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Stability and quantum efficiency performance of silicon photodiode detectors in the far ultraviolet

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Recent improvements in silicon photodiode fabrication technology have resulted in the production of photodiodes which are stable after prolonged exposure to short wavelength radiation and which have efficiencies in the far ultraviolet close to those predicted using a value of 3.63 eV for electron–hole pair production in Si. Quantum efficiency and stability data are presented in the 6–124-eV region for several variations on the basic successful design and on devices with extremely thin silicon dioxide antireflecting/passivating layers. The results indicate that the oxide is dominant in determining many of the performance parameters and that a stable efficient far ultraviolet diode can be fabricated by careful control of the Si–SiO_2 interface quality.

I. Background

Most detectors now in general use in the far ultraviolet use the photoemission from a suitable material as the radiometric parameter. At photon energies greater than ~12.4 eV these detectors must be operated in an open, or windowless, configuration. Consequently, they are vulnerable to modification of their photoefficiency by relatively minute quantities of surface contaminants, often originating from the vacuum system in which they must be operated.

Solid state photodiodes have, as a general class, attractive characteristics as radiometric standard detectors for the far ultraviolet. The internal collection of carriers, for example, gives the photodiodes an inherent stability compared with the surface sensitive emission from photoemissive devices. Additionally, the production of electron–hole pairs within the semiconducting material can be characterized in terms of a specific photon energy, so that an efficiency which is linear with energy can be predicted for the ideal diode. Implied at sufficiently high photon energies are quantum efficiencies (electrons per photon) much greater than unity, as opposed to much less than unity for the typical photoemitter.

There have been several reports of charge-coupled devices (CCDs) and other spatially resolved solid state detectors which have been used with some success in the far ultraviolet.[1,2] Certain GaAsP and GaAs Schottky photodiodes have also been found to be satisfactory detectors in this region.[3] However, recent studies of commercial Si photodiodes in the 6–5-keV region have shown radiation-induced instabilities which would make them unsuitable for use as radiometric standards.[4]

We report here the results of tests on the efficiency, stability, and spatial uniformity of a new class of Si photodiodes whose fabrication parameters have been optimized for the far ultraviolet and which appear attractive for radiometric applications. In this regard, we consider quantum efficiency stability with time and after exposure to energetic radiation, with a reasonable degree of spatial uniformity, to be of paramount importance.

II. Devices

N-on-*p* windowless photodiodes with a 1-cm^2 circular active area were fabricated on ⟨111⟩ silicon wafers using phosphorus or arsenic diffusion. Figure 1 shows a schematic of the configuration investigated. A detailed description of the techniques used in the fabrication of these devices is found in Refs. 5 and 6. Devices made for the present study had the thermally grown oxide layer etched to thicknesses in the 20–250-Å range. The final oxide thicknesses were determined by ellipsometric measurements.

III. Experimental Results

The National Institute of Standards and Technology[7] (NIST) far ultraviolet detector calibration facilities[8] were used in the investigations reported here. As in the NIST calibration program, the SURF-II electron storage ring was used as a source of synchrotron radiation for the 25–124-eV region and a laboratory

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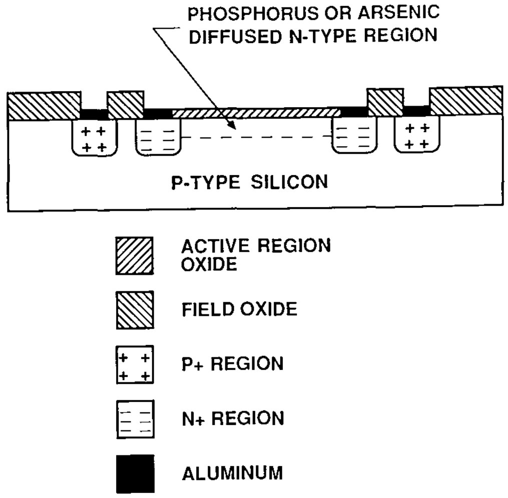

Fig. 1. Schematic of the photodiode type investigated.

