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Stable silicon photodiodes for absolute intensity measurements in the VUV and soft x-ray regions

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Stable silicon photodiodes with 100% internal quantum efficiency have been developed for the vacuum ultraviolet and soft x-ray regions. It is demonstrated that the response of these detectors can be reasonably well represented by a simple model for photon energies above 40 eV. The measured efficiency is consistent with a constant electron-hole pair creation energy for Si above 40 eV. Radiation damage is demonstrated to result in loss of carriers to recombination at the front surface. The uniformity of the diodes is shown to be better than 0.1% RMS at 110 eV.

1. Introduction

There is an increasing need for stable detectors in the vacuum ultraviolet (VUV) and soft x-ray spectral regions. This need arises, in part, due to the development of high brightness third generation synchrotron sources which produce intense x-ray beams. Other areas of application include x-ray astronomy, x-ray and EUV lithography, x-ray microscopy and plasma diagnostics. In addition to stability, many experiments require accurate measurement of intensity, thus the need for absolute detectors.

Silicon photodiodes with 100% internal quantum efficiency were developed a few years ago [1]. Since then substantial improvements have been made in the resistance to radiation damage of these photodiodes [2]. It is demonstrated that the response may be modeled for photon energies greater than 40 eV by considering only the photoabsorption of the oxide and assuming a photon energy-independent pair creation energy. Measurements are presented on the radiation stability of these photodiodes. Since there is no surface recombination of carriers, these photodiodes have a very high response uniformity.

2. Experimental

The photodiodes discussed here are described in detail in reference [2]. The devices are n on p type where the front region was phosphorus diffused and the oxide was nitrided in a nitrous oxide or an ammonia atmosphere.

The measurements at NIST were performed at the Synchrotron Ultraviolet Radiation Facility (SURF II) far ultraviolet radiometry beamline [3], and in the NIST far ultraviolet detector calibrations laboratory. The measurements at Lawrence Berkeley National Laboratory (LBNL) were performed using a laser-produced plasma source [4] and at the calibrations and metrology beamline at the Advanced Light Source.

3. Spectral Response

In Fig. 1 the measured device quantum yield is shown versus photon energy for four different types of photodiodes used or proposed as transfer standards. The upper curve is representative of the Si photodiodes that are discussed here. The semiconductor photodiodes clearly have the advantage of a much higher device quantum yield as compared to the photoemissive detectors. In addition, since charge is collected internally, the semiconductor diodes are inherently less sensitive to surface contamination than the photoemissive diodes. In this section, it is shown that the response may be given to a good approximation by a very simple model.

In the absence of surface recombination the spectral response may be calculated from the absorption in the oxide. The responsivity (Amps/Watt) is given by,

$$R = \frac{Y}{h\nu} = \frac{1}{W} \exp\left(-\mu_o t_o\right) \qquad (1)$$

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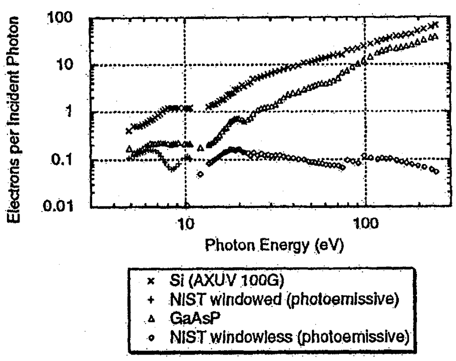

Figure 1. The typical measured quantum yield of various detectors which are used as transfer standards for radiometry in the VUV and soft x-ray regions.

