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BIOLOGICAL AND CLINICAL DOSIMETRY

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I. SUMMARY

An extensive series of measurements comparing cavity ionization with calorimetrically determined absorbed dose as a function of depth in carbon irradiated by 20 MeV electron has been completed. Theoretically computed values of the mean stopping power ratio between carbon and air including the polarization effect (2) are in good agreement with those measured.

The G(Fe++) of the Fricke (ferrous sulfate) dosimeter was determined at several depths for 20 MeV electrons and was found to be constant.

The RBE of 20 MeV electrons is being investigated at depths of 1.0 and 8.7 gm/cm² (H₂O equivalent) with HeLa cells. No significant difference in cell survival is found.

Utilizing an intensity calorimeter, the dose rate dependence of the CaF₂:Mn dosimeter was investigated up to 5 x 10¹² rads/sec. Dose control by use of beam limiting apertures was found to be satisfactory and depth dose data obtained.

Further experimental investigations were made of the energy dependence of LiF and CaF₂:Mn thermoluminescent dosimeters for fast electrons and cobalt-60 gamma rays with the carbon calorimeter. No significant energy dependence was found for teflon matrixed phosphors.

A preliminary survey of the performance of semiconductor detectors for high energy radiation dosimetry has been completed, and their suitability for dose distribution determination demonstrated.

An active program of consultation to assist the National Bureau of Standards in establishing its electron beam calibration service is in progress.

A miniature diode was constructed with a "wrap-around" junction geometry which provides approximate azimuthal symmetry around an axis through the diode parallel to the junction. An increase in sensitivity is also associated with this geometry which is aimed at the measurement of absorbed dose from cobalt-60 gamma rays in tissue equivalent material.

Three separate square arrays of lithium drifted diodes were constructed at Sloan-Kettering Institute in two distinct configurations and tested for eventual use in position indicating nuclear particle counting systems, e.g., a low energy gamma camera. The diode elements of each array have a common compensated region. The most promising of the three units fabricated is a 1.5 centimeter square matrix of 36 diodes. The most difficult single problem connected with the operation of such arrays, that of obtaining a sufficiently high interdiode resistance, appears to have been solved. The aim of this work is to demonstrate that a diode array of this configuration is suitable for use as the unit in counting systems of larger arrays of diodes.

Approximate efficiency curves for gamma counting with silicon and germanium diodes were calculated and are presented, based on primary photoelectric interactions. A 150 micron diode window was assumed.
II. ABSORBED DOSE MEASUREMENTS WITH MICROCALORIMETER

A. Comparison of Calorimetric and Ionometric Dose Determination

The comparison of ionization and absorbed dose as a function of depth for carbon irradiated by 20 MeV electrons has been completed, utilizing the carbon extrapolation chamber described in the previous report (1). In that report attention was called to the ratio of positive to negative charge collected and its variation with depth. One possible explanation for this is the Faraday cage effect, that is the stopping of electrons in the collecting electrode and its associated structures. Measurements were, therefore, made of the charge collected with zero chamber volume. If the charge collected in this fashion was responsible for the discrepancy, it would be equal to one half the difference between the negative and positive charge collected with an air volume present. This is to be expected, since the stopped electrons would add to the negative charge and subtract from the positive charge collected. Since the current at zero chamber spacing varied between 1 and 7 percent of the mean current at the smallest normal chamber spacing (1.083 mm), the accuracy of this comparison was somewhat limited. Nevertheless, satisfactory agreement was obtained and the mean of the positive and negative charge collected was taken as the true ionization.

Utilizing the extrapolation chamber and carbon calorimeter, values of esu/cc monitor unit and rad/monitor unit were determined at 13 depths between 1.76 and 12.8 gm/cm² of carbon. By the use of electrodisintegration thresholds, the incident electron energy was determined to be 20.35 ± 0.15 MeV. Assuming a constant value of 33.73 ev for the W of air one can directly determine from these measurements the mean stopping power ratio between carbon and air for the electron spectra traversing the cavity at each depth. This is of particular interest since it directly displays the influence of the polarization effect (2); and therefore the relative influence of high and low energy electrons upon the ionization produced.

