Silicon Absolute X-Ray Detectors

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Abstract. The responsivity of silicon photodiodes having no loss in the entrance window, measured using synchrotron radiation in the 1.75 to 60 keV range, was compared to the responsivity calculated using the silicon thickness measured using near-infrared light. The measured and calculated responsivities agree with an average difference of 1.3%. This enables their use as absolute x-ray detectors.

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INTRODUCTION

Silicon photodiodes (AXUV series) are being used as absolute devices for 50 eV to 1500 eV photons because of their well known device parameters, mainly the Internal Quantum Efficiency (IQE). The IQE is 100% from 270 to 800 nm and higher at shorter wavelengths due to the creation of multiple electron-hole pairs by a single high energy photon.[1] IQE is defined as the percentage of internal charge generated in the diode per incident photon. Figure 1 shows the cross-section of the photodiode investigated. A thin 4 to 7 nm nitrided silicon dioxide front window has minimal absorption of x-rays above 1100 eV,[2] and thus the AXUV diodes are expected to have near theoretical responsivities for the x-ray photons with energies above 1100 eV.

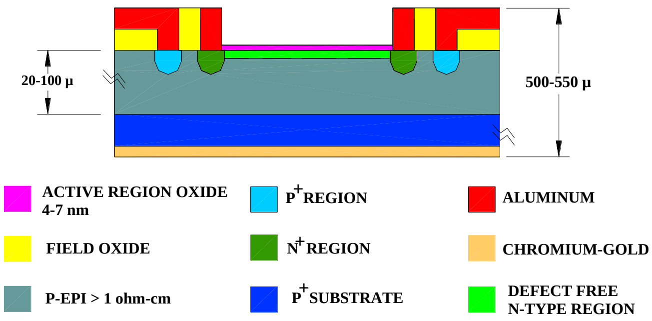

FIGURE 1. Cross-section of the silicon photodiode investigated.

As the AXUV diodes have 20 to 100 microns of effective silicon thickness, a significant fraction of photons with energies above 4000 eV transmit through the active silicon, reducing the devices quantum efficiency from the

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designed 100% value. Therefore, if the effective silicon thickness is measured, these devices can be used as absolute x-ray detectors.

From 900 to 1100 nm, light propagation distances are also longer than silicon thicknesses, leading to a reduction in the number of photons absorbed and the measured IQE. Since the detectors have 100% efficiency in the active silicon, the reduction in the measured IQE arises strictly from photon absorption. Thus, near-IR measurements may be used to calculate the estimated thickness using

$$I/I_0 = 1 - P = 1 - IQE = Exp(-\alpha(\lambda)\,x) \qquad (1)$$

In Equation 1 the relative intensity of light propagating in the bulk is I/I_0, the absorption coefficient is `a(l)` (μm^{-1}), P is the fraction of photons absorbed, and the absorption depth is x (µm). Setting the absorption depth x equal to the effective silicon thickness t and rearranging yields:

$$t = -(1/\alpha(\lambda))\,Ln(1-P) \qquad (2)$$

Second order corrections in the above thickness calculations are not detailed here, but include reflections off the back surface of the detector.

Once the thickness is known, the responsivity as a function of photon energy {s(ε_{Ph})} is found using

$$s(\varepsilon_{Ph},t) = F_f\,T_{SiO_2}(\varepsilon_{Ph},t_{SiO_2})\,\frac{\mathrm{A_{Si}}(\varepsilon_{Ph},t_{Si})}{3.66}\ \ \text{(A/W)} \qquad (3)$$

Silicon absorption $\mathrm{A_{Si}}(\varepsilon_{Ph},t_{Si})$ and silicon oxide transmission $T_{SiO_2}(\varepsilon_{Ph},t_{SiO_2})$ values are commonly tabulated and found in public databases provided by LBL (10 eV – 30 keV)[2] and NIST (1 keV – 20 MeV).[3] NIST values are presented as mass-energy absorption coefficients. Oxide thicknesses t_{SiO_2} are measured through a variety of standard ellipsometry or reflectometry techniques. The value of 3.66 is an average value for electron-hole pair creation energy (eV) in silicon.[4] The factor F_f accounts for K-shell fluorescence and reabsorption in silicon above 1838 eV, and for LBL calculations is taken as 0.98 to account for about 2% silicon x-ray fluorescence yield (which was a 5% fluorescence yield before reabsorption of the fluorescent photons). Silicon fluorescence yield has been experimentally measured for photons with energy up to 9 keV.[5] As some of the silicon fluorescence gets reabsorbed for higher energy photons, F_f will be larger for the high energy x-rays. NIST mass energy absorption coefficients already include fluorescence reabsorption effects and F_f may be set equal to 1 for calculations.

