IRD UV PHOTODIODES
Absolute UV Silicon Photodiodes - AXUV Series

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AXUV Operating Principles

When these diodes are exposed to photons of energy greater than 1.12 eV (wavelength less than 1100 nm) electron-hole pairs (carriers) are created. These photogenerated carriers are separated by the p-n junction electric field and a current proportional to the number of electron-hole pairs created flows through an external circuit. For the majority of XUV photons, about 3.7 eV energy is required to generate one electron-hole pair. Thus more than one electron-hole pair is generally created by these photons. This results in device quantum efficiencies (electrons seen by an external circuit per incident photon) much greater than unity, which increase linearly with photon energy.

Two unique properties of the AXUV photodiodes provide previously unattainable stable, high quantum efficiencies for XUV photons. The first property is the absence of a surface dead region i.e. no recombination of photogenerated carriers in the doped n-region or at the silicon-silicon dioxide interface. As absorption depths for the majority of XUV photons are less than 1 micrometer in silicon, the absence of a dead region yields complete collection of the photogenerated carriers by an external circuit resulting in 100% carrier collection efficiency and near theoretical quantum efficiency.

The second unique property of the AXUV diodes is their extremely thin (3 to 7 nm), radiation-hard silicon dioxide junction passivating, protective entrance window. Owing to these two outstanding properties, the quantum efficiency of AXUV diodes can be approximately predicted in most of the XUV region by the theoretical expression Eph/3.7, where Eph is the photon energy in electron-volts.

The only quantum efficiency loss is due to the front (3 to 7 nm) silicon dioxide window at wavelengths for which (mainly for 7 to 100 eV photons) oxide absorption and reflection are not negligible.

At wavelengths shorter then about 0.41 nm or longer then about 700 nm, the response of the photodiode will be limited by the "effective silicon thickness" diode. The exact wavelengths where the effect becomes important depends on the effective silicon thickness. Incident light at these wavelengths will transmit through the active collection region of the silicon and responsivity will be reduced from its ideal value. The effective silicon thickness can be measured at IRD's radiometric characterization facility; due to the absolute nature of the detectors, this thickness can be used to calculate diode responsivity up to energies of 50 keV (see the Absolute X-ray Detectors page).

Figure 1 shows typical quantum efficiency plots for AXUV photodiodes with various oxide and silicon thicknesses.

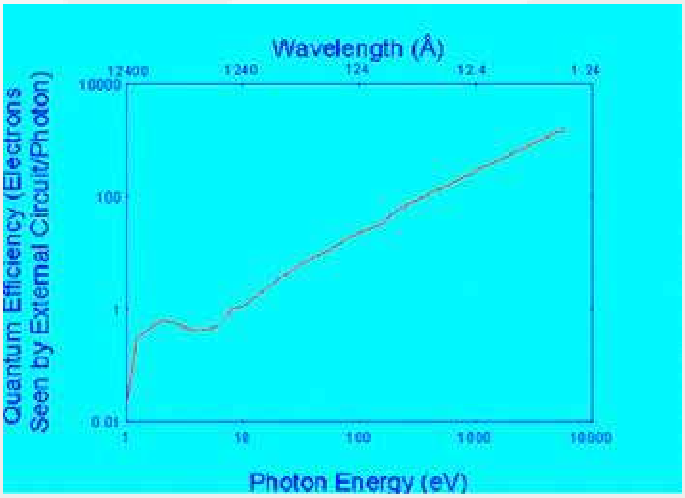


Figure 1 - Typical quantum efficiency of the AXUV photodiodes.

Owing to their extremely thin (3 to 7 nm) entrance window, AXUV diodes exhibit near theoretical response to low energy electrons and hydrogen ions. Figure 2 shows the responsivity of AXUV photodiodes to photons with 10 to 4000 eV energy and to electrons and hydrogen ions with 100 to 40,000 eV energy.

