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Silicon photodiodes with stable, near-theoretical quantum efficiency in the soft x-ray region

Raj Korde

United Detector Technology, Hawthorne, CA 90250, USA

L. Randall Canfield

National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

ABSTRACT

Silicon photodiodes having practically no carrier recombination at the Si-SiO_2 interface or in the front diffused region have been developed by defect-free n-type impurity diffusion into p-type silicon. These photodiodes exhibit very high quantum efficiencies in the 10 eV to 150 eV photon energy region, typically 37 electrons per photon at 150 eV, which is about 300 times the quantum efficiency of the more commonly used photoemissive type soft X-ray detectors. The quantum efficiency of the developed diodes has been found to be stable to a few percent after exposure to photons in the region of 5eV to 200eV, with fluences in excess of $10^{14}/cm^2$. No significant change in the quantum efficiency was observed after storage in air for several months.

1. INTRODUCTION

A great deal of interest is being generated among the scientific community in the soft X-ray spectral region because of new and potential applications of soft X-ray photons. Major interesting research and development areas to be noted are the study of plasmas radiating in the soft X-ray region as encountered in the magnetic and laser fusion programs [1], X-ray astronomy [2], X-ray lithography for developing submicron electronic integrated circuits [3], imaging at submicron resolution for biological applications [4] and fundamental studies in atomic, molecular and solid state spectroscopy [5]. A simple diagram of a typical X-ray measurement system is shown in Figure 1.

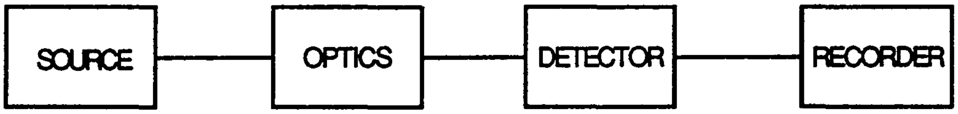

FIGURE 1

BLOCK DIAGRAM OF A TYPICAL X-RAY MEASUREMENT SYSTEM

This paper describes the recently developed silicon photodiode detectors exhibiting extremely high quantum efficiency and stability in the vacuum UV and soft X-ray region (This region has been called X-UV region in this paper as the same photodiode can be used as an excellent detector over the complete spectral region which classically has been separated as vacuum UV, extreme UV and soft X-ray regions.). The advantages of using silicon photodiode detector instead of the commonly used X-UV detectors are several. Silicon is the main-stream material of the electronic industry and hence its technology has been well developed. This facilitates remarkably the modification of the basic structure developed either to increase the detector active area up to 100 mm^2 or realize thousands of pixels as required in imaging applications [6]. Unlike ion chambers, photomultiplier tubes and microchannel plates [7], silicon detectors do not need high voltages for their operation. It is well known for almost twenty years that silicon detectors are ultra-high vacuum and cryogenically compatible. Silicon detectors have very low noise, large dynamic range and very high collection area to size ratio making them extremely attractive for space applications. Electron mobilities in silicon are adequately high leading to fast charge collection and high photon counting rates. Silicon detectors reported in this work have the highest quantum efficiency of all the X-UV detectors suitable for use as radiometric standards. These silicon detectors operate at room temperature hence they have a distinct advantage over the older lithium drifted silicon detectors which need liquid nitrogen temperature for their operation [7].

2. X-UV SILICON PHOTODIODE FABRICATION

Earlier efforts to develop silicon diodes for X-UV photon detection were unsuccessful either because the diodes had a dead region at their surface [8] or they were unstable in quantum efficiency [9]. Realizing the problem of internal quantum efficiency instability in silicon photodiodes, intensive efforts were devoted in early 1986 at United Detector Technology [10] to understand and correct the quantum efficiency instability problem in silicon photodiodes. These efforts have materialized into extremely stable n on p diffused UV-enhanced photodiodes having practically no dead region at their surface [11,12]. The performance of these photodiodes in the vacuum UV range after optimization of their passivating silicon dioxide coating was reported by us recently [8]. This paper describes the potential use of these photodiodes in the soft X-ray region. Figure 2 shows a schematic of the 1 cm^2 active area X-UV silicon photodiode made by defect-free phosphorous diffusion into p-type silicon. The device fabrication information is available in detail in our earlier publications [8,12]. This chip was mounted on a UDT standard BNC package using epoxy and anode and cathode contacts were made by ultrasonic wire bonding. The National Institute of Standard and Technology (formerly NBS) SURF-II facilities were used to make the quantum efficiency measurements reported here.

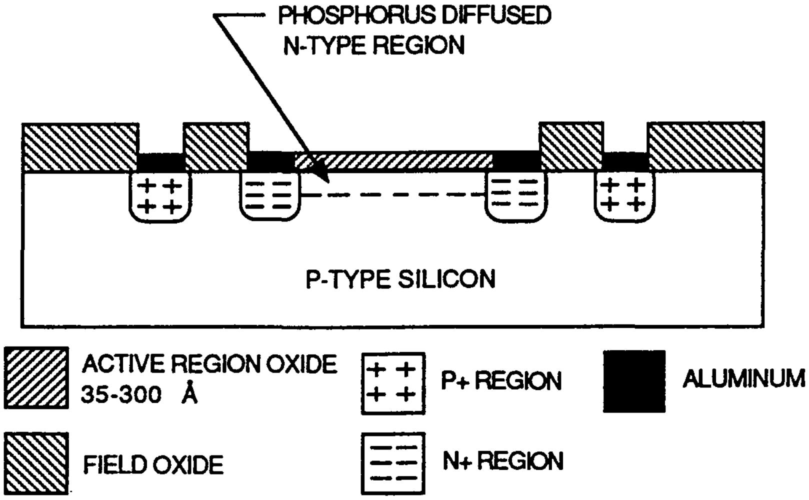

FIG. 2

SCHEMATIC OF THE X-UV SILICON PHOTODIODE

3. QUANTUM EFFICIENCY DATA

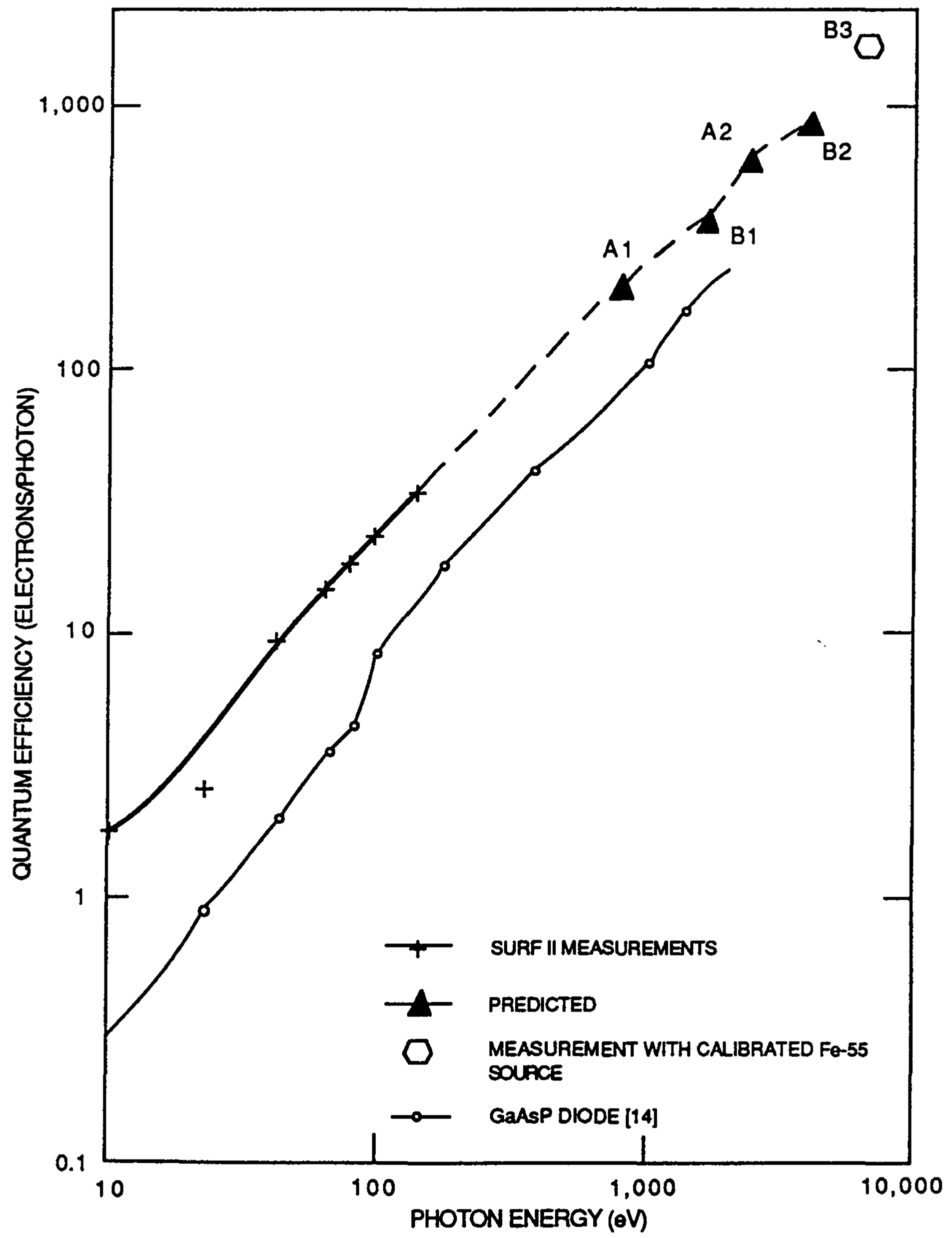

FIG. 3
QUANTUM EFFICIENCY OF THE X-UV SILICON PHOTODIODE

Figure 3 shows the measured and calculated quantum efficiency of the developed X-UV silicon photodiodes in the photon energy range of 10 eV to 3.8 KeV. The quantum efficiency measurement up to 150 eV were performed at the SURF-II facility. Extrapolation of quantum efficiency up to 3.8 KeV was done from the published [13] silicon absorption coefficient data (Fig. 4) and the measured internal quantum efficiency data on these devices in 200 nm to 900 nm spectral range as shown in Figure 5 [12]. Figure 5 shows that the phosphorous diffused UV enhanced photodiode has nearly 100% internal quantum efficiency up to 650 nm where the absorption depth in silicon from Figure 4 is about 2 microns.

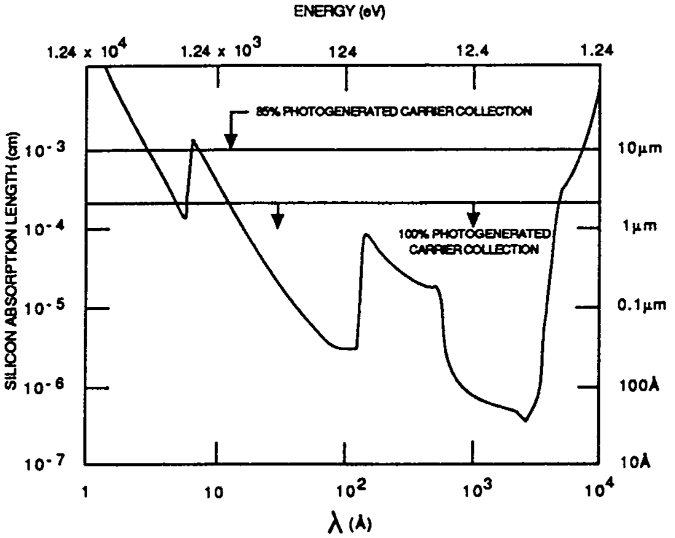

FIG. 4

PHOTON ABSORPTION DEPTH IN SILICON [13]

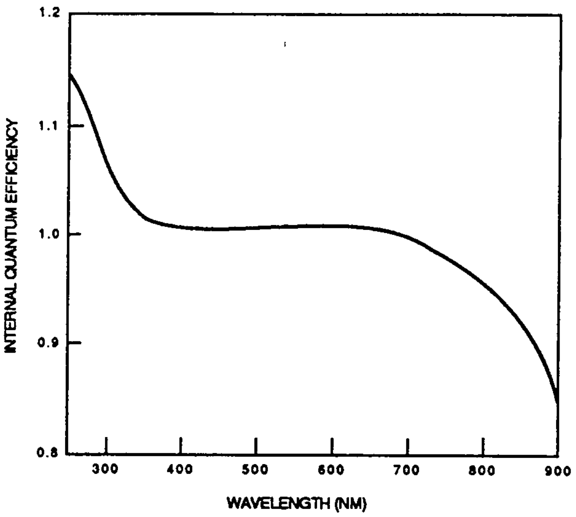

FIG. 5

INTERNAL QUANTUM EFFICIENCY PLOTTED AGAINST WAVELENGTH FOR PHOSPHOROUS DIFFUSED PHOTODIODE [12]

Thus, any photogenerated carriers within 2 microns from the surface are completely separated by the p-n junction leading to a current proportional to numbers of photons arriving in silicon. As Figure 4 shows soft X-ray photons of energy up to about 870 eV have an absorption depth less than 2 microns in silicon. Thus we anticipate that the quantum efficiency of the X-UV silicon photodiode should follow the E(ph)/3.8 relationship up to 870 eV as shown up to point A_1 in Figure 3. (Although 3.63 eV value has been commonly used in the literature for e-h pair creation in silicon, 3.8 eV has been used here as it yields a conservative estimate of the quantum efficiency and also takes into account any small losses associated with the photodiode). Any photon having an energy larger than 870 eV will penetrate deeper than 2 microns, leading to a loss of photogenerated carriers by recombination events which occur at distances larger than 2 microns from the surface. Once again comparing the absorption depth for infrared photons and using the quantum efficiency value from Figure 5, we conclude that about 85% of the photogenerated carriers are seen by the external circuit at photon energies of about 1.7 KeV. This is shown by point B_1 in the quantum efficiency plot of Figure 3. However, for photon energies slightly above this value the photon energy is such that it approaches the silicon K-shell binding energy causing the penetration depth of photons to become less than 2 microns. Thus, the diode once again becomes 100% internally quantum efficient and hence the soft X-ray quantum efficiency is on the E(ph)/3.8 line, as shown by point A_2 in Figure 3. For photons with energies greater than 1.9 KeV, we anticipate that the quantum efficiency will be less than the E(ph)/3.8 value because the carrier generation depth becomes larger than the 2 micron complete carrier collection length. Once again comparing the 85% internal quantum efficiency value at about 900 nm, we conclude that the quantum efficiency of 3.8 KeV soft X-ray photons (which have the same absorption depth as the 900 nm photon as seen from

Figure 4) is .85xE(ph)/3.8 as shown by point B_2 in Figure 3. This figure also shows the experimentally-measured quantum efficiency value (point B_3) obtained using a calibrated X-ray source (Fe-55) emitting 5.95 KeV photons. The quantum efficiency value of 1730 shown by point B_3 demonstrates that the developed photodiodes indeed have extremely high quantum efficiency in the soft X-ray region.

Figure 3 also shows the quantum efficiency plot of 21 mm^2 active area GaAsP Schottky barrier photodiode which has been reported to be a good semiconductor radiation detector in the soft X-ray region [14]. It may be noted from this figure that the quantum efficiency of the GaAsP photodiode is several times lower than the quantum efficiency of our silicon photodiode over the full X-UV range. Additionally, the larger active area (100 mm^2) GaAsP photodiodes were found to be too noisy, making the quantum efficiency measurement nearly impossible [15]. Thus, we feel that the silicon photodiode described in this work is more suitable as a X-UV semiconductor detector than the GaAsP photodiode.

The X-UV quantum efficiency of photodiode reported here was found to be stable within a percent after exposure to 124 eV photons with $2\times10^{14}/\mathrm{cm}^2$ fluence. Additionally, no noticeable change in the quantum efficiency of 10 eV to 150 eV photons was noticed after room temperature storage of these photodiodes for several months. The detailed results of the quantum efficiency stability of the developed silicon photodiodes will be reported separately [16].

The other electro-optical characteristics of the developed X-UV diode are described in the following table:

TABLE 1.

ELECTRO-OPTICAL SPECIFICATIONS OF X-UV100
SILICON PHOTODIODE AT ROOM TEMPERATURE

PARAMETER	MIN	TYPICAL	MAX
ACTIVE AREA	—	1 cm^2	—
SHUNT RESISTANCE	10 MΩ	150 MΩ	—
Q.E. @ 200nm	50%	62%	—
N.E.P.	—	4×10^{-14} w/√HZ	1.55×10^{-13} w/√HZ
CAPACITANCE @ 0 V	—	6 nF	8 nF

4. CONCLUSIONS

Silicon photodiodes with near-theoretical quantum efficiency in the far-UV and soft X-ray spectral region have been developed. No noticeable change in the quantum efficiency was observed after storage of these devices in ambient conditions for several months and also after soft X-ray photon exposure with fluence up to 2×10^{14} photons/cm^2. Efforts to measure quantum efficiency from 150 eV to 3.8 KeV are under progress. Silicon photodiodes with 3cm^2 active area are presently being characterized for quantum efficiency, stability, and uniformity. Such large active area soft X-ray detectors will be extremely useful for soft X-ray telescopes which presently are being built using orthodox detectors [17]. The developed photodiode will likely prove advantageous, both in performance and economy, as a replacement for the older detector types in the following applications:

1. Soft X-ray dosimetry, particularly during X-ray lithography.
2. Early detection of human circulatory system problem by digital subtraction angiography.
3. Biological and medical examination with X-ray microscopes in the 1 nm to 10 nm spectral range.
4. Macromolecular crystallography of protein and virus structures in the 1-1.5Å spectral range.
5. Holography of biological samples in the 1 to 10 nm spectral range.
6. Scanning transmission X-ray microscopy of thick, wet and unstained biological samples in the 2-4 nm spectral range.
7. Studying structures and functions of biological molecules in the near and far ultraviolet spectral region.
8. Laser and magnetic fusion programs in which analysis of emitted X-rays of 100-1000 eV is extremely important.
9. Absorption and reflection spectroscopy to determine optical constants of materials in the X-UV region.
10. Soft X-ray fluorescence experiments to determine valence electron structure of various materials.
11. Photo-emission experiments for investigating the electronic properties of solids, molecules and atoms.
12. Radiometry (as a secondary standard).
13. X-UV radiation imagers.
14. X-ray diffractometer for analysis in the metal industry.
15. Wavelength dispersive X-ray fluorescence spectroscopy for concentration determination and chemical bonding information of different atomic species.
16. Angular resolved photoelectron spectroscopy for investigating electron energy bands in materials.
17. Surface Extended X-ray Absorption Fine Structure (SEXAFS) for exact determination of bond lengths on material surfaces.
18. Photoelectron spectroscopy to determine chemical reactions at surfaces, for example, gold on silicon.
19. Soft X-ray reflectometry for surface roughness evaluation during thin film deposition
20. Study of the far ultraviolet solar spectrum.
21. Ionospheric density distribution by remote sensing of X-UV emissions.

5. ACKNOWLEDGMENTS

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