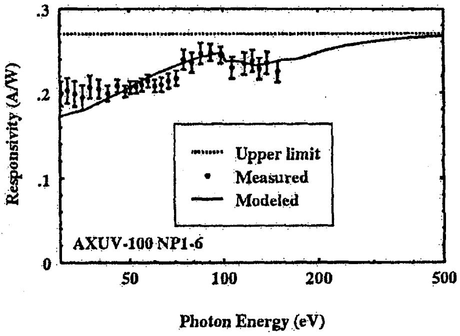

Figure 2. The responsivity of a photodiode calibrated at NIST. The solid curve is not a fit but rather the modeled responsivity based on the measured oxide thickness (9 nm) and assuming a photon energy-independent pair creation energy of 3.70 eV. The dashed line is the theoretical upper limit of R=1/W.

where Y is the device quantum yield in electrons per incident photon, $h\nu$ is the photon energy in eV, W is the average electron-hole pair creation energy in eV, μ_o is the absorption coefficient of the surface oxide layer, and t_o is the oxide thickness. At the photon energies of interest here ($h\nu < 500$eV) it is safe to neglect losses in the rear of the detector. For higher photon energies these losses are readily included in the model [5]. At lower energies the reflectivity of the front interfaces must be taken into account.

In Fig. 2, calibrations performed at NIST are compared with the responsivity calculated from Eq. (1). It should be noted that the solid curve is not a fit to the responsivity measurements, rather the model parameters were independently determined. The oxide thickness was obtained by three methods: 1) the self-calibration procedure of Krumrey and Tegeler [5]; 2) x-ray reflectivity vs angle; 3) visible ellipsometry. All three methods were in agreement and yielded the value 9 nm±1 nm. The oxide transmission was calculated using the measured thickness and the atomic scattering factors of Henke, Gullikson and Davis [6]. A value of 3.70 eV was assumed for the pair creation energy. The NIST measurements are plotted with the associated uncertainties of 1σ. The model agrees with the measured responsivity to within the uncertainty of the measurements down to about 40 eV.

At energies below 40 eV the measured responsivity is significantly higher than predicted by Eq. (1). This is likely due to an increasing contribution of carriers (holes) from the oxide [10]. The apparent oxide contribution can be very significant in the region around 10 eV.

The pair creation energy W is, in general, a function of the photon energy. It is usually assumed that W is a constant for photon energies well above the band gap of Si ($\approx 10 \times E_g$ [7]). Recently however, Monte Carlo simulations of the pair creation energy [8] have predicted a rather significant photon energy dependence up to a few hundred eV. In addition, a 4% discontinuity in W was predicted at the Si L edge. In order to accurately model the photodiode response, the energy dependence of W must be known. We have assumed here a photon energy-independent value of 3.70 eV±0.07 eV as measured by Krumrey and Tegeler [5]. From the comparison in Fig. 2 it appears that the measured responsivity is in agreement with the model calculation assuming a constant pair creation energy. Unfortunately the 1

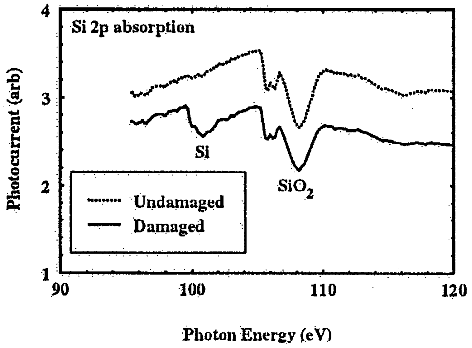

Figure 3. Photocurrent from a non-nitrided silicon photodiode, measured near the Si 2p absorption edge before and after extended exposure to 124 eV radiation. Before radiation damage, there is essentially no drop at the Si absorption edge (99.8 eV). Radiation damage, which produces surface recombination, results in a drop in efficiency at 99.8 eV. The absorption due to the 40 nm thick SiO_2 is apparent above 105.4 eV.

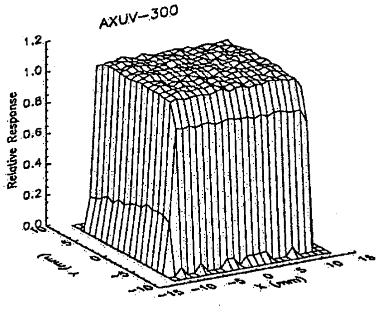

Figure 4. Uniformity of a 3 cm^2 photodiode measured at 95 eV.

sigma uncertainty in the NIST calibration is in the 4 to 8% range, so it is not possible to observe an energy dependence of W at a level smaller than this. The large uncertainty in the NIST calibration is inherent to the use of an ion chamber as the primary standard of intensity, and in the radiation impurity problems common with continuum sources. More accurate meaurements may be possible with an electrical substitution radiometer [9].