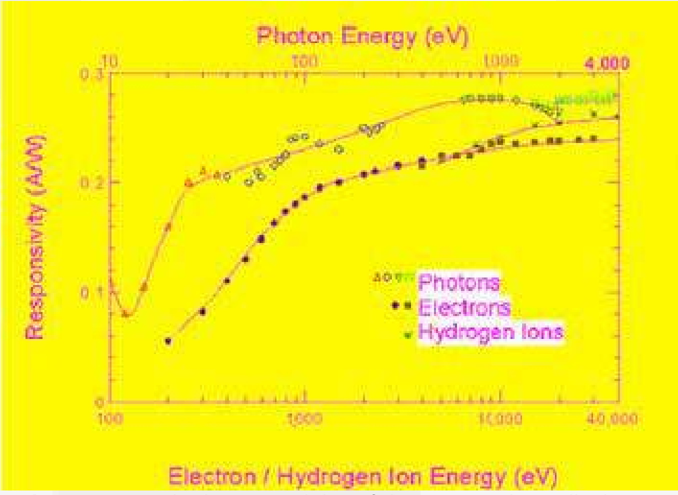
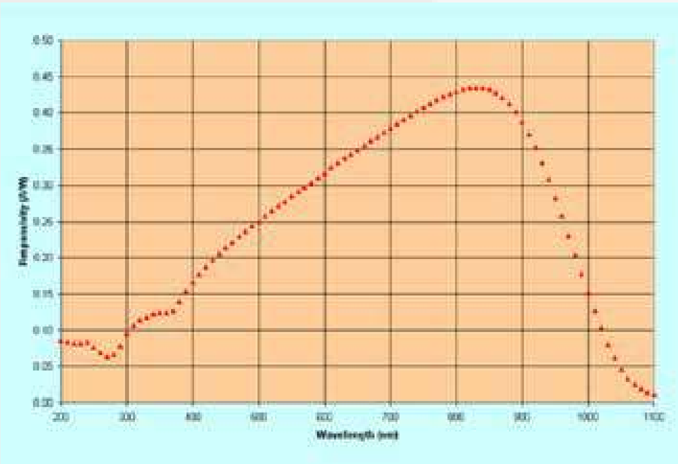


Figure 2 - Typical responsivity of the AXUV photodiodes to photons, electrons and hydrogen



Typical UV/Visible responsivity of the AXUV photodiode, 50 µm effective Si Thickness

AXUV Photodiode Applications

The AXUV photodiodes have several advantages over the orthodox tube-type XUV detectors. The AXUV photodiodes exhibit very low noise, do not need external voltages for their operation, are insensitive to magnetic fields, cost less to fabricate, have low mass and have large collection area to size ratio making them extremely attractive for use in satellites and deep space probes.

These diodes have been approved as transfer standards in the XUV spectral range because of their ease of use, excellent stability and spatial homogeneity of quantum efficiency, large dynamic range (over eight orders of magnitude), small size, ruggedness, and ultrahigh vacuum compatibility. These diodes are operated in the open face configuration down to Angstrom wavelengths, even in the presence of gases. This feature gives the AXUV diode based spectrometers an important advantage over present XUV spectrometers based on conventional detectors, which need to be used either in vacuum or with a window.

Due to these unique features, AXUV photodiodes have been successfully used in the European SOHO and Coronas-Photon, and American SNOE, SORCE, GOES, TIMED and EOS solar space instrumentation.

An AXUV multi-element diode array has been successfully used in a Ring Accelerator Experiment (RACE) at Lawrence Livermore National Laboratory and also by other fusion research laboratories around the world to obtain radiated power vs. length and radius profiles of the plasma. Owing to its fast response speed, the array was found to yield excellent time resolution of power in quasisteady plasma transients.

Small active area AXUV diodes optimized for high response speed were found to be ideal detectors for XUV measurements in a joint US/Russian magnetized target fusion experiment. The performance of the AXUV diodes tested was found to be comparable with that of diamond detectors with orders of magnitude lower cost.

Several quadrant AXUV diodes with central holes and rectangular slit openings have been built specifically for synchrotron beam intensity monitoring and position sensing. Because of its 5 micron physical silicon thickness, the AXUV36 diode can be used in transmission mode for continuous intensity monitoring of the x-ray beam. These devices have proven to be very useful since the unstable nature of synchrotron radiation beam is an important source of experimental error.

AXUV Photodiode Applications

Silicon electron detectors (AXUV-series, p-n junction photodiodes) have been developed by IRD for detection of electrons and low energy ions. Unlike common photodiodes, these diodes do not have a doped dead-region and have zero surface recombination resulting in near theoretical quantum efficiencies for low energy electrons and ions.

