at room temperature (295 K) is 0.025%/C and is well within the measured change in the AXUV and SXUV photodiode responsivity presented in Table I.

The variation in the change in responsivity values with wavelength in both the AXUV and SXUV photodiodes might be related to the variation of the Si absorption coefficient with wavelength as well as temperature. However, it is also possible that such a wavelength variation is related to the difficulty of measuring small changes in responsivity over a wide wavelength range where the effect of surface contamination is highly variable and significant. Other possible errors contributing to the above variation are instability in the photodiode responsivity during the measurements (related to the response time of the photodiodes and the settling time before taking data at each temperature) and incomplete accounting of the variation of the incident radiation especially when the intensity is low.

It should be pointed out that previous work reports less than 0.01%/C temperature dependence of the responsivity in the 205–885 nm wavelength range where the responsivity was concluded to be independent with temperature [8]. Those photodiodes were p-on-n which are difficult to produce with 100% internal quantum efficiency (because the passivating oxide which has fixed positive charge attracts the minority carrier electrons generated in the front p-region by the strongly absorbing UV photons). Thus, it is likely that these devices had surface recombination which is known to have negative temperature dependence [13]. As quantum yield exists for all photons with wavelength shorter than 350 nm [8], its positive temperature dependence will offset the negative temperature dependence of surface recombination resulting in the observed low temperature dependence. At wavelength above 350 nm, the only explanation of why the responsivity might be independent of temperature could be that the diffusion length of minority carriers in such p-on-n devices is longer than the involved photon penetration depth. The temperature dependence of photodiode responsivity above 350 nm is beyond the scope of this study and should be the topic of future study.

V. Conclusion

The changes in the responsivity with temperature of two types of silicon photodiodes were measured in the 3- to 250-nm wavelength range. The change in responsivity with temperature is positive for all wavelengths and can be explained by increased quantum yield (reduced pair creation energy) owing to reduced silicon bandgap with increasing temperature. Variations of the change in responsivity values with temperature and wavelength were observed that are attributed to the effect of surface contamination (in particular moisture condensation at low temperature), the variation of Si absorption coefficient, and possible measurement errors for such small changes. The measured change in responsivity values range from 0.013%/C to 0.053%/C for the AXUV photodiode and 0.020%/C to 0.084%/C for the SXUV photodiode, in the 3- to 250-nm wavelength range and at room temperature.

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