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Temperature and Polarization Performance of EUV Silicon Photodiodes

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Abstract. The performance characteristics of a silicon photodiode (type AXUV100) were determined using the beamline X24C at the National Synchrotron Light Source. The diode sensitivity was measured in the temperature range of -92^{o} C to +41^{o} C and in the wavelength region of 3.0 nm to 88.2 nm. This work is important for understanding variations of the diode sensitivity in environments that are colder or hotter than ambient room temperature, such as on a spacecraft or under intense synchrotron or laser irradiation. In addition, the sensitivity of a AVUV100 diode with a multilayer interference coating was measured as a function of the polarization of the incident radiation and the angle of incidence. The Mo/Si multilayer coating, when operating at an angle of incidence of 45^{o}, was designed to selectively transmit the P polarized radiation for detection by the underlying diode and to efficiently reflect the S polarization. The results demonstrate the ability to accurately measure the polarization of radiation within the reflectance profile of the multilayer centered at 13.5 nm. By optimizing the transmittance and reflectance profiles of the multilayer coating for the desired wavelength range and angle of incidence, this new multilayer-coated photodiode technique can be used to measure the polarization of incident radiation from solar, astrophysical, synchrotron, or other laboratory sources over a wide range of extreme ultraviolet and soft x-ray wavelengths.

TEMPERATURE DEPENDENCE OF THE PHOTODIODE RESPONSIVITY

The change in the responsivity of an AXUV100 silicon PIN photodiode with temperature was measured over the range -92^{o} C to +41^{o} C. The photodiode was mounted on a thermal stage, and the surface of the photodiode was perpendicular to the incident synchrotron radiation beam (National Synchrotron Light Source beamline X24C). At each of eight fixed temperatures, the wavelength of the incident radiation was scanned over eight narrow wavelength intervals centered at 3.0 nm, 5.0 nm, 9.2 nm, 13.9 nm, 18.0 nm, 26.3 nm, 56.8 nm, and 88.2 nm. It was found that the change in responsivity, in units of % change per degree C, was approximately constant within a wavelength interval. The change in responsivity varied from one wavelength interval to another as indicated in Fig. 1. The error bars represent the change in responsivity within each wavelength interval. At the two longer wavelengths (56.8 nm and 88.2 nm), the incident radiation intensity was rather weak, and this contributed to the large error bars.

As seen in Fig. 1, the change in responsivity with temperature is positive and tends to increase with wavelength. A smooth curve was fitted to the data points using the least squares technique, and several data points significantly deviate from the curve. This suggests that the change in responsivity may depend on factors other than simply the wavelength. The dependence of the change in responsivity on the depth at which the photon energy is deposited in the photodiode was investigated using the computational model described in Ref. 1. This model calculates the complex Fresnel coefficients and the energy attenuation as a function of depth into the photodiode based on the optical properties of the photodiode layers. By comparison to the measured absolute responsivity of the AXUV100 diode, the charge collection efficiency was determined to be 15% in the 6 nm thick SiO_2 surface layer and rapidly increasing to 100% in the underlying silicon.

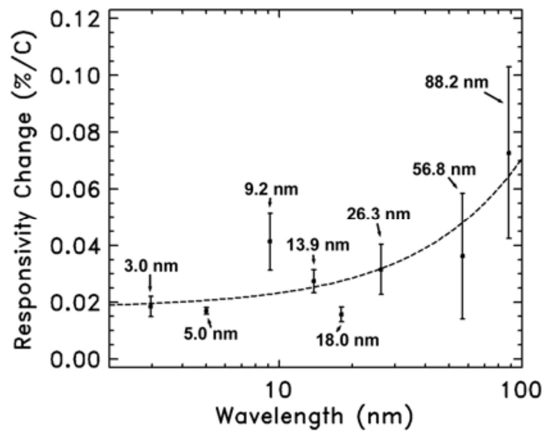

FIGURE 1. The measured change in the responsivity of the photodiode as a function of the incident wavelength.