The AXUV photodiode behavior is characterized by electron gain Ge, which is the number of charges generated per electron incident upon the detector, or responsivity R, the number of charges generated per incident energy ε. The following relation exists between Ge and R for monoenergetic electrons incident upon the detector:

$$G_e = R \times \varepsilon$$

Responsivity is proportional to the number of electron hole pairs generated in the AXUV photodiode. As the photodiode is exposed to electrons and ions, electron- hole pairs (carriers) are created; the electric field in the p-n junction separates the charges and drives the current in the external circuit. The silicon electron-hole creation energy is found to be 3.71 eV in silicon [1]. For photons, this value can be used to calculate the ideal responsivity in a lossless system, RA = 1/3.71 electron charge/eV = 0.27 C/J = 0.27 A/W.

Particles incident upon a detector surface have additional loss mechanisms not present for photons. For electrons, these losses are summarized in Equation 1, taken from Reference [1].

$$R_m = R_A \,(1 - \Delta_{DL} - \Delta_B - \Delta_R - \Gamma)$$

Equation 1: Electron response equation, including terms for responsivity loss.

R_m - Measured responsivity (A/W)

R_A - Ideal responsivity (A/W) 0.27 A/W in Si

Δ_{DL} - Fractional losses due to dead layer absorption

Δ_B - Fractional losses due to incident electron backscattering

Δ_R - Fractional losses due to residual loss effects in photodiode

Γ - Low incident energy enhancement factor from electron-hole generation in dead layer

In the AXUV series photodiodess, dead layer and residual losses are minimized. Residual losses are dominated by recombination of the electron-hole pairs generation in the silicon-silicon oxide interface, which is non-existant in the 100% internal efficency AXUV photodiodes. Dead layer losses in the the 30 - 70 Â front oxide window are less than 0.1% at ε > 2 keV, increasing at energies lower than 2 keV [1]. This leaves backcattering from the front surface as the dominant loss mechanism at ε > 2 keV. As absorption depths for the low energy ions and electrons are less than 1 micrometer in silicon, when losses from the front oxide window and backscattered electrons are subtracted measured data indicates 100% internal carrier collection efficiency and near theoretical gain/responsivity.

Measured responsivity data is shown in Figure 3, while Figure 4 shows the same results in terms of electron gain.