EXPERIMENTAL DATA

Silicon photodiodes with measured 23.5 µm effective silicon thickness were measured for responsivity between 600 and 1900 eV at the BESSY II electron storage ring in PTB, Germany.[6] A monochromator with a plane grating serves as the x-ray selection source for synchrotron radiation, while photon flux and energy is calculated from fundamental electrodynamics based on direct measurement of the source ring current. Fig. 2 shows measured responsivity data, as well as a fit to the data using Equation 3. Below 1838 eV, a line calculated using t = 23.5 µm thick silicon and Equation 3 fits very well with observed data. Above the 1838 eV silicon K-edge, three calculations are plotted: diode responsivity with no fluorescence, diode responsivity with 5% losses due to fluorescence, and diode responsivity with 5% loss and reabsorption.

A second set of PTB calibration measurements was performed in the 1.75 to 60 keV energy range and is shown in Figure 3. Also shown is the responsivity modeled using the effective silicon thickness, 104.5 µm, measured using near-infrared light. The average difference between the modeled and calculated responsivity for NIST values is 1.3%. Thus the measurement of the effective silicon thickness using near-infrared light enables the use of the device as an absolute x-ray detector without having to perform the calibration at x-ray energies using synchrotron radiation.

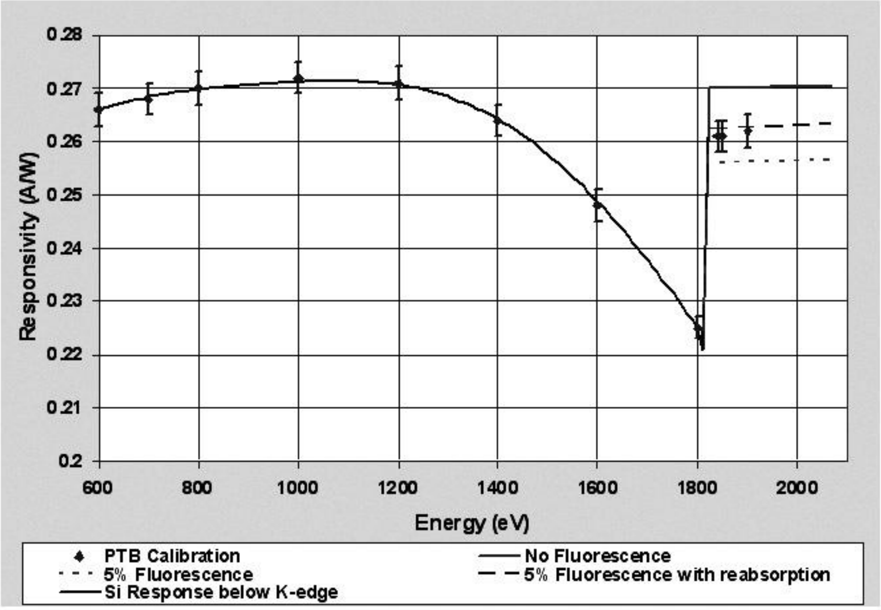

FIGURE 2. Calibrated and modeled responsivity of AXUV photodiode, 23.5 µm Si thickness.

