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Angular dependence of dose sensitivity of surface diodes

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Commercially available surface diodes are found to have as great as ±12% change in sensitivity with the angle of incidence of radiation. This work is a study of the cause of angular dependence in diode sensitivity and how it can be decreased. A number of different surface diodes were used in these measurements: A commercially available diode and four prototype diodes. A number of the diodes were constructed with the silicon chip, the die, mounted on a circuit board that had a plane of copper on its back side. These diodes had angular dependence of sensitivity as great as ±10%. It was hypothesized that the copper plane on the circuit board was the cause of the anisotropy in sensitivity of the diodes. To test this hypothesis, diodes with a new design [Patent No. 61/035,257 (pending)], without a copper back plane, were fabricated and characterized in this work. These diodes were found to have the following characteristics: A dependence on incident angle of radiation of ±3.6%; after 10 kGy of pre-irradiation, a 1.6% change in sensitivity for a 260-fold change in dose per pulse; an areal density of 0.08 $\mathrm{g/cm^2}$. © *2009 American Association of Physicists in Medicine*. [DOI: 10.1118/1.3125644]

Key words: diodes, *in vivo* dosimetry, optically stimulated luminescent dosimeters, OSLDs

I. INTRODUCTION

Radiation treatments of cancer patients require deliveries of high dose, usually 180 cGy or more per day, for 30–40 consecutive daily treatments. *In vivo* dosimetry is desired for cancer patients to ensure that the patient is not overexposed or underexposed and that the exposure occurred in the desired region.[1] *In vivo* dosimetry has traditionally been provided by thermoluminescent dosimeters,[2] *PN*-junction-type diodes,[3] MOSFET detectors,[4] and recently optically stimulated luminescent dosimeters[5] (OSLDs).

The use of diodes for *in vivo* dosimetry has been extensively reviewed.[6–8] Generally diodes are packaged in buildup caps designated for use in ranges of x-ray energies, are placed on the surface of the patient, and are related to dose delivered at the depth of maximum dose.[8,9] Diodes are also designed to measure surface dose and dose from electron fields.[8,10–18] This work is a study of diodes that are semiconductor detectors designed to measure surface dose. The surface-dose characteristic is accomplished with packaging that has an areal density of less than 0.1 $\mathrm{g/cm^2}$ on the entrance side of the diode.

Commercially available surface diodes are found to have as great as ±25% change in sensitivity with the angle of incidence of radiation.[8,11,14–21] This becomes a problem if the measured surface has an irregular shape, which will cause the front surface of the diode to be oblique to the incident direction of the radiation. A similar problem occurs if there is significant scattered dose from adjacent surfaces. Also, this prohibits the use of this type of diode in any type of arc therapy.

This work is a study of the cause of angular dependence of diode sensitivity and how it can be decreased. A new diode design has been devised and prototype diodes have been fabricated. The characteristics of these diodes are investigated in this work.

II. MATERIALS AND METHODS

The x-ray beams used in this work had nominal energies of 6 and 15 MV. For these energies, respectively, the percentage depth doses of x rays at depth of 10 cm, $\%\mathrm{dd}(10)_x$, were 66.6 and 77.8, which were measured at source-to-surface distance of 100 cm, according to the TG-51 protocol.[22] The electron beam that was used had a nominal energy of 9 MeV, which had depths of 50% maximum dose R_{50} of 3.61 that was measured at source-to-surface distance of 100 cm, according to the TG-51 protocol.[22] The radiation beams were generated by a KD2 linear accelerator (Siemens Medical Systems, Concord, CA) or a Varian Trilogy (Varian Medical Systems, Milpitas, CA) linear accelerator.

Absolute dose measurements were made with a cylindrical ion chamber, model N30001 (PTW Hicksville, NY), which had been calibrated at the University of Wisconsin Dosimetry Calibration Laboratory. All doses delivered by the accelerators were compared against ion chamber measurements that were traceable to TG-51 (Ref. 22) calibrations.

Depth-dose measurements for x-ray beams were made with a parallel-plate ion chamber, Markus N23343 (PTW, Freiburg, Germany). For this ion chamber a 3 cm thick slab of solid water was used which had been machined to fit the chamber with its top surface flushed with the top surface of the solid water block. Variations in the depth were made by adding different thicknesses of slabs of solid water.