Table 1 gives the measured values of esu/cc/monitor unit and rad/monitor unit, and the mean stopping power ratio computed from them. The uncertainties indicated are the square root of the sum of the squares of all experimental deviations and estimated errors associated with each value.

A graphical representation of the measured stopping power ratio compared with values computed by two methods is given on Fig. I. The primary and secondary electron spectra for a 20 MeV electron beam penetrating water have been calculated as a function of depth by Kessaris (3). Dr. Kessaris has kindly recomputed these spectra for carbon including the effect of higher order electrons; and from the resulting spectra calculated the mean stopping power ratio.

Harder (4) has stated that the stopping power ratio for a cavity ionization chamber at a given depth may be adequately represented by that calculated for the mean electron energy at the depth. The mean electron energy is given by the formula:

\[ E_m = E_0 (1 - d/R_p) \]

Where \( E_0 \) = Incident energy
\( d \) = depth of interest
\( R_p \) = practical extrapolated range
Agreement between either set of calculated values and the experimental results is within 2.5% for all points except those in the tail of the electron dose curve where the bremsstrahlung (approximately 4% of the maximum dose) becomes a strong influence. Indeed, the experimental value of the stopping power ratio at a depth of 12.8 gm/cm² (0.959) is in agreement with the values given by Skarsgard (5) and Bewley (6) for 20 Mev x-rays.

Since the uncertainty of the computed stopping powers is of the order of ± 1%, both methods of calculation are in excellent agreement with experimental results. It appears on the basis of the comparison with the values computed by Dr. Kessaris, that the contribution to cavity ionization by electrons whose energies are sufficiently low to avoid the polarization effect is small.

B. Energy Dependence of Thermoluminescent Dosimeters for High Energy Radiation (See footnote)

1) Lithium Fluoride

The energy dependence for lithium fluoride exposed to high energy electrons and cobalt-60 gamma rays reported by this laboratory (7) and corroborated by others (8) was further investigated in our last progress report (1). Recent measurements by Almond (9) confirmed these observations and extend them from 24 keV x-rays to 35 mev electrons. Almond compares the response of the dosimeter with the mean LET for the various radiations as computed by Burch (10) and suggests that the response variation may arise from an LET sensitivity of the phosphor. This explanation is of particular interest at high energies, since the energy absorption characteristics of LiF are such that a negligible variation between the ratio of dose in the phosphor to dose in either the Fricke dosimeter or carbon calorimeter occurs. The stopping power ratios of LiF to carbon and water are given below:

<table>
<thead>
<tr>
<th>Radiation</th>
<th>LiF/carbon</th>
<th>LiF/H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>cobalt 60 gamma-rays</td>
<td>0.926</td>
<td>0.820</td>
</tr>
<tr>
<td>1 MeV electrons</td>
<td>0.921</td>
<td>0.808</td>
</tr>
<tr>
<td>6 &quot; &quot;</td>
<td>0.913</td>
<td>0.809</td>
</tr>
<tr>
<td>10 &quot; &quot;</td>
<td>0.915</td>
<td>0.809</td>
</tr>
<tr>
<td>20 &quot; &quot;</td>
<td>0.921</td>
<td>0.809</td>
</tr>
</tbody>
</table>

The response of LiF teflon disc dosimeters was measured by integrating the photomultiplier current produced by the light emitted during a heating cycle in a Con Rad 5100A dosimeter reader. These dosimeters are of special utility in biological and clinical applications. The integrated photomultiplier current/rad (carbon) was determined for cobalt-60 gamma-rays and 6, 8, 10, 12, 15, 18 and 20 MeV electrons with the calorimeter. These results, together with the previous data on the powdered phosphor, are shown in Figure II. The response/rad has been normalized at the 20 MeV value, and the cobalt-60 point is plotted at an energy corresponding to the mean energy of the Compton electrons. There is a striking variance between the results; while the loose phosphor encapsulated in 1 mm wall polyethylene capsules shows increasing response with decreasing energy, the LiF teflon dosimeters do not. The reason for this

Note: All Dosimeters discussed were obtained from Controls for Radiation, 130 Alewife Brook Parkway, Cambridge, Mass.
discrepancy is not understood. If the variation of response of the phosphor were due to the change in LET of the radiation, it should be as evident for thin (0.3 mm) as for thick (3.0 mm) dosimeters. Additional work must evidently be performed to clarify this problem.