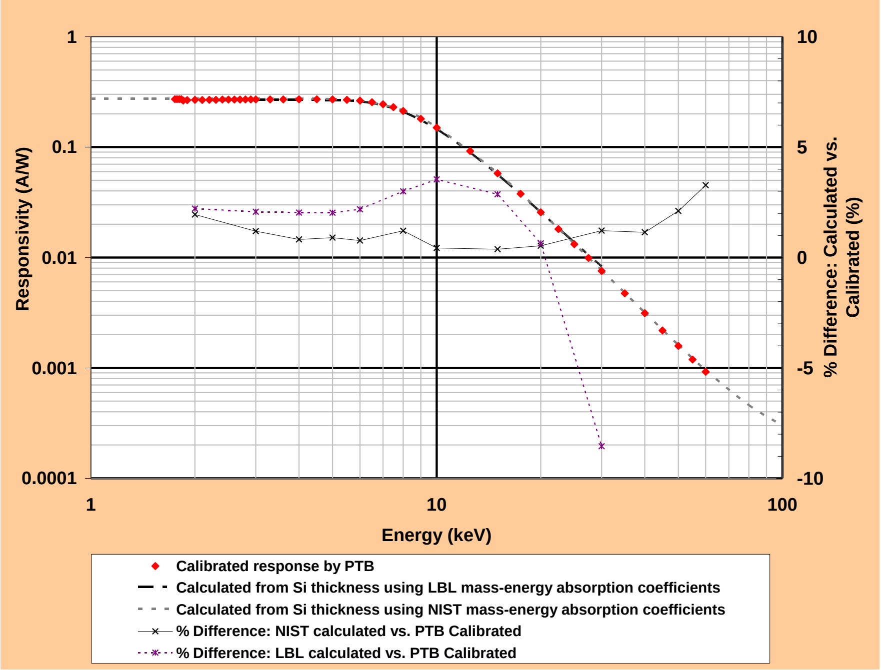

FIGURE 3. Measured and modeled responsivities of an AXUV diode to X-rays.

A third set of high energy responsivity measurements, not shown in detail here, was performed on 52 µm and 104 µm thick silicon devices using 17 keV to 45 keV x-rays. Monochromatic radiation at the SOLEIL synchrotron's CRISTAL undulator was used to make the measurements. An absolute detector ($LaCl_3$ scintillator coupled to a photomultiplier which is connected to a counting electronic readout) was used as a reference to measure the photodiode responsivity. Aluminum and stainless filters were used for respectively low and high energies to reduce incoming flux. Absolute incident flux was deduced from the counting measurement divided by the filter transmission which is calculated with the NIST database.[3] After removing the attenuators, the scintillator is replaced by the AXUV photodiode read through a FEMTO DLPCA-200 electrometer. Responsivity is obtained as follows:

$$s(\varepsilon_{Ph}) = \frac{I_{Ph} / MI_2}{\left(N_{Ph} \times \varepsilon_{Ph} \times q\right) / MI_1} \qquad (4)$$

where I_{Ph} is the photodiode current, N_{ph} is the absolute incident flux, ε_{Ph} is the photons energy, q is the elementary charge, and MI_1 and MI_2 are the intensity monitor current respectively associated to the absolute incident flux measurement and the photodiode current measurement. As for the PTB calibrations, the measured responsivities were in good agreement with the modeled responsivities using the known silicon thicknesses.

The advantage of the AXUV photodiodes can be seen in Table 2 of reference 7. Measurements indicate that AXUV photodiodes have sensitivities up to 20% higher then comparable photodiodes for incident fluxes at 5.8 keV and 6.5 keV energies. Since AXUV photodiodes are the only photodiodes with 100% IQE and no dead layer, the lower responsivity of comparable photodiodes is attributed to a dead layers hundred of angstroms thick. As beam energies increase sensitivities converge and the dead layer becomes a less important contributing factor to diode measurements.

CONCLUSIONS

Silicon photodiodes with 100% internal quantum efficiency and with known silicon thickness can be used as absolute detectors for 600 eV to 60 keV x-rays. As the silicon optical constants for the higher energy x-rays are well known, it is possible to use these devices as absolute detectors for x-rays with much higher energy. In effect they have a self-calibration that depends only on the effective silicon thickness that can be easily measured using near-infrared light. This makes these devices extremely useful for x-ray dosimetry compared to other silicon dosimeters that require calibrations using energetic x-rays.

ACKNOWLEDGMENTS

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