The commercially available diode used in these measurements was a *P*-type semiconductor surface diode, model 1113000-0 (SunNuclear, Melbourne, FL). More details about this diode, which is designated as "SN," are given in Table I.

TABLE I. Types of diodes used in this work.

Diode designation	Diode description
SN	*P*-type, 10 kGy pre-irradiation, $1.6\times1.6\times0.05\ mm^3$ active volume, semiconductor chip is soldered onto a 0.051-mm-thick copper contact pad on a printed circuit board, encased in a thin epoxy housing with an intrinsic buildup of $0.11\ g/cm^2$
SI1	*P*-type, no pre-irradiation, have a 1.0-mm-diameter $\times$0.250-mm active volume, mounted on printed circuit board with a single layer of copper, 0.0178-mm thick, behind the diode, see Fig. 1(A), encased in a light-tight epoxy housing of 0.4-mm thickness
SI2	Same as SI1 except pre-irradiation with 10 kGy
SI3[23]	Same as SI1 except mounted on a fiberglass board with a copper connection tab adjacent to the diode, see Fig. 1(B)
SI4[23]	Same as SI3 but with a 2-mm diameter, 0.05-mm-thick disk of copper placed over the front side of the diode on top of the epoxy cover layer

Experimental diodes used in this work were provided by Standard Imaging, Madison, WI. More details about these diodes, which are designated as "SI1–SI4," are given in Table I and Fig. 1.

All diode outputs were measured with a clinic built amplifier that integrated charge during radiation exposures or with a Max4000 electrometer (Standard Imaging, Madison, WI) operated in the zero-bias mode.

The OSLDs that were used were InLight/OSL Dot dosimeters (Landauer, Inc., Glenwood, IL). The OSLDs are 7 mm diameter, 0.2 mm thick plastic disks infused with aluminum oxide doped with carbon (Al_2O_3:C) synthetic sapphire. These disks are encased in a $24\times12\times2\ mm^3$ light-tight plastic holder. The OSLDs have been shown[5] to have an areal density of $0.04\ g/cm^2$.

OSLDs were read with an InLight microStar reader (Landauer, Inc., Glenwood, IL). This reader was operated with a 1 s duration illumination-read period. The reader was set in its "hardware test" modality using the low intensity LED beam for pre- and postirradiation measurements. All OSLDs were read before irradiation and reported signals were the difference between the postirradiation and pre-irradiation signals reported in photomultiplier counts. OSLDs were reused after optically bleaching between irradiations. A 15 W compact fluorescent lamp mounted in the reflective housing of a film reader was used to bleach, optically anneal, the irradiated OSLDs after they had been read. OSLDs were bleached for at least 4 h. After bleaching the OSLD signal was measured immediately before use to determine what level of residual signal remained.

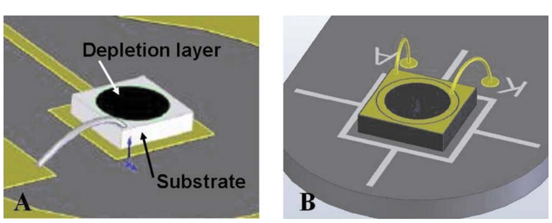

FIG. 1. A diagram of the diodes used in this work. (A) The original configuration of the diodes, SI1 and SI2, described in Table I. (B) The new configuration of the diodes, SI3 (Ref. 23) and SI4 (Ref. 23), described in Table I. The depletion layer is 10 μm deep in a silicon substrate that is 250 μm thick.

Irradiations of the detectors that were done orthogonal to the front surface had a source-to-detector distance of 100 cm. A 0.5-cm-thick piece of Superflab was placed immediately over the detectors, which conformed to the irregular shapes of the detectors without large air gaps. An 8-cm-thick block of solid water was placed behind the detectors to provide backscatter of radiation.

For dose-per-pulse dependence, a cylindrical ion chamber and diode were mounted adjacent to each other on a plastic bracket attached to the end of a 30-cm-long plastic rod. The detectors were mounted in miniphantoms[24] of 10 cm water equivalent depth to avoid interference from contamination electrons.[25,26] This assembly was mounted on a cart that could be moved to various distances from the linear accelerator source position. This arrangement avoided large changes in scatter to the detectors while allowing for change in dose per pulse with distance. The linear accelerator gantry was at 90° with a $10\times10\ cm^2$ field size. The number of pulses produced by the linear accelerator in an irradiation was determined by the pulse counter of a profiler, a diode linear-array detector (Sun Nuclear, Melbourne, FL). The period of the pulses was determined by dividing the irradiation time by the number of pulses counted. The pulse width was determined by measuring the time duration of the target current with an oscilloscope, model 2247A (Tektronics, Beaverton, OR).