2) Calcium Fluoride: Manganese

CaF₂: Mn Teflon disc dosimeters were compared to the carbon calorimeter for the same radiations used above. The results are shown in Figure III. The response of these dosimeters appears to be relatively constant for high energy radiations and their reproducibility, as indicated by the standard deviations, somewhat better than the LiF teflon dosimeters although larger doses are required because of lower sensitivity. Similar measurements employing the powdered phosphor have not yet been performed because of the more cumbersome technique required and reported in the 1965 progress report (11).

C. Response of Semiconductor Detectors for High Energy Radiations

Because of the effort required by other projects it has not yet been possible to mount and thoroughly evaluate the response to high energy radiations of one of the specially fabricated p-i-n dosimetry diodes described in section VI of this report. In order to obtain preliminary data on this extremely promising area of application, however, evaluation has been made of two types of commercially available pn devices. A portion of this work performed in cooperation with the Department of Medical Physics of Memorial Hospital is reported in (12).

A Texas Instrument TI-53 general purpose diode was substituted for the miniature ionization chamber normally utilized with the automatic depth dose plotting apparatus (13) developed here. This permitted comparison with conventional depth dose distributions; measurements were made for cobalt-60 gamma-rays, 6 and 20 MeV electrons. The diode was operated in the short circuit current made with an operational amplifier integrator. These curves which show apparent agreement between the responses of the ion chamber and the diode, except for the 6 MeV build up region, are presented in Figs. IV, V, and VI.

It was suspected that this discrepancy arose because of scattering from the massive copper alloy heat sink incorporated in the diode structure. This was substantiated by two methods. First a small piece of copper wire was attached to the diode case in close proximity to the silicon wafer. This resulted in an elevation of approximately 4 per cent in the measured response. Additionally, measurements made with a silicon micro-diode in which the terminal configuration minimizes the effect of high atomic number materials, displayed the initial build-up in the 6 MeV distribution (see Figure V).

The encouraging performance of the micro-diode made it desirable to make a preliminary determination of energy dependence with one of these devices in comparison to the calorimeter. A Micro Semiconductor MC-150A diode was mounted in a carbon sleeve to permit its insertion into the calorimeter phantom and the integrated short circuit current per rad (carbon) measured for 6, 8, 10, 12, and 20 MeV incident electrons and cobalt-60 gamma-rays. The response to electrons normalized to the 20 MeV value and plotted as a function of mean electron energy at the diode is shown in Figure VII. The response is extremely uniform and within experimental limits a constant value.
Measurements for cobalt-60 gamma-rays however showed a variation of sensitivity of up to 11% depending on the orientation of the diode relative to the direction of the beam. This was not observed for the electron irradiations. It is not certain whether this effect arose because the diode leads were bent back over the device to permit insertion in the phantom; or from the asymmetry of the silicon wafer which is approximately $\frac{1}{3}$ mm thick by 1 mm in diameter. The results however indicate that special efforts must be made in design and mounting of a diode intended for general dosimetry applications.

D. Response of Fricke Dosimeter as a Function of Depth for 20 MeV Electrons

The yield of the Fricke (ferrous sulfate) dosimeter was determined at depths in carbon corresponding to the 100, 73, 45, and 18 percent dose levels for 20 MeV incident electrons. The dosimeter solution was irradiated in thin (1 mm) walled polystyrene capsules in a carbon phantom which located the central plane of the dosimeter at the same depth (gm/cm$^2$) as central plane of the calorimeter absorber. The results are shown in Figure VIII. The slight elevation ($\pm 2\%$) of the $G(Fe^{++})$ at the 9.07 and 10.7 (gm/cm$^2$) depths is not considered significant since it may reflect the experimental difficulties caused by the reduced dose rate and steep gradient in the radiation fields. In any case the values of $G(Fe^{++})$ determined for these two depths are within the range of published values, and within two standard deviations of the value at the dose maximum.

