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Note: Effect of photodiode aluminum cathode frame on spectral sensitivity in the soft x-ray energy band

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Abstract

Silicon photodiodes used for soft x-ray detection typically have a thin metal electrode partially covering the active area of the photodiode, which subtly alters the spectral sensitivity of the photodiode. As a specific example, AXUV4BST photodiodes from International Radiation Detectors have a 1.0 μm thick aluminum frame covering 19% of the active area of the photodiode, which attenuates the measured x-ray signal below ~6 keV. This effect has a small systematic impact on the electron temperature calculated from measurements of soft x-ray bremsstrahlung emission from a high-temperature plasma. Although the systematic error introduced by the aluminum frame is only a few percent in typical experimental conditions on the Madison Symmetric Torus, it may be more significant for other instruments that use similar detectors.

Key Topics

Aluminium
Photodiodes
Silicon
Brightness
Soft X-rays

Silicon photodiodes are used in experimental plasma physics to measure continuum and line radiation in the soft x-ray (SXR) energy band. At the Madison Symmetric Torus (MST), photodiodes made by International Radiation Detectors (IRD)[1] provide SXR brightness that is used for both tomographic emissivity reconstruction and electron temperature (Te) via the double-filter technique.[2,3] During an assessment of the uncertainty in the effective area of the silicon photodiode, it was learned that the photodiode cathode, a small aluminum frame around the edge of the detector, actually alters the effective area of the detector for incident photons with energies below 6 keV.[4]

In addition to impacting absolute brightness measurements, an energy-dependent change in the silicon thickness also affects the electron temperature determined from the double-filter technique. In the double-filter technique, the SXR brightness is simultaneously measured from a single region of the plasma using two different filters.[5–7] If the emission is due to continuum radiation, then the ratio (R) of these two signals is a function of Te alone, because the filters select emission from different portions of the electron distribution function. To convert the measured ratio into a temperature, ideal Te versus R curves are generated assuming a pure bremsstrahlung emission spectrum and folding in the filter transmission and silicon absorption functions of the diagnostic. The spectral sensitivity of the detectors must be accurately modeled in order to reliably infer the electron temperature. Because the aluminum feature of the photodiodes impacts energy-dependent measurements, a characterization of this effect has been undertaken and is reported here.

A schematic of the IRD AXUV4BST photodiodes used at MST is shown in Figure 1. For the data presented in this note, a 2.0 mm × 2.0 mm silicon p-n junction semiconductor, with a thickness of 35 μm is mounted on a printed circuit board base with a conducting chromium-gold bottom surface that acts as the circuit anode.[8] The cathode current is drawn from a thin aluminum frame on top of the silicon. This frame measures 100 μm in width and 1 μm in thickness. The stated uncertainty in the aluminum frame dimensions is ±10% − 15%.[9] For 2.0 mm × 2.0 mm square photodiodes, the aluminum frame covers 19% of the active area.

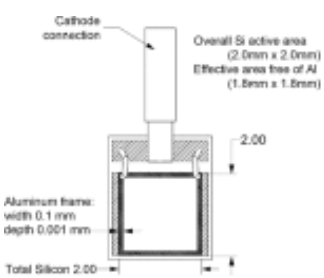

FIG. 1.
Top-down view of photodiode showing 1 μm thick aluminum frame (dark hatching) covering outer-most 100 μm of the diode's 2.0 × 2.0 mm silicon active area. The silicon is mounted on a printed circuit board with a conducting anode base (hidden).

Considering the aluminum to be an additional filter for the SXR signal, its impact on detector sensitivity was examined. Figure 2 shows the response curves for an ideal Si detector compared with the as-manufactured AXUV4BST, as calculated from the Center for X-ray Optics database.[10] The response curve for an ideal detector with 35 μm pure silicon is plotted in solid red, while the effective curve including an additional 1 μm of aluminum overlaid on 19% of the silicon surface area is shown in dashed blue. On MST, the absorption features are avoided by using high-pass beryllium (Be) filters (421 and 857 μm thick), but the reduced sensitivity below ~6 keV still impacts the measured signal.

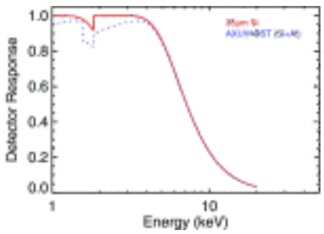

FIG. 2.
Detector response curve for ideal 35 μm silicon (solid red), compared to the effective curve for the AXUV4BST diode, where 19% of the silicon is overlaid with 1 μm of aluminum (dashed blue). The addition of aluminum to the silicon reduces detector sensitivity below about 6 keV and introduces additional absorption features (on MST the absorption features are avoided by using high-pass berylliun filters).

A simulation has been used to characterize the impact of the aluminum frame on the SXR brightness and resulting Te measurements. First, a model generated SXR emissivity from pure bremsstrahlung plasmas with electron temperatures from 0.3 to 2.0 keV.[11] Those emissivities were line-integrated into brightness, which was then convolved with the detector sensitivity functions to create a synthetic datase of ideal measured brightness. To incorporate the fact that the aluminum frame acts as an additional filte but does not impact the entire area of the diode, a second synthetic dataset was created in which 81% c the line-integrated brightness from the plasma was measured through the beryllium filters using pure silicon, while 19% of the total brightness was measured through the combined silicon and aluminum detector. The Te(R) curves, which assume beryllium-only filters, were then applied to the synthetic datasets to see how much the aluminum affects the resulting temperature measurement. To assess the uncertainty in the aluminum frame dimensions, a third synthetic dataset was generated to represent the worst-case scenario, where the aluminum frame was both thicker and wider by the maximum stated uncertainty of 15%.

The impact of the aluminum frame on SXR brightness is small, decreasing the total signal through the 421 μm filter by ~2%, and the 857 μm signal by ~1.5%. Likewise, the impact on the Te calculated from the brightnesses is also less than 2%, for a 1.5 keV plasma. It is important to note however, that the correction is temperature dependent. Figure 3 shows the ratio of the electron temperature calculated in the presence of the aluminum frame over the temperature calculated from an ideal diode with no aluminum frame. This plot demonstrates that the temperature measured by the detectors if the frame is not properly accounted for can be up to 1.8% higher than the true electron temperature for a 2.0 keV plasma. If the maximum quoted uncertainties (+15%) in the aluminum thickness and width are incorporated, then the error in the temperature increases to 2.3% at 2.0 keV.

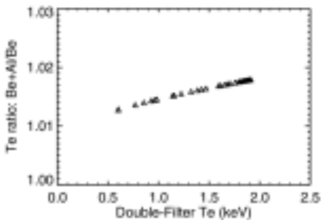

FIG. 3.
Fractional increase in apparent Te due to the effective aluminum filter versus the Te from an ideal diode with no aluminum frame, as inferred from the double-foil technique. While the overall effect of the aluminum is only a few percent in this example, the effect increases with plasma temperature.

Fortunately, MST plasmas do not typically exceed 2.0 keV, so the effect of the aluminum frame on Te is not large. The impact of the aluminum is much smaller than the statistical uncertainty of ~10% in the experimental Te measurement. However, it is important to note that because this effect is energy dependent, it may be more of a concern in experiments with different filters or temperature ranges. The effect is also a function of silicon thickness and total detector area, becoming smaller as total area gets larger. Nonetheless, the aluminum introduces a non-trivial systematic change to the measured energy spectrum, which may be of concern to others using IRD silicon photodiodes to measure absolute brightness or electron temperature.

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