For measurements of angular dependence, cylindrical phantoms with 3.6 cm diameter and 5 cm length were fabricated to provide buildup that was homogeneous in all directions. The phantoms were cast from well stirred, molten material, M3,[27,28] which is water equivalent. The cylinders were sawed in half and each hemicylinder was carved out at the geometric center to fit an OSLD in its light-tight case or a surface diode. The hemicylinders were then reassembled into cylinders and held together with tape. The cylindrical phantom was then mounted on a 20 cm tall block of high-density Styrofoam, which had been marked off in degrees of rotation. This experimental apparatus is shown in Fig. 2. The Styrofoam block provided an easy way to set the angular position of the detectors in the cylindrical phantom and to avoid inadvertent scatter from the treatment couch. For these measurements the accelerator gantry was stationary and was set at 90° so that the beam axis was parallel to the floor. A $10\times10\ cm^2$ field size was used. The long axis of the cylindrical phantom was the axis of rotation and it was vertical, which was perpendicular to the central axis of the accelerator beam. Zero degree of rotation corresponded to the front surface of the various detectors.

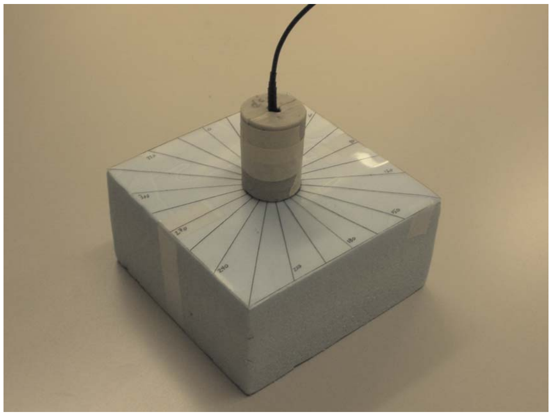

FIG. 2. Experimental apparatus for measuring angular dependence. This photograph only shows 8 cm of the total 20 cm stack of high-density Styrofoam.

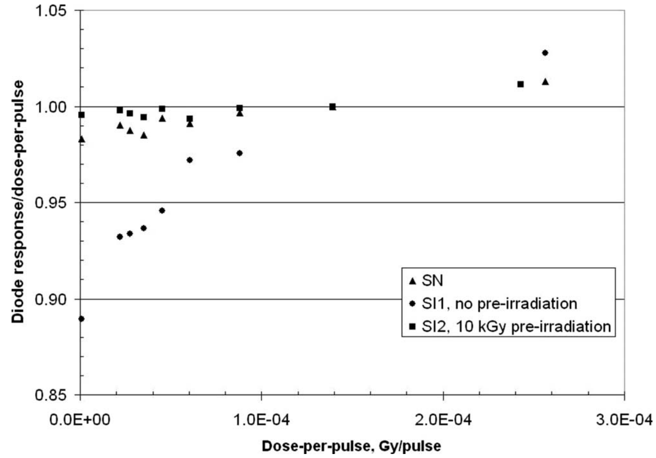

FIG. 3. Dose response of the SN surface diode and Standard Imaging diodes, SI1 and SI2, as a function of dose per pulse of a 6 MV x-ray beam. Exposures were made with a 10×10 cm^2 field measured at 100 cm from the radiation source of a linear accelerator. The relative dose-per-pulse value was varied from 2.57×10^{-4} to 2.22×10^{-5} Gy/pulse by changing the distance to the detector from 75 to 250 cm. The relative dose-per-pulse value of 9.84×10^{-7} Gy/pulse was obtained by irradiating the detector with it positioned under a solid-collimator jaw. The diode response is normalized to 1.0 at the detector-to-source distance of 100 cm, which corresponds to 1.39×10^{-4} Gy/pulse.