E. Calorimetric Determination of Absorbed Dose for Low Energy X-rays

At the time of writing, no experiments have yet been carried out in this area. However, two diamond thermistors have been received from General Electric Corporation and are being evaluated for radiation stability and sensitivity.

III. BIOLOGICAL EFFECTIVENESS OF ELECTRONS AS A FUNCTION OF DEPTH

A considerable research effort has been directed in recent years to the question of whether or not a significant variation occurs in the biological effectiveness of high energy electrons in the terminal region of their penetration in tissue (14, 15, 16, 17, 18). Since both enhanced and unenhanced biological effectiveness has been reported for the terminal region by other laboratories, a series of experiments to elucidate this problem are in progress.

In cooperation with Dr. Jae Ho Kim of this institute, we are irradiating HeLa cells with 20 MeV electrons at both the plateau region and terminal portion of the depth dose curve. Cell survival, recovery ability and size of clones are being utilized as analytic criteria. A full account of these experiments will be published (19) and consequently only a preliminary presentation of the survival experiment will be made in this report.

Central axis dose distributions were determined in both opaque high impact polystyrene and water for 20 MeV betatron electrons scattered by .010" Pb and .027" Al for a 10 cm diameter field. Measurements in water utilized a miniature (0.3 CC) ionization chamber of tissue equivalent conducting plastic, those in polystyrene were made with Kodak type R film exposed at a 3° angle to the beam direction to avoid distortion due to the increased scattering by the emulsion.
These distributions indicated that the 99% and 25% dose levels were to be anticipated at 1.0 gm/cm² and 8.7 gm/cm² water equivalent depths. Field flatness determinations indicated less than ±5% variation over an area equal to that of the cell culture plates. Accordingly, allowing for an effective density of 0.97 for polystyrene and 1.03 for the cell culture medium, an irradiation phantom was constructed of polystyrene with suitable dimensions to place the cell layers at the specified depths. By the use of inserts, polystyrene capsules 4 mm thick and 3.8 cm in diameter could be located in the phantom so as to place the central planes at the same depths (mass/unit area) as the cell layers on the culture plates. Utilizing a G Fe+++ value of 15.5 as recommended in the SCRAD electron beam dosimetry protocol (20) the absorbed dose delivered to the cell layers as a function of the readings on the betatron monitor was determined. The standard deviations of these calibrations was approximately one per cent for both irradiation depths, and were repeated several times during the experiment.

To avoid spurious effects on cell survival, irradiations were carried out in a temperature regulated chamber, and the irradiated culture media replaced prior to incubation.

An initial series of cell irradiations tended to indicate a pronounced increase in lethality for higher doses of radiations at the 8.7 gm/cm² depth. It was noted however that a 2 to 3 mm air space was often present between the cover and the medium filling of the culture plate. While the presence of a variable air space would not appreciably alter the dose delivered to cells in the plateau region of the electron depth dose, the effect at the 8.7 gm/cm² depth was significant. Measurements indicated that the presence of this air space elevated the dose at the 8.7 gm/cm² depth approximately 14% by reducing the effective depth of irradiation.

This problem was circumvented by the use of culture dishes with a depressed cover and a polystyrene insert which filled this depression. The cover plate was now in uniform contact with the medium and the irradiation phantom a continuous volume of polystyrene except at the periphery of the dishes, an area excluded from scoring.

To verify that individual specimens received the prescribed dose, and to provide a check upon shift in beam energy, or other problems in technique, such as influenced the initial experiments, lithium fluoride-teflon dosimeters were placed under each culture plate.

Figure IX shows the surviving fraction for cells irradiated with doses from 100 to 800 rads at 1.0 and 8.7 gm/cm² depths. Within limits of experimental error there does not appear to be a significant difference in biological effectiveness.

Our experience leads us to believe that the variety of results on this question are in part the result of variations in dosimetric and biological techniques.