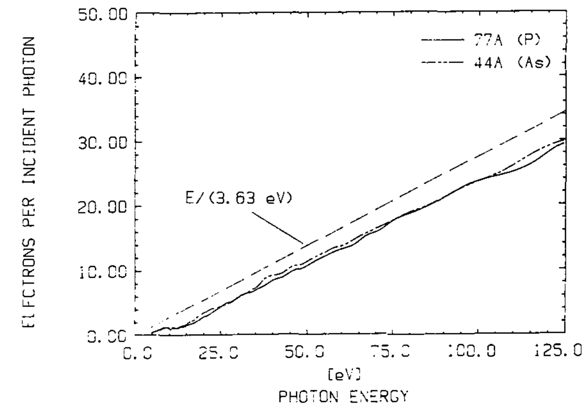

Fig. 2. Quantum efficiency of As- and P-doped photodiodes with oxide thicknesses as indicated. The straight line represents the quantum efficiency of Si based on a value of 3.63 eV per electron–hole pair, not including reflection losses.

line source for lower energies. Secondary standard photoemissive diodes were used to determine the efficiencies of samples in monochromatic radiation.

Preliminary results of these investigations in the 3.9–12.4-eV region have been reported elsewhere.[9] Further information on this region will be included here with results for higher energies.

In Fig. 2 it is seen that the quantum efficiency for a photodiode of this type nearly approaches the predicted slope of 3.63 eV per electron–hole pair created,[10,11] regardless of whether the dopant was P or As. Near 10 eV the absorption of SiO_2 is at a maximum and efficiency differences between devices with different oxide thicknesses would be expected. Figure 3 shows the efficiencies of several devices with different oxide thicknesses in this region with oscillations in efficiency which suggest optical interference related to oxide thickness.

If we assume that the efficiency of pair production in the Si will be determined only by the energy of the photons and the flux transmitted into the Si (after oxide absorption and reflective losses), the Fresnel equations for the case of a single absorbing film on an absorbing substrate may be used to predict the device efficiency. Figure 4 gives the results of such calculations using published[12] optical constants for amorphous SiO_2 and crystalline Si with an oxide thickness of 77 Å in the 9–124-eV region. Measured efficiency data from a photodiode with this oxide thickness are also shown. It is seen that the measured efficiency is greater than that predicted over an energy range where the oxide absorption is significant; suggesting that there may be some electronic contribution from a portion of the photon absorption events in the oxide. The dashed curve shows the result from making the arbitrary assumption that 20% of the absorption events in the oxide produce carriers in the Si.

Exposure stability tests were conducted by measuring the quantum efficiency of a photodiode at intervals during long-term exposure to radiation. Figure 5 shows the normalized results of these tests at three

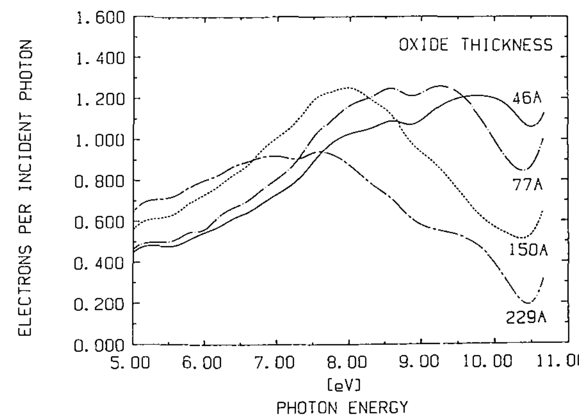

Fig. 3. Quantum efficiency of photodiodes, with different oxide thicknesses, in the region of oxide absorption.