III. RESULTS

The linear accelerator delivers dose by giving square pulses of the electron beam at a frequency of a few kilohertz. The dose rate of the accelerator is altered by changing the frequency of the pulses, not the amplitude or the duration of the pulses of the electron beam. For 6 MV x rays on the Siemens KD linear accelerator, the beam current pulse duration was measured to be 2.6 μs. A dose of 1 Gy at source-to-axis distance of 100 cm was found to be delivered with 7200 pulses. This is a dose per pulse, an instantaneous dose rate, of 1.39×10^{-4} Gy/pulse or 53.4 Gy/s during the pulse. The sensitivity of diodes has been shown[29–35] to change when the dose per pulse is of this magnitude. This has been found to be a more significant problem for *N*-type diodes.[29,31,32] However, more recent work[30,36,37] has shown that *N*-type diodes with high doping are equivalent to *P*-type diodes in their dose-per-pulse sensitivity.

The responses of an SI1 and a SunNuclear surface diode (SN) at different dose-per-pulse values are shown in Fig. 3. The value of dose per pulse was varied by making measurements at different distances from the source and placing the detector under the solid-collimator jaw of the accelerator. The dose-per-pulse value itself was measured with an ion chamber with sufficient bias voltage to avoid charge-recombination errors. The data in Fig. 3 indicate that the SI1 diode that was not pre-irradiated had a change in sensitivity of 16% while the SN diode changes sensitivity by 3% for a dose-per-pulse change of 260-fold. SI2 diodes were pre-irradiated with 10 kGy from a Co-60 source. These pre-irradiated diodes had a decrease in sensitivity of 1.6% for the 260-fold decrease in dose per pulse, as shown in Fig. 3. Pre-irradiation of SI diodes greatly decreased their dose-per-pulse sensitivity and diodes that had been pre-irradiated by 10 kGy were used for all of the subsequent measurements presented in this work. Due to the low dose-per-pulse dependence of diodes SI2–SI4, no corrections for dose rate were made to data measured with these diodes.

The angular dependence of the detectors was determined by irradiating them with 50 cGy of 6 MV x rays collimated into a 10×10 cm^2 field. Figure 4 shows these data for the SI2 and SN diodes. The two types of diodes have a similar response with the SN diode having a slightly greater dependence on angle. The diodes have a complicated dependence on the incident angle of the radiation with a 10% high sensitivity at 0°, a 10% low sensitivity at 105° and 255°, and an 8% low sensitivity at 180°.

A change in detector sensitivity with angle shown in Fig. 4 is interpreted to be due to a lack of symmetry around the detector. Since buildup is provided by a symmetrical cylindrical phantom the asymmetry must be in the diode itself or

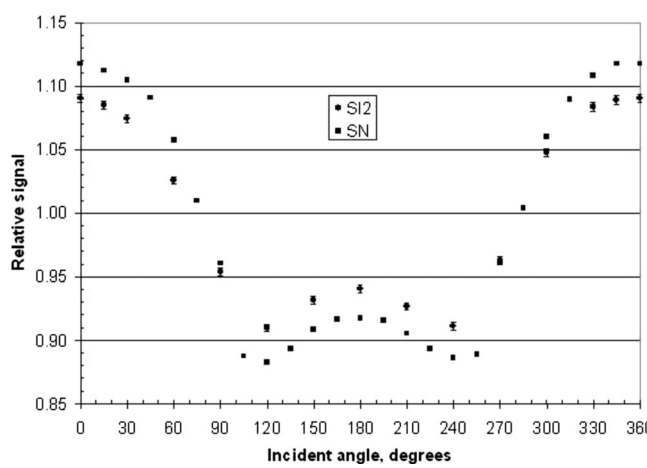

FIG. 4. The radiation sensitivity of an SI2 and a SN diode as a function of the angle of incidence of x-ray radiation. All signals were normalized to the midrange, (max+min)/2, sensitivity. The incident angle is with respect to the top surface of the diode. 0° is the incident angle of the central axis of the beam when it was perpendicular to the front surface of the detector. Repeated measurements with the diode at any angle have an uncertainty of 0.3%, which is shown as an error bar.