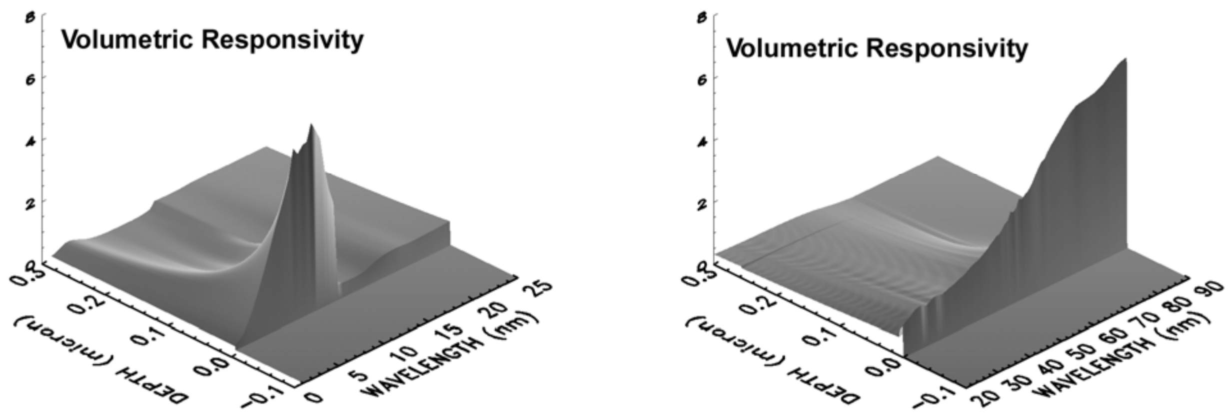

Figure 2. The calculated volumetric responsivity (in units of A/Wμm) of the photodiode as a function of the incident wavelength and the depth into the device.

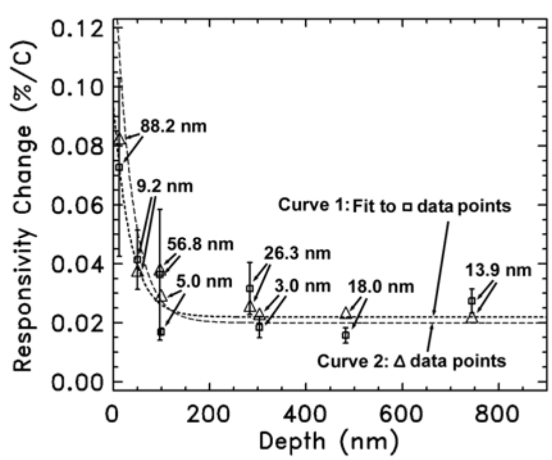

FIGURE 3. The change in responsivity as a function of the average depth of the photon energy deposition.

Shown in Fig. 2 is the calculated volumetric responsivity (VR), the ratio of the current generated per unit volume in the device and the radiation power per unit area incident on the surface, in units of A/Wμm. For the two longest wavelengths (88.2 nm and 56.8 nm), the SiO_2 surface layer is relatively absorptive, and the VR is highest within the SiO_2 surface layer and decreases rapidly with depth below the surface layer. At the 9.2 nm wavelength, shorter than the Si L attenuation edge at 12.4 nm where Si is absorptive, the VR is relative high in the silicon region just below the SiO_2 surface layer. At the two shortest wavelengths (3.0 nm and 5.0 nm), SiO_2 and Si are transmissive and the VR decreases slowly with depth. This is also true of the 13.9 nm wavelength just above the Si L attenuation edge where SiO_2 and Si are transmissive.