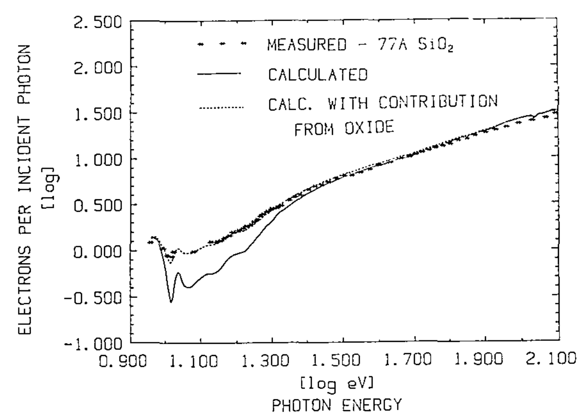

Fig. 4. Calculated (solid curve) and measured (*) quantum efficiencies of a photodiode with 77 Å of oxide. The calculated curve is based on an efficiency of 3.63 eV per pair for electron–hole production in Si and includes losses due to reflection and oxide absorption. The dashed curve is calculated based on the additional assumption that 20% of the photons absorbed in the oxide contribute carriers to the Si.

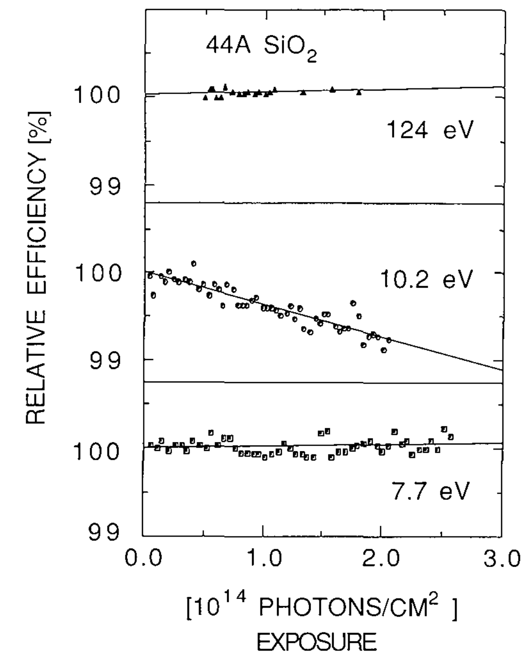

Fig. 5. Measured effect of radiation exposure on a photodiode with 44 Å of oxide at three photon energies.

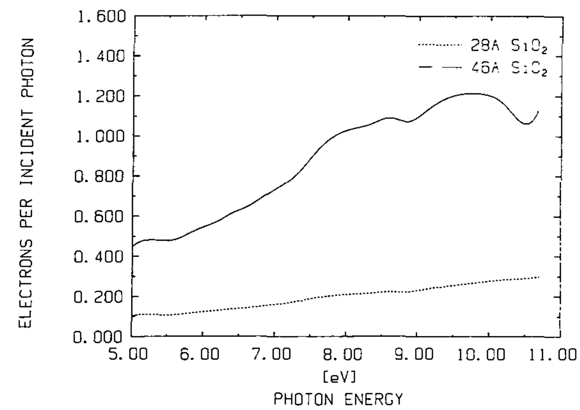

Fig. 6. Measured quantum efficiency of photodiodes with 46 and 28 Å of oxide.

energies. The 10.2 eV results show degradation due to exposure; only at this energy (of those measured) is there significant oxide absorption. (Previous studies[6] have emphasized the importance of the oxide in the production of stable photodiodes.) No significant difference was seen in the exposure stability between P- or As-doped samples.

It was also found that there is a critical thickness for the passivating oxide layer, below which the device performance is seriously degraded. Figure 6 shows the measured quantum efficiencies of two photodiodes, one with 46 Å of oxide and the other with 28 Å. Not only is the efficiency of the 28-Å sample reduced, but its exposure stability is quite poor. Figure 7 gives the result of an exposure test at 10.2 eV. Similar increases in efficiency were observed even at energies with little oxide absorption, but the stability of the efficiency before or after exposure was relatively poor, indicating that the increases seen were temporary.