IV. DOSIMETRY OF ULTRA-HIGH INTENSITY RADIATION SOURCES

Work in this area, utilizing our 600 kv field emission electron source, had been delayed by difficulty in obtaining a qualified individual in the senior research aide position. The beam intensity calorimeter described in the previous report (1) was calibrated for total energy inputs between 0.03 and 3.5 Joules by discharging a capacitor through the conducting plastic wafer. This calibration was used to interpret the data reported below.
Since some difficulty in calibration was encountered, apparently arising from electrical characteristics of the conducting plastic under impulse conditions, a second calorimeter employing standard resistors for heating has been fabricated.

Because of the pressing needs for biological experiments, emphasis was placed upon surveying the suitability of CaF₂:Mn teflon dosimeter discs. This type of dosimeter is attractive because of the wide dose range approximately 1 rad to 1 megarad and previously reported dose rate studies (21) indicated dose rate independence to 10⁹ rad/sec. Further, the small size of these dosimeters (0.250" diam. x .015" or .005" thick) makes them particularly suitable for simultaneous irradiation with biological specimens in addition to dosimetric information, the biological experiments could be facilitated by a method of varying dose per pulse without the necessity of varying the source to specimen distance. Such control might be achieved by aperturing the beam close to the tube window, and this was also investigated.

Calorimetric data are presented in Figure X for the mean axial intensity of the electron beam as a function of distance and beam defining aperture. The utility of aperturing the beam is evident; and by the combination of distance and aperture selection dose control over almost three decades is conveniently obtained. Figure XI presents a set of curves with the dose measured by .015" thick CaF₂:Mn teflon dosimeters placed in a dummy calorimeter to assure identical irradiation conditions. The rad values are derived from a low dose rate (3000 rad/min) cobalt-60 calibration in polystyrene. This method was chosen since the mean energy of the Compton electrons from the medium, which are the irradiating particles for a thin dosimeter, is approximately the same as the average energy of the electrons from the field emission source after transmission through the tube window. Despite the approximate nature of the cobalt calibration technique, it is possible to divide the TLD response by the beam intensity for corresponding points on the curves and obtain information on the dose rate dependence of the system. Within a standard deviation of ± 9%, this ratio was found to be constant and therefore for a pulse width of 30 nanoseconds no dose rate dependence is evident up to 5 x 10¹² rads/sec. The accuracy of this determination was impaired by the lack of a suitable pulse monitoring system since the calorimeter and dosimeter exposures must be made separately. Repetitive measurements with the calorimeter indicated variation of machine output to be about ± 5% of the mean value per pulse. Therefore, while the measurements will be repeated utilizing a pulse monitoring system, CaF₂:Mn appears free of any strong rate dependence.

The depth dose distribution measured in a stack of .005" CaF₂:Mn dosimeters in a teflon phantom is shown in Figure XII. This distribution, while not identical to that which would be measured in water, provides approximate information on beam penetration in a low material.

While the work reported here must be considered preliminary because of the limited effort it represents, it indicates that the goals of the research program in this area can be attained.

V. INTERLABORATORY INTERCOMPARISONS

Intercomparison procedures and results have been described in previous reports. This laboratory has actively assisted the National Bureau of Standards in
organizing its high energy electron beam calibration service. This service is being established in accordance with the techniques outlined in the SCRAD protocol for high energy electron dosimetry (20).

VI. SOLID STATE DETECTOR EVALUATION

A. DC Probes

1. Initial measurements

In a previous proposal (22) it was suggested that miniature silicon pn junction diodes might be of significant usefulness in the measurement of absorbed dose in tissue equivalent material from high energy electrons. Supportive reasons advanced included the sufficiently small variation of the stopping power ratio of silicon to water between .2 and 20 MeV, and the availability of diodes with dimensions smaller than the range of a 1 MeV electron. Initial measurements in the short circuit mode with a diode of 1.5 mm dimensions lent support to the proposed application but ionization induced surface effects on the unpassivated diode surface produced unstable current levels. Improvement was obtained but it became apparent that only with a surface passivated device could the problem be effectively eliminated. It was thought that varnish passivation or potting of the diode in polystyrene would be adequate. Extensive measurements with commercially produced pn junctions are reported in a previous section of this report.

2. Construction of symmetric probe

Miniaturization of pn junction diodes used in radiation measurements emphasizes the effect of dimensional