At each of the eight wavelengths, the average depth of the photon energy deposition was calculated by using the VR as a weighting factor. The change in responsivity as a function of the average energy deposition depth is shown by the square data points with the error bars in Fig. 3. Curve #1 in Fig. 3 was fitted to these data points, and this curve is an initial representation of the change in responsivity with depth. As expected, the longer wavelengths 88.2 nm and 56.8 nm, and the 9.2 nm wavelength below the Si L attenuation edge, have small average photon absorption depths. The relatively transmissive 13.9 nm and 18.0 nm wavelengths have the largest average energy deposition depths. Two pairs of wavelengths have similar average energy deposition depths, 5.0/56.8 nm and 3.0/26.3 nm. Since the pair creation energy (3.65 eV) is independent of wavelength in the EUV region, each pair of wavelengths would be expected to have similar change in responsivity values. However, as seen by the square data points in Fig. 3, the change in responsivity at the longer wavelength in each pair is higher than for the corresponding shorter wavelength in each pair. This is because, although the two wavelengths have nearly the same VR-weighted average energy deposition depths, more of the longer wavelength energy is deposited in the SiO_2 surface layer where the change is responsivity is high, while more of the shorter wavelength energy is deposited deeper in the device where the change in responsivity is lower. Thus the change in responsivity was calculated by using the curve #1 fitted to the square data points and the VR as a weighting factor. The resulting average changes in responsivity, weighted by the VR, are shown by the triangular data points in Fig. 3 and the fitted curve #2. The discrepancies between the 5.0/56.8 nm and 3.0/26.3 nm wavelength pairs are reduced to the level of insignificance (within the error bars). The curve #2 in Fig. 3, the final inferred change in responsivity, indicates that the change in responsivity is relatively high (up to 0.12 %/C) in the 6 nm thick SiO_2 surface layer and rapidly decreases to the constant value 0.02 %/C at depths greater than 200 nm. The change in responsivity of a type SXUV100 photodiode was also determined and was found to be smaller near the surface. The rapid changes is responsivity near the surfaces of the photodiodes appear to be associated with the surface treatments. The positive change in responsivity with temperature may result from a widening of the depletion region with temperature resulting from increased diffusion of charge carriers.

POLARIZATION PERFROMANCE OF A MULTILAYER-COATED PHOTODIODE

A standard technique for measuring the polarization of EUV radiation is by detection of the polarization component that is reflected at an angle of 45^o from a mirror with a single opaque layer such as gold or with a multilayer coating. The EUV reflectance is sensitive to contamination or oxidation of the surface of the mirror. A newly developed polarization measurement technique is to deposit a multilayer interference coating on a silicon photodiode and to selectively detect the polarization component that is transmitted through the multilayer coating to the underlying photodiode.[2] This technique has the advantage that the transmittance of the coating is relatively insensitive to the surface conditions, and the device is monolithic, having an integrated detector and polarizing element. These advantages can be critically important when the polarization device must hold its calibration in a hostile environment such as for spaceflight instrumentation and intense laboratory sources of radiation.

The multilayer transmissive polarimeter consists of a multilayer coating deposited onto the surface of a silicon photodiode. The first device implemented a Mo/Si coating on an AXUV100 photodiode. The coating was computationally designed to selectively transmit the P-polarized component of 13.5 nm wavelength radiation at an angle of incidence of 45^o and to efficiently reflect the S-polarized incident radiation. The coating was deposited at Lawrence Livermore National Laboratory by dc-magnetron sputtering. The multilayer included a thin B_4C barrier layer at the Mo-on-Si interfaces which enhanced the reflectance and stability of the coating. The performance of the multilayer-coated device was measured using polarized, monochromatic synchrotron radiation at the NSLS X24C beamline.

The transmittance and reflectance of the multilayer coating on the photodiode, determined after accounting for the polarization of the incident radiation beam, are shown in Fig. 4. At an angle of incidence of 45^o and 13.5 nm wavelength, there is high contrast between the S and P polarization values: T_P=8.4%, T_S=0.2%, R_P=2.4%, and R_S=69.9%. Thus the P polarization is selectively transmitted and the S polarization is primarily reflected.