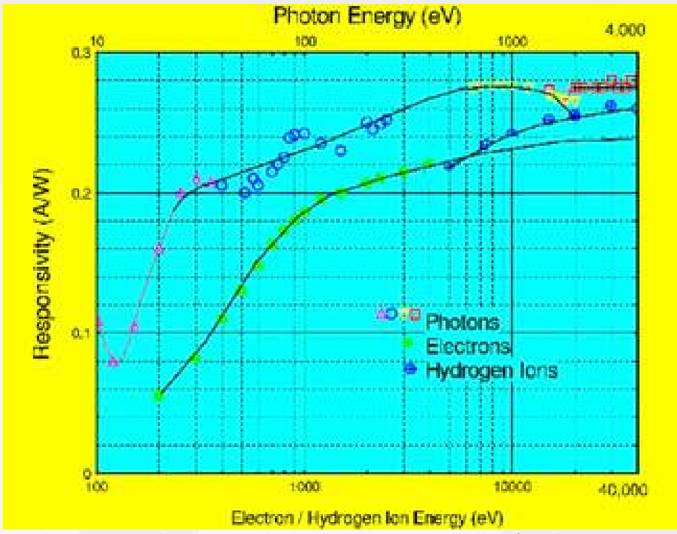


Figure 3 - Photon and electron responsivity for the AXUV photodiode

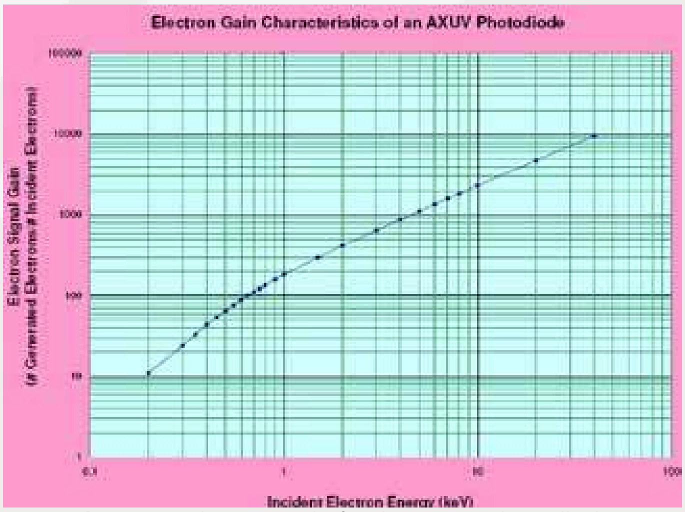


Figure 4 - Electron gain for the AXUV photodiode

AXUV Absolute X-ray Detectors

AXUV standard photodiodes have an effective silicon thickness of 30 to 105 microns. Thus, a fraction of photons with energies above 4000 eV will transmit through the active silicon reducing their quantum efficiency from the designed 100% value. As this reduction is solely caused by the limited silicon thickness, the AXUV diodes can also be used as absolute x-ray devices if silicon thickness is known. AXUV100 photodiodes (10mm x 10mm active area) with measured silicon thickness up to 55 microns with a measurement uncertainty of ±1.5 microns are available as standard products. The AXUV-20HE1 photodiodes have a silicon thickness of 425 microns and will have 100 % collection of photons up to 10 keV. However, because of high noise in these devices, use of the AXUV100 devices with known silicon thickness is recommended. Photodiodes with custom thicknesses can also be manufactured.

Theoretical responsivity as a function of x-ray energy may be obtained once the absorption A(eph) of the silicon layer is known. The absorption may be obtained from public sources such as LBL for photon energies up to 30 keV [1] and NIST for photon energies above 30 keV [2]. Once the absorption is known, the following formula may be used to calculate the responsivity

$$S(\varepsilon_{ph})=Q\ (\varepsilon_{ph})/\varepsilon_{ph}= \frac{0.98\ A(\varepsilon_{ph})}{3.65}(A/W)$$

The value of 3.65 is an average value for electron-hole pair creation energy (eV) in silicon. The factor .98 accounts for 2% x-ray fluorescence yield in silicon for photons with energy larger than 1838 eV and includes estimates for reabsorption of a fraction of the fluorescent light. Silicon fluorescence yield has been experimentally measured for phoons with energy up to 9 keV [3].

Figure 5 shows calculated responsivity for 45, 100 and 425 µm thick silicon.

Figure 6 shows a comparison of responsivity calculated using NIST and LBL data for 53 µm silicon thickness.

Figure 7 shows recently obtained data for a AXUV100GX device with 104 µm thick silicon.

The device was calibrated at PTB and compared against responsivity calculated using the above formula, with ideal results. Calculations included 2% reabsorbance of fluorescent photons. Calculations included 2% reabsorbance of fluorescent photons.

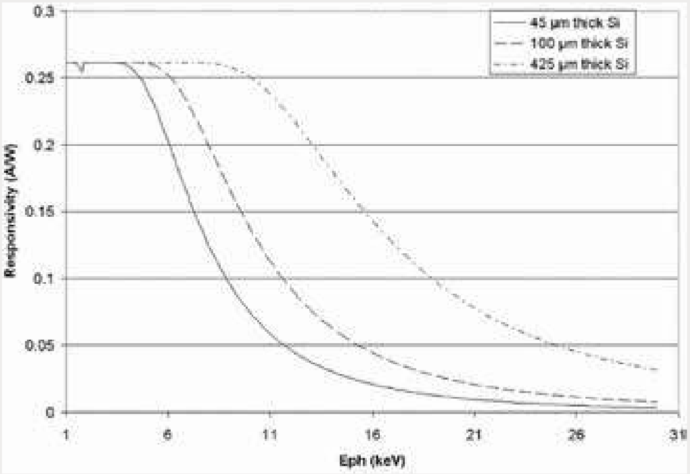


Figure 5 - Responsivity of AXUV photodiodes with 45, 100 and 425 micron effective Si thicknesses.