Further insight into the behavior of excessively thinned photodiodes may be derived from measurements of efficiency around the Si $L_{II,III}$ edge near 100 eV. As the photon energy is increased beyond the Si absorption edge, the $1/e$ absorption length for photons within the silicon decreases by more than an order of magnitude,[12] placing generated carriers much nearer the Si–SiO_2 interface. One can conclude from Fig. 8 that in the case of the 46-Å sample, the carriers reach the junction with very little recombination regardless of the depth at which they originated. In the case of the 28-Å sample, the device efficiency is substantially lowered on the high energy side of the edge where photon absorption has moved closer to the oxide and surface recombination reduces the collection efficiency.

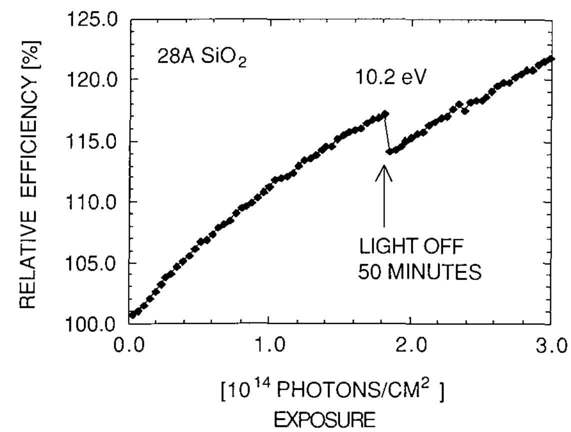

Fig. 7. Measured effect of radiation exposure on a photodiode with insufficient (28-Å) oxide.

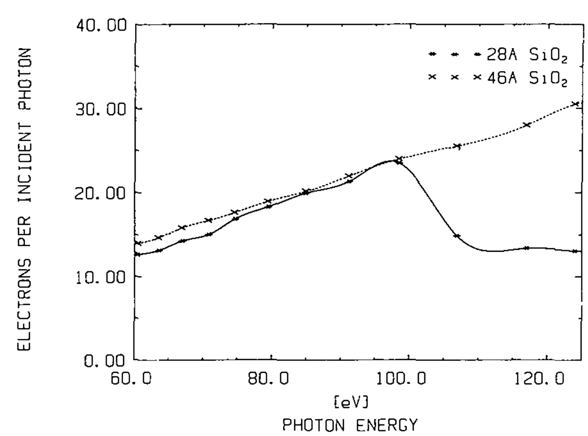

Fig. 8. Measured quantum efficiency of photodiodes with 46 and 28 Å of oxide in the vicinity of 100-eV photon energy, at which energy the $1/e$ absorption length in Si decreases by more than an order of magnitude.

IV. Conclusions

The new Si photodiodes look very promising as radiometric standards in the far ultraviolet. Predictable efficiencies and relative immunity to exposure damage can be routinely achieved with careful processing and control of passivation layer thicknesses. The only problem region remaining corresponds to energies at which appreciable absorption of the incident radiation occurs in the oxide, $\sim$9–25 eV, where exposures of $\sim 2 \times 10^{14}$ photons/cm^2 have been found to cause a permanent decrease of $\sim$1% in efficiency. The spatial uniformity of the present devices appears to be within $\sim$2% over the working areas, except in the region of oxide absorption, where small nonuniformities in the oxide thickness could be responsible for the deviations seen.

Indications are that Si photodiodes which have 100% internal quantum efficiency can be excellent far ultraviolet detectors, except for residual problems associated with the passivating oxide layer. Reduction of the thickness of this layer is limited by a critical thickness below which device behavior is unacceptable. Improvements in the performance of these photodiodes will likely require improved oxide formation techniques.

An interesting variation of this type of detector is created with the addition of an appropriate thin film window deposited directly on the surface of the oxide. In the far ultraviolet several materials have transmitting regions[13] and can easily be employed to discriminate against unwanted radiation. The extremely fragile nature of unsupported films has limited their usefulness in the past. Direct application of the film material to the photodiode will greatly lessen this limitation. An aluminum-coated photodiode with response from $\sim$15.5 to 73 eV has been made and will soon be used to study the far ultraviolet solar spectrum as part of a rocket experiment. Details of this aspect of the program will be reported later.

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