The transmissive polarization performance is defined as $P_T=(T_S-T_P)/(T_S+T_P)$. The reflective polarization performance is the same except T is replaced by R. As shown in Fig. 5, the value of P_T is -0.95 in an operating window that is 0.75 nm wide near 13.5 nm wavelength (the negative value of P_T is a sign convention). The value of P_R exceeds +0.80 over a broader wavelength range and has a maximum value of essentially +1.0. This illustrates the high values of polarization performance that can be achieved with the multilayer polarimeter device. A more detailed analysis of the Mo/Si multilayer polarimeter will appear in Applied Optics.[2] Work is in progress to study a similar transmissive multilayer polarimeter using a Mo/Y multilayer in the 9 nm wavelength region.

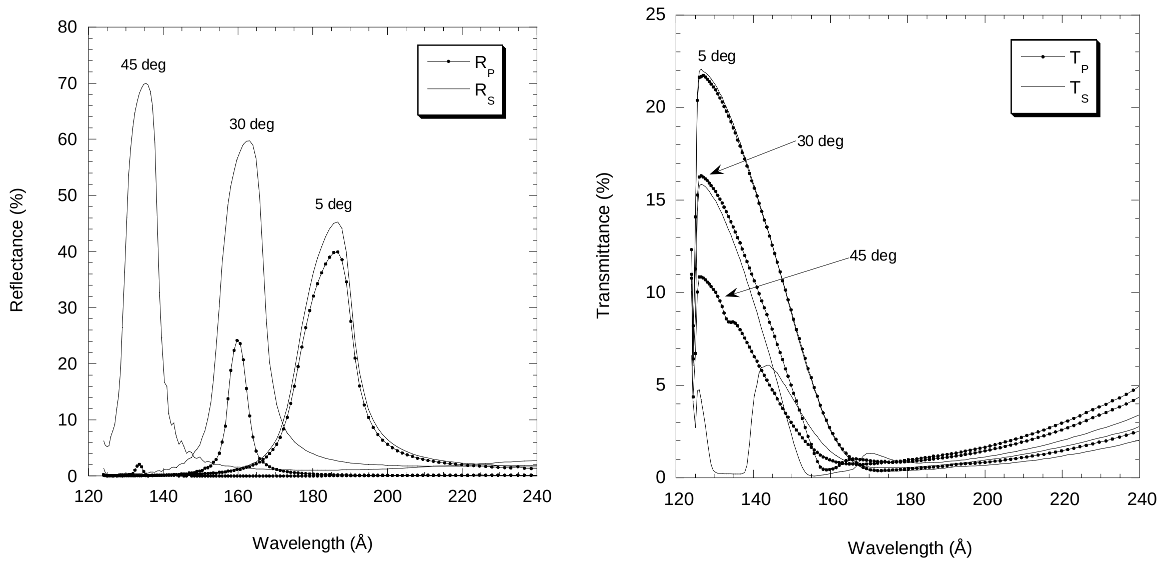

FIGURE 4. The reflectance and transmittance of the multilayer coating on the photodiode.

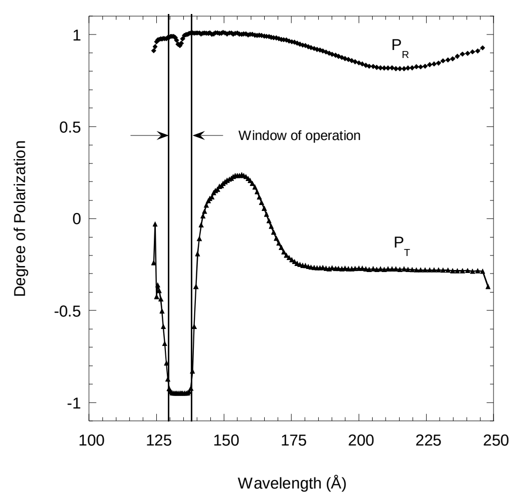

FIGURE 5. The polarization performance P_R in reflection and P_T in transmission.

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1. Seely, J., Proc. S.P.I.E. vol. 4139, 1-7 (2000).
2. Kjornrattanawanich, B., Bajt, S., and Seely, J., Appl. Opt. (in press).