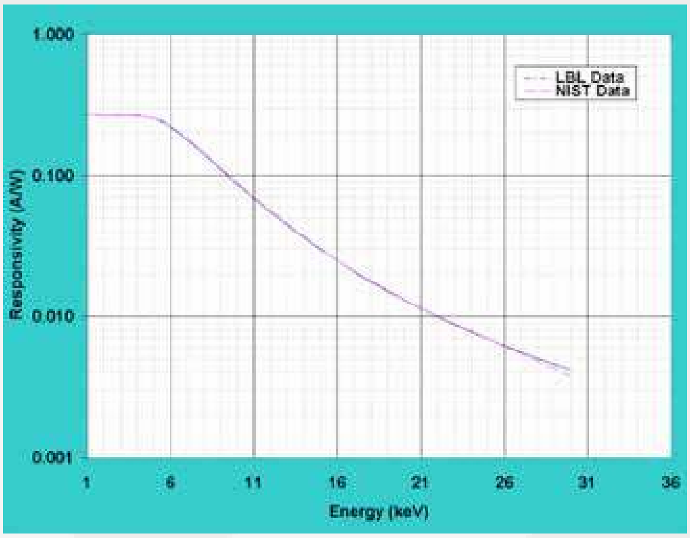


Figure 6 - Responsivity calculated using both NIST and LBL transmission values for the photoelectric effect, 52 µm effective Si thicknesses.

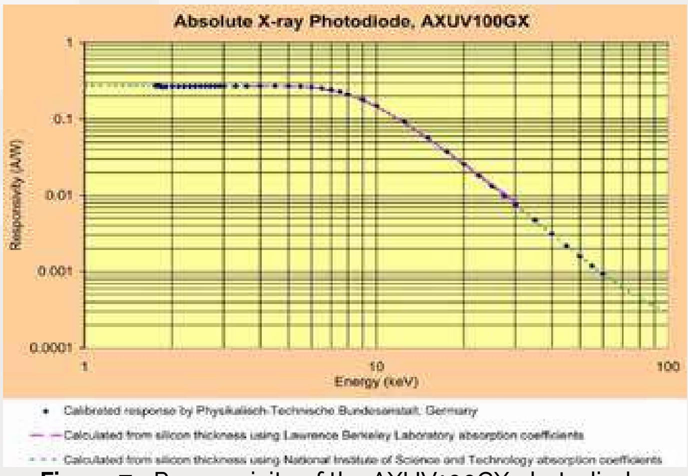


Figure 7 - Responsivity of the AXUV100GX photodiode, vcompared against calculations using both NIST and LBL transmission values, 104 µm effective Si thicknesses.

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About Opto Diode Corp.

Opto Diode (part of Illinois Tool Works, Inc.) designs and manufactures high-quality standard and custom silicon (Si) photodiodes, LEDs, IR LEDs, and LED arrays, Ultraviolet (UV)/Extreme UV/Absolute X-Ray photodetectors, opto-electronic assemblies, and custom solutions.

Their custom solutions include line sources, point sources, custom geometry photodiodes, and custom packaging. Comprehensive testing of chips, wavelengths, and output power is also available.

With a domestic in-house manufacturing facility and state-of-the-art wafer fab they are able to provide economical, high-quality products in low to high volume quantities.

For more information about Opto Diode Corp. visit www.optodiode.com.

References

[1] H. O. Funsten, D. M. Suszcynsky, S. M. Ritzau, and R. Korde, "Response of 100% Internal Quantum Efficiency Silicon Photodiodes to 200 eV to 40 keV Electrons." IEEE Transactions on Nuclear Science, Vol. 44, No. 6, December 1997, 2561- 2565

[2] Herbert O. Funsten, Stephen M. Ritzau, Ronnie W. Harper, and Raj Korde, "Response of 100% Internal Carrier Collection Efficiency Silicon Photodiodes to Low-Energy Ions" IEEE Transactions on Nuclear Science, Vol. 48, No. 6, p. 1785-1789, 2001

[3] H. O. Funsten, S. M. Ritzau, R. W. Harper, and R. Korde "Fundamental limits to detection of low-energy ions using silicon solid-state detectors." Applied Physics Letters, Vol. 84, No. 18, p. 3552-3554, 2004

Figure Sources

Figure 5 - *Center for X-ray Optics, Lawrence Berkeley Laboratory - http://www-cxro.lbl.gov/optical_constants/*

Figure 6 - *Physical Laboratory Physical Reference Data, National Institute of Science and Technology - http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html*

Figure 7 - *J.L. Campbell et. al. "Experimental K-shell fluorescence yield of silicon" J. Phys. B: At. Mol. Opt Phys., Vol. 31, 4765-4779 (1998)*

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