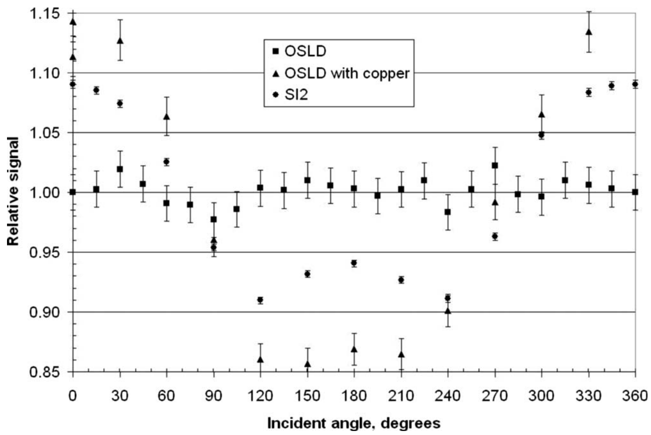

FIG. 5. The radiation sensitivity of an SI diode, an OSLD, and an OSLD with copper as a function of the angle of incidence of x-ray radiation. All signals were normalized to the midrange, (max+min)/2, sensitivity. The incident angle is with respect to the top surface of the diode. 0° is the incident angle of the central axis of the beam when it was perpendicular to the front surface of the detector. The error bars indicate one standard deviation in repeated measurements made at any angle.

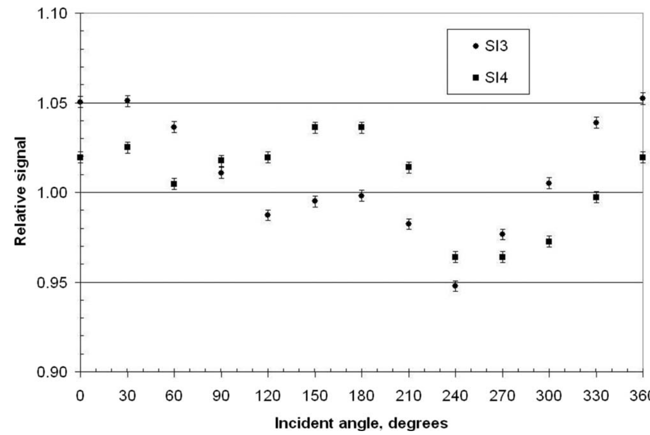

FIG. 6. The radiation sensitivity of the SI3 and SI4 diodes as a function of the angle of incidence of x-ray radiation. All signals were normalized to the midrange, (max+min)/2, sensitivity. The incident angle is with respect to the top surface of the diode. 0° is the incident angle of the central axis of the beam when it was perpendicular to the front surface of the detector. The error bars indicate one standard deviation in repeated measurements made at any angle.

in the diode mounting. To test this concept a detector with very symmetric response with angle, an OSLD,[5] was measured. A major difference between the OSLD and the diodes is that the OSLD is a homogeneous detector in a plastic case with no high atomic-number material present, while the diodes are mounted on a circuit board with a plane of copper on the back. Low energy electrons are scattered up and down beam from interfaces of low and high atomic-number materials.[37,38] It was hypothesized that the copper plane on the circuit board was the cause of the anisotropy in sensitivity of the diodes. One test of this hypothesis was to attach a disk of copper to the back side of an OSLD disk. Figure 5 shows that an OSLD in its light-tight plastic case has no angular dependence within experimental uncertainty. Next the symmetry of the OSLD is purposefully altered by adding a 7-mm-diameter, 0.127-mm-thick disk of copper on the back side of the OSLD. The angular dependence of the OSLD with copper has now become highly variable and resembles that of an SI2 or SN diode as shown in Fig. 5.

Based on the results shown in Fig. 5, it was believed that the large angular dependence of diodes could be reduced by changing the conventional diode design. A new diode, SI3 in Table I, was fabricated and mounted on fiberglass, not a copper-backed printed circuit board as shown in Fig. 1(B). The angular dependence of SI3 is shown in Fig. 6 and is found to be ±5.3%.

It has been suggested[21] that the directional dependence of a diode is due to the asymmetry inherent in the silicon chip with the depletion layer closer to the front surface. Another variation in the diode design was SI4 in Table I, which had a 0.05-mm-thick disk of copper added to its front side. The low energy electrons scattered from the copper disk will balance those scattered from the asymmetric silicon chip. This diode had the smallest extent of angular dependence that could be achieved, which was ±3.6% in Fig. 6. This is a significant improvement compared to the SI2 and SN diodes in Fig. 4 but not quite as good as the OSLD in Fig. 5. The SI4-type diode was used for all of the subsequent measurements presented in this work.