In Fig. 3, the photocurrent versus photon energy is shown in the region around the Si L (2p) absorption edge. The upper curve was obtained for a region of the detector which was not exposed to radiation and the lower curve was for a region which had been exposed to 10^{18} photons/cm^2 at 124 eV. As can be seen from the measurement on the undamaged detector, the discontinuity at the Si L edge (99.8 eV) is small. Careful measurements of the relative response on both this type of photodiode and on a Si surface barrier detector put an upper limit of 0.5% for any jump in response at the Si L edge. The structure above 105 eV is due to absorption in the relatively thick 40 nm of oxide present on this photodiode. This illustrates the difficulty in distinguishing the energy dependence of W at the Si L edge from recombination of carriers at the surface.

4. Stability

There has been a great deal of research on the radiation hardness of nitrided silicon devices. The stability has been measured for 10.2 eV and typically about a 3% drop in efficiency occurs for a fluence of 10^{16} photons/cm^2 [2]. Partial recovery was observed when the radiation exposure was stopped for several hours. Since the photodiodes must be operated without protective windows, there was also concern about the stability during shelf storage. The long term shelf life of the diodes was illustrated by an extended exposure to 100% humidity shown in reference [2]. Supporting measurements were made in the spectral region in which oxide absorption is greatest (near 10 eV) with no significant change in device efficiency observed after 4 weeks of 100% humidity exposure.

5. Uniformity

The uniformity of response is crucial for certain applications. For example, in reflectometry a nonuniform detector response may lead to errors if the reflected and direct beams strike different parts of the detector, or if the incident radiation is not spatially uniform at the experiment. The

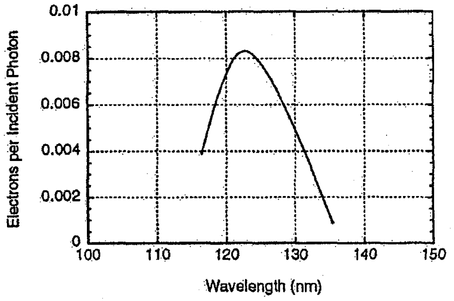

Figure 5. The efficiency of a filtered photodiode with a bandpass around the H Lyman alpha line.

uniformity of a 3 cm^2 photodiode is shown in Fig. 4 for a photon energy of 95 eV. A particularly difficult region is for photon energies above the Si L edge (99.8 eV) up to about 200 eV. In this region the x-ray penetration depth is short ($\approx$ 50 nm) and any surface recombination will have a large effect on the responsivity. In many detectors this leads to a very nonuniform response. Since these detectors have a negligible surface recombination they have excellent uniformity in this energy region. The uniformity at 110 eV of a typical AXUV-100 photodiode was measured to be better than 0.1% RMS.

Photodiodes have been constructed with a variety of geometries including quadrant diodes with openings in the center for beam position and intensity monitoring. Filtered photodiodes have also been made by depositing metal layers over the oxide [11]. In this way detectors can be made with a limited band pass response, which may prove useful for various VUV/soft x-ray applications. In Fig. 5 is shown the response of a diode coated with an Al/MgF$_2$ interference filter giving a band pass around the H Lyman alpha line. This particular diode was designed for space applications in solar physics.

6. Conclusions

The performance of absolute silicon photodiodes has been reviewed. It has been demonstrated that the response is given by a simple model for photon energies above 40 eV to about the present level of calibration uncertainty. Until the modeling is improved it is necessary to calibrate individual photodiodes as transfer standards for intensity measurements at lower energies. The photodiodes have excellent uniformity. Radiation damage is demonstrated to result in loss of carriers to recombination at the front surface.

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