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**Soft X-Ray Silicon Photodiodes
with 100% Quantum Efficiency**

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Soft X-Ray Silicon Photodiodes with 100% Quantum Efficiency

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Abstract

Silicon p-n junction photodiodes (AXUV diodes) with nearly 100% quantum efficiency (QE) for soft x-ray photons (up to about 6 keV) were recently developed. This implies no recombination of photo-generated charge carriers in the front doped region and at the Si-SiO₂ interface. This work reports fabrication and testing of the AXUV diodes with 100% quantum efficiency for photons with energy up to 10 keV. Response of the new diodes was measured using electron-beam x-ray generators with copper and molybdenum anodes that, when filtered properly, provide K x rays at 8 and 17.5 keV respectively. AXUV photodiodes fabricated on high-resistivity silicon were found to exhibit gain in their response to these x rays. The x-ray signal was observed to increase, by up to a factor of 25, when the bias voltage was raised above the level required for full depletion of the silicon. A similar gain was found in the response to α particles when the diodes fabricated on high-resistivity silicon were operated in pulse mode. A diode fabricated from low resistivity silicon, with low leakage current, did not exhibit any gain in its x-ray response.

I. INTRODUCTION

Silicon p-n junction photodiodes (AXUV, absolute XUV diodes) with 100% internal quantum efficiency (no recombination of photogenerated carriers in the doped n⁺ region and at the Si/SiO₂ interface) were reported by one of us recently [1, 2] for soft x-ray photons up to 6 keV. Quantum efficiency of these diodes was found to decrease for photon energies greater than 6 keV owing to limited silicon thickness. This paper describes fabrication and testing of AXUV diodes with larger silicon thickness which are expected to have 100% quantum efficiency for photons with energy up to 10 keV.

Fig. 1 shows a schematic of the 1-cm² active area AXUV photodiode fabricated on three-inch diameter, high resistivity (> 20,000 Ω -cm), 450- μ m thick p-type silicon wafers procured from Topsil and Westinghouse. No substantial difference was noticed in the quality of the diodes fab-

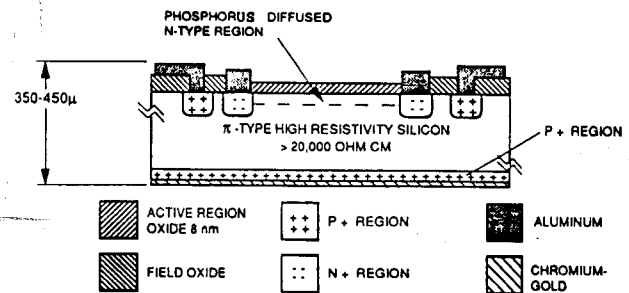


Figure 1: Schematic of the fabricated AXUV photodiode

ricated on the starting materials from these two manufacturers. After the standard p⁺ channel stop and n⁺ guard ring diffusion, phosphorous diffusion was carried out to achieve zero surface recombination without a diffused dead region[3]. The passivating silicon dioxide coating was thinned down to 80 Å after completion of the phosphorous diffusion. Subsequent processing involved masking, aluminum metallization, post metal anneal, Cr-Au deposition on backs and sawing. More details on the diode fabrication are available in references [1, 3].

The fabricated chips were assembled in two-lead International Radiation Detectors (IRD) standard ceramic packages. Response of the diodes was measured using two different electron-beam x-ray generators. In one generator, the x-ray flux to the detectors was mechanically chopped, and in the other generator an AC signal was created by the full-wave-rectification of the accelerating voltage. An AC-coupled transimpedance amplifier was then used to measure the resultant photocurrent (see Fig. 2). For absolute x-ray response measurements, the AXUV signal was compared to the signal from a previously-calibrated silicon surface barrier diode (SBD) [4]. More details on this method are available elsewhere [5].

This paper reports two sets of AXUV response measurements. In the first set, the absolute x-ray response of AXUV detectors was determined by comparing the signals of the AXUV and SBD when they were subjected to the same x-ray flux. In the second set, the relative AXUV and

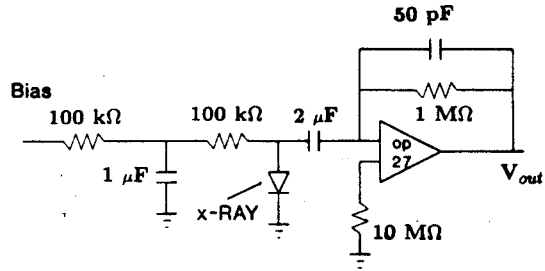


Figure 2: This AC-coupled transimpedance amplifier was used to measure the x-ray generated photocurrents.

SBD response was determined when they were subject to similar x-ray fluxes. In this case the response was measured over a much broader range of applied bias voltage, and the photocurrent gain was observed at high values of applied bias voltage.

II. ABSOLUTE X-RAY RESPONSE

A. 8-keV Copper K Response

The response of the AXUV detectors was measured using Cu K line radiation at 8 keV. The x-ray generator was run in this case with an anode voltage of 16 kV. Both the AXUV diode under test and the SBD were covered with 25- μm copper foil for visible light rejection and bremsstrahlung rejection. This filtering produces nearly monoenergetic Cu K radiation (see [5]). Fig. 3 shows the ratio of the AXUV diode signal to the SBD signal. The AXUV quantum efficiency is near 100%, since the SBD quantum efficiency is $82 \pm 18\%$ at this energy (see [4]). Because the fabricated AXUV diodes have silicon thickness up to 450 μm , they will exhibit 100% quantum efficiency for photon energies up to 10 keV.

B. 17.5-keV Molybdenum K Response

The response of the AXUV detectors was also measured using Mo K line radiation at 17.5 keV. The x-ray generator was run in this case with an anode voltage of 25 kV. Both the AXUV diode under test and the SBD were covered with 124- μm molybdenum foil for visible light rejection and bremsstrahlung rejection. Fig. 4 shows the ratio of the AXUV diode signal to the SBD signal. This figure shows that the quantum efficiency of the AXUV diodes is not significantly more than that of the SBD, due to the fact that the diode thicknesses are similar. The thickness of these detectors is small compared to the penetration depth (e^{-1}) of 17.5 keV x rays (660 μm).

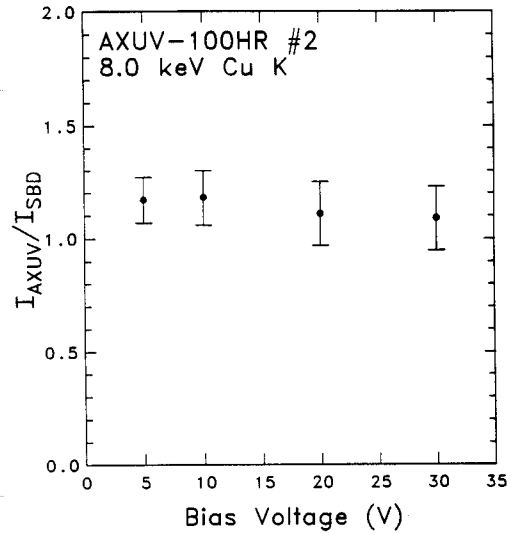


Figure 3: The ratio of the AXUV response to the SBD response is shown for the case of 8-keV copper K radiation.

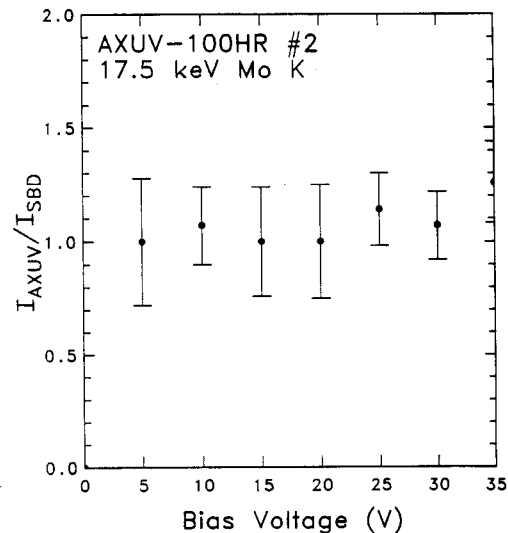


Figure 4: The ratio of the AXUV response to the SBD response is shown for the case of 17.5-keV molybdenum K radiation.

III. GAIN IN THE RELATIVE X-RAY RESPONSE

Earlier work on silicon surface barrier diodes (SBD) demonstrated no dependence of the photocurrent on bias voltage. This observation showed that the x-ray sensitive portion of these SBD detectors was comprised of the entire physical thickness, not the depletion layer thickness [4]. We later found that SBD response to charged particle radiation was also independent of bias voltage in partially depleted diodes [6]. More recently, the x-ray response of XUV diodes for x-ray energies above about 6 keV was found to be degraded as compared to the x-ray response of SBDs with similar silicon thickness [5]. This was attributed to higher charge-carrier recombination in the bulk silicon. None of the detectors examined in these earlier studies exhibited gain as the bias voltage was increased; normally at high bias voltage (above about 75 to 100 V) increased noise appeared on the detector signals. We therefore examined the AXUV diode response over a broad range of applied bias voltage.

In this section we report an experimental observation of photocurrent gain in AXUV diodes. Gain was observed when the diodes were operated with bias voltage above that required for full depletion. Gain was only found in diodes fabricated on high-resistivity p-type silicon whose leakage current increases strongly with the applied bias voltage. Diodes fabricated on low-resistivity silicon (70-100 Ω -cm), which exhibited low leakage current over a wide range of applied bias voltage, did not exhibit any gain. This fact implies that the amplification of radiation signals and of the leakage current may be due to the same mechanism. We present data here from two representative diodes: high-resistivity diode AXUV-A did show strong increase of the leakage current with bias voltage and gain (Fig. 5); low-resistivity diode AXUV-B showed neither strong increase in leakage current nor gain (Fig. 6). Other than the resistivity of the silicon, the characteristics of these diodes were identical (*e.g.*, geometry, manufacturing process).

The x-ray sources were run in an AC mode so that the oscillating x-ray signal could easily be discriminated from the DC background due to leakage current. The DC leakage current, which was in some cases considerably larger than the typical x-ray signal, did not contribute to the output of the amplifier, because of a 2.2 μ F blocking capacitor (see Fig. 2).

Figs. 5 and 6 show the diode leakage current and the normalized x-ray response of the AXUV detectors as a function of bias voltage (different detectors were used for Figs. 3 and 4). The AXUV signal was normalized to the SBD signal. Note that the curve for diode AXUV-A has the characteristic shape shown by typical proportional counters. It may be important that the behavior of the gain is roughly the same as the behavior of the leakage current. That may indicate that the mechanism responsible for increasing leakage current with bias voltage

is also responsible for increasing the photocurrent as the bias voltage is increased. An observed gain in photodiodes has previously been reported in Ref. [7].

The high value of leakage current shown in Fig. 5 cannot be explained based on the doping and minority carrier lifetime. However, leakage currents of 5-mm diameter active area diodes fabricated on the same material at the same time were consistent with the values of minority carrier lifetime and doping. This suggests that the extremely high resistivity ($> 20,000 \Omega$ -cm) p-type silicon has defects, possibly n-type pipes, causing abnormally high leakage currents. Note that the yield of 5-mm diameter diodes with good leakage current was low, less than 20%. Presence of these submicron n-type pipes may also explain the observed gain based on avalanche multiplication.

IV. ALPHA PARTICLE RESPONSE MEASUREMENTS

To verify that the gain observed in the x-ray response was real, we also tested the response of the AXUV detectors to energetic α particles. In this case, the diodes were operated in pulse mode. Their signal was fed into a charge-sensitive preamplifier (EG&G ORTEC 142), then a shaping amplifier (EG&G ORTEC 590), and subsequently into a multichannel analyzer. It was important in this application to lower the series resistance built into the preamplifier bias line. Otherwise the voltage drop due to the leakage current across this large resistance (100 M Ω) would prevent sufficient bias from appearing on the detector. We therefore reduced the resistance to 200 k Ω . The leakage current was monitored and compensated for during these measurements.

Energy spectra of α particles emitted by a radioactive ^{226}Ra source were obtained with different bias voltages applied to the diode. This source emits four dominant α particles with energies of 4.7, 5.4, 5.9, and 7.6 MeV. Fig. 7 shows the pulse height measured for the 7.6-MeV α particle for each of the AXUV detectors and also for the SBD. Again, diode AXUV-A showed substantial gain in the radiation signal. Neither diode AXUV-B nor the SBD showed any evidence of strong gain with bias voltage. Additional measurements are being carried out to determine the gain mechanism and to understand the different AXUV responses to x rays and charged particles.

V. CONCLUSIONS

Recently-developed AXUV detectors were found to have 100% quantum efficiency for x-ray energies up to 8 keV. Owing to their thick depletion region, they are expected to exhibit 100% quantum efficiency for photon energies up to 10 keV. In addition, photocurrent gain in the diodes was observed as the applied bias voltage was raised above about 30 V. This presents an opportunity for unique ap-

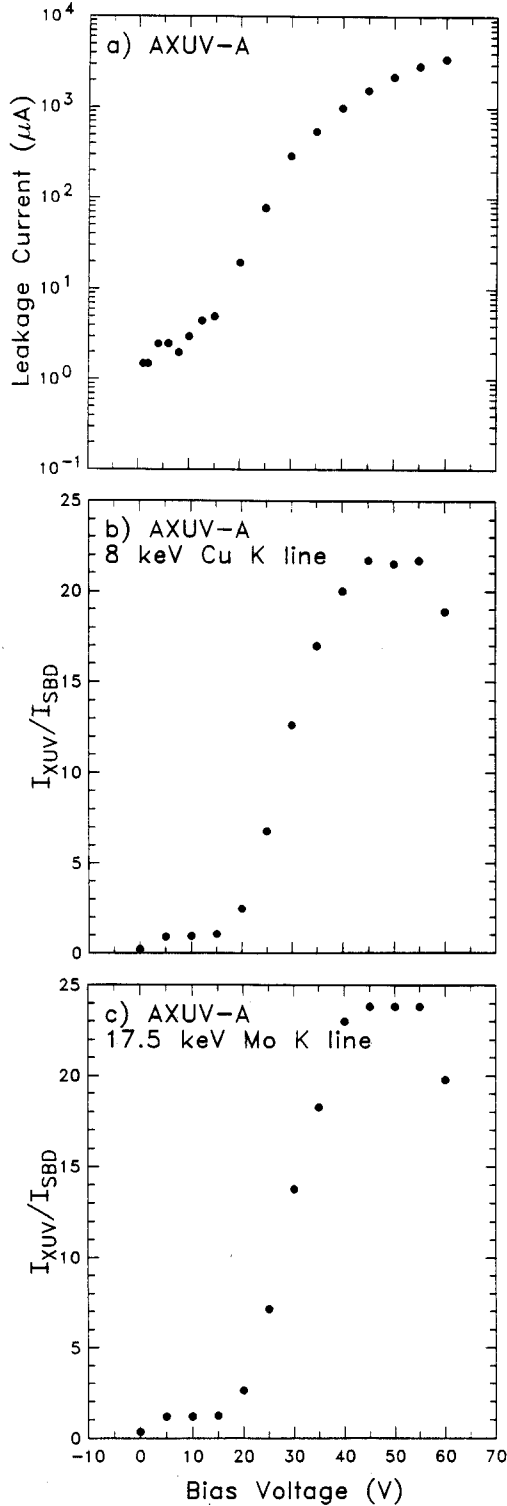


Figure 5: a) The leakage current of this diode increased by more than three orders of magnitude as the bias voltage was increased (full depletion occurs at about 25 V). b) The x-ray response current at 8 keV, normalized to the monitor SBD, increased 21 times as the bias voltage was increased. c) The x-ray response at 17.5 keV showed similar gain.

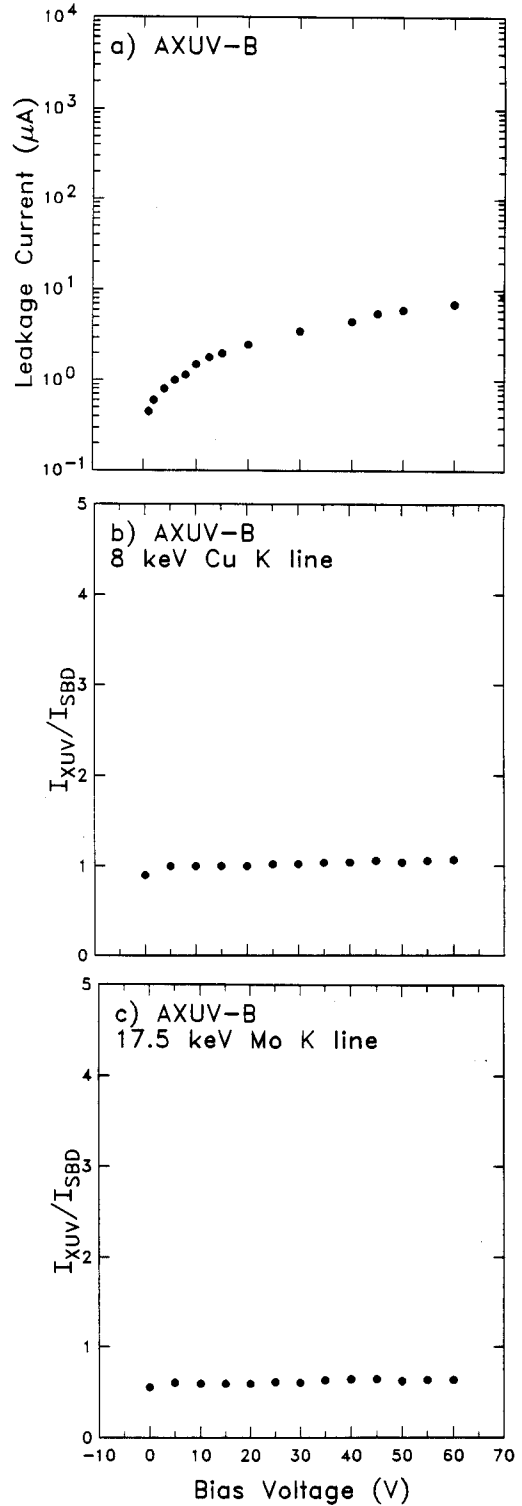


Figure 6: a) Between zero and 50 V, the leakage current from this diode increased from 0.3 to 6 μA . The maximum current was two orders of magnitude below the leakage current of the other diode (see Fig. 5). b) The x-ray response at 8 keV of the low-leakage diode showed no dependence on bias voltage. c) The 17.5 keV x-ray response was also independent of the bias.

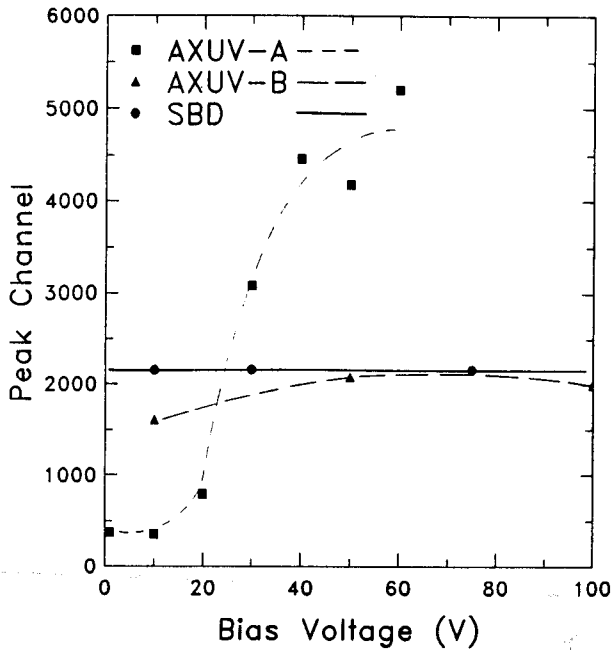


Figure 7: The pulse height corresponding to the 7.6-MeV α particle is shown as a function of the bias voltage applied to both AXUV detectors and the SBD. Only AXUV-A, the high-resistivity diode exhibits an increase in pulse height with applied bias.

plication of the diodes. These diodes should be useful for measurement of low-level, pulsed x radiation.

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