Next the angular dependence of the detectors was determined by irradiating them with 50 cGy of 9 MeV electrons collimated with a 10×10 cm^2 cone. Figure 7 shows these data for the SI2 and SI4 diodes. As can be seen the SI2 diode has a marked angular dependence with a range of sensitivities of ±11% with a maximum at 45° and 315° and a minimum at 105° and 255°. The SI4 diode has a greatly diminished angular dependence with a range of sensitivities of ±3.3%. The SI4 design shows low angular dependence for x rays and electrons.

The diode is encapsulated in a light-tight, water equivalent epoxy coating of 0.4 mm thickness. With the 0.05-mm-

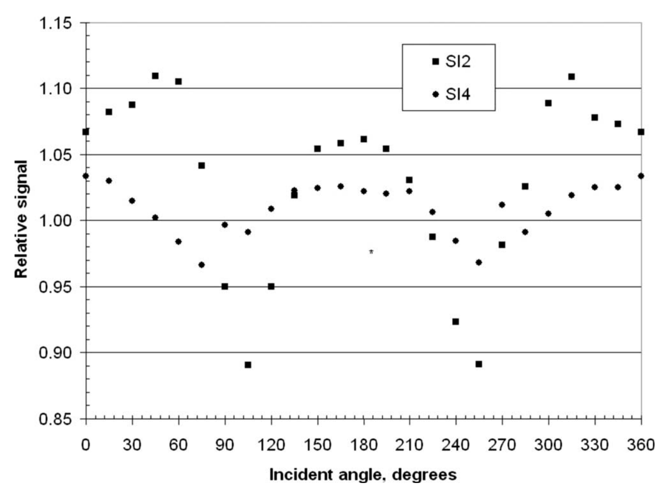

FIG. 7. The radiation sensitivity of the SI2 and SI4 diodes as a function of the angle of incidence of electron radiation. All signals were normalized to the midrange, (max+min)/2, sensitivity. The incident angle is with respect to the top surface of the diode. 0° is the incident angle of the central axis of the beam when it was perpendicular to the front surface of the detector.

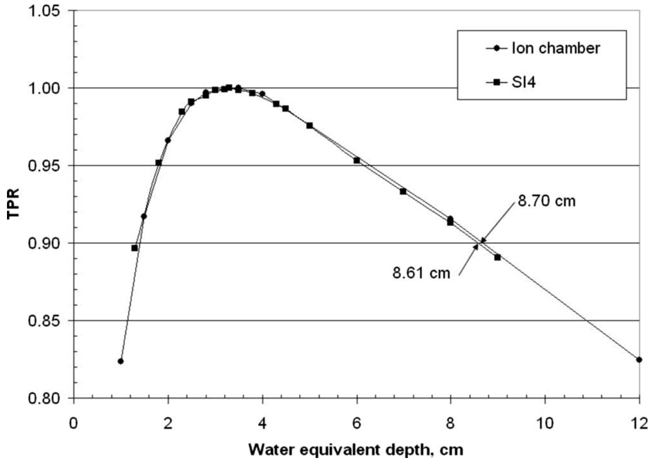

FIG. 8. The tissue phantom ratio (TPR) of a 15 MV x-ray beam measured with a parallel-plate ion chamber and an SI4 diode. The source-to-detector distance for these measurements was kept constant at 100 cm. The depth was adjusted by adding pieces of solid water and a 5 mm piece of Superflab directly over the parallel-plate ion chamber and the surface diode. For these measurements, a 1 mm thick protective plate was not used on the parallel-plate ion chamber. All data are normalized to the maximum value at a depth of 3 cm.

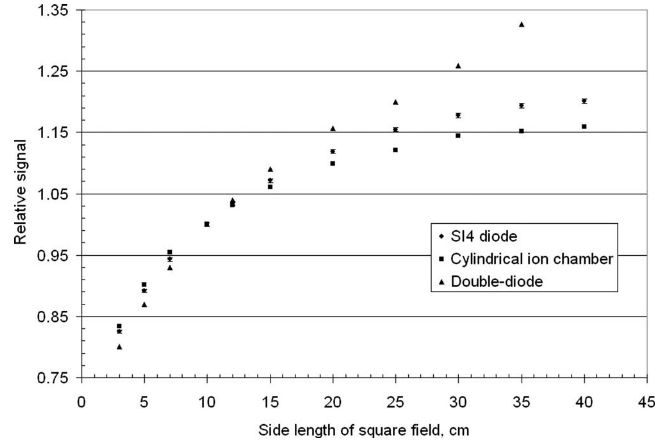

FIG. 9. Total output factor measured at a depth of 10 cm in a water tank. Measurements were made on a 6 MV x-ray beam. Data for a double diode, taken from Fig. 4(a) of Ref. 21, are also shown.

thick copper disk on the top of the diode the areal density is 0.08 g/cm^2. This should make the SI4 diode an ideal surface detector. To test this characteristic, an SI4 diode was compared to the depth-dose response of a parallel-plate ion chamber. These data are shown in Fig. 8. All of the detectors had a maximum response at a depth of 3 cm, which is expected for a 15 MV beam.[39] The SI4 diode had a small amount of intrinsic buildup compared to the parallel-plate ion chamber. This is seen as a shift in the crossing of the data at the 90% relative dose line, 8.61 cm for the SI4 and 8.70 cm for the ion chamber. This shift is equivalent to 0.09 g/cm^2, which is very close to what is expected from the areal density of the light-tight case and the top-side copper disk.

A useful test of diode energy response is to measure total output factors at large field sizes. Under these conditions, Compton scattering will result in low energy photons in the phantom that will impinge on the diode. Due to the high atomic number of silicon compared to air of an ion chamber, at large field sizes the diode will over-respond compared to an ion chamber. Measurements of output factors are shown in Fig. 9. As expected, the SI4 diode over-responds compared to the ion chamber at field sizes larger than 15×15 cm^2. At a 35×35 cm^2 field size, the double-junction diode over-responds by 16% compared to an ion chamber, while the SI4 diode over-responds by 3%.

IV. DISCUSSION

An important characteristic of a surface detector is a small dependence on the angle of incidence of the radiation. As shown in Fig. 4, surface diodes of conventional design have a large angular dependence. It was hypothesized that this angular dependence was a result of asymmetry in the mounting of the diode and in the diode substrate. The common mounting of a diode is to solder the die to the copper plane on a circuit board, Fig. 1(A). This arrangement is intrinsically asymmetric due to the plane of high atomic-number copper. It is known that low energy electrons are scattered up and down beam from interfaces of low and high atomic-number materials.[37,38] A test of this explanation for surface diodes was to take a symmetrical device, an OSLD, and make it asymmetrical with an added plane of copper. This was shown to occur by comparing the original and modified OSLDs, Fig. 5. A diode fabricated without mounting on a plane of copper was found to have greatly reduced angular dependence, Fig. 6. The remaining angular dependence is due to the asymmetric structure of the diode, which is shown in Fig. 1(B) as a depletion layer 10 mm from the front surface of the 250 mm thick silicon chip. The thick silicon chip scatters low energy electrons back into the depletion layer. A 0.05 mm thick copper disk added to the front of the diode was found to partially compensate, Fig. 6, for the intrinsic asymmetry of the die structure.

A different approach to compensating for the asymmetry of the die structure was to have two dies mounted back to back, a so-called double diode.[21] This arrangement has a reported angular dependence of $\pm 3.0\%$. One of the disadvantages of the double diode is that the additional mass of silicon of the two dies causes the diode to over-respond to low energy scattered photons.[21] This over-response should not be a problem with a single die diode such as SI4. The comparison of measured SI4 data to double diode data, which is shown in Fig. 9, demonstrates the advantage of having a single die.

Table II is a comparison of diode angular-response data reported in selected literature. These data can be separated into two groups. In the first group, Refs. 15, 16, and 21, and this work, the diode was placed in the center of a phantom at a depth of maximum dose. In this way the diode response, not the scatter and attenuation of the phantom, was measured. Reference 21 and this work showed diode directional dependence less than 3.5%. In the second group, Refs. 11, 14, 17, and 18, the diode was placed in no phantom or on the

TABLE II. Comparison of diode angular response reported in selected literature.

Reference	Diode	Experimental details	Results (maximum diode differences)
16	*P*-type, Scanditronix	Mounted on central axis of cylindrical polyethylene phantom, measurement angles 0° to 130°, 6 MeV electrons	+2% at 45° −12% at 105°
12	*P*-type, Scanditronix	Mounted on surface of cylindrical acrylic phantom, measurement angles −45° to +45°, 6 MeV electrons	+4.5% at ±45°
12	*P*-type, Scanditronix	Mounted on surface of plane acrylic phantom, measurement angles 0° to 360°, 6 MeV electrons	+6.5% at ±45°
17	*P*-type, Scanditronix	Mounted on central axis of cylindrical polyethylene phantom, measurement angles 0° to 130°, 6 MeV electrons	+2% at 60° and 300° −9% at 90°, 200°, and 270°
22	*P*-type, Scanditronix	Mounted on central axis of cylindrical water phantom, measurement angles −150° to +150°, 18 MV x-rays	−3% at −150° −1% at +150°
15	*P*-type, Sunnuclear, Scanditronix, and PTW	Mounted on surface of cylindrical acrylic phantom, measurement angles −50° to +150°, 4.5–21 MeV electrons	+15% at ±50°
17	*P*-type, Scanditronix	In air, no phantom, measurement angles −80° to +80°, 12 MeV electrons	+14% at ±80°
19	*P*-type, Scanditronix	Mounted on surface of plane solid water phantom, measurement angles 0° to +80°, 6 and 10 MV x-rays	+20% at 80°
This work	*P*-type, Standard Imaging	Mounted on central axis of cylindrical M3 phantom, measurement angles 0° to 360°, 6 MV x-rays and 9 MeV electrons	−3.5% at 240° +2.5% at 30° and 150°

surface of the phantom. With this experimental geometry the angular response of the diode and the scatter and attenuation of the phantom were convolved and the response of the diode could not be separated. This was useful for evaluating surface measurements but did not assist in characterization of the diode itself.

If diodes are to be used for frequent surface measurements of entrance dose, then the perturbation of the dose in the shadow of the diode is important.[11,18] The SI4 diode would be expected to be of use for this type of measurement since it will have low attenuation with the copper connection plane removed. It was concluded[18] that the calculation of entrance dose, dose at dmax, based on surface-dose measurements was ill advised due to the large number of correction factors required. This conclusion is not overturned by this work. The SI4 diode is ideal for measurement of the dose at the skin surface. Attempts to determine entrance dose based on measurements of surface dose are not encouraged.

The use of diodes for clinical electron dosimetry requires extreme caution, especially when low energy electrons may be present.[17] It is interesting that diodes have been reported[17] to give distorted depth-dose curves, with diodes over-responding compared to parallel-plate ion chamber by 20%–40%. Others[15,16,40] found 1%–2% differences between diodes and ion chambers only at shallow depths. Caution is advised for anyone that will be using a diode for electron depth-dose measurements.

The sensitivity of diodes to dose-per-pulse instantaneous dose rate has been widely reported in the literature.[5,29–36] A theoretical analysis has been presented[41] with the dominant factor being the lifetime of minority charge carriers in the semiconductor. Defects in the semiconductor crystal, which can be generated by added impurities[36,41,42] or radiation damage,[31–34,43] are associated with recombination-generation (RG) centers. Radiation induced charge carriers can be trapped and dissipated at the RG centers, which is observed as a decrease in the diode sensitivity to radiation. At high levels of dose per pulse the RG centers become saturated and the diode sensitivity is seen to increase.[41] Pre-irradiation forms a higher concentration of RG centers and the saturation behavior with large dose per pulse is diminished. The diodes studied in this work have behavior, Fig. 3, which is consistent with this model.

V. CONCLUSIONS

Based on the data presented here, the following conclusions are made concerning angular dependence of diodes and an attempt to mitigate this dependence. (1) The anisotropy of angular dependence of diode sensitivity is largely due to the mounting of the diode on a circuit board that has a plane of copper and to the intrinsic asymmetry of the die construction. (2) Low energy electrons are backscattered at the interface of low and high atomic-number materials and this results in higher diode sensitivity to photons that enter from the directions of the front and back surfaces of the diode. (3) Diodes that are modified and not mounted near a plane of copper have greatly reduced angular dependence. (4) A thin copper disk mounted on the front side of the diode can partially compensate for the intrinsic asymmetry of the die construction. (5) This type of diode with a single *PN* junction has only a significantly lower over-response to low energy photons than a double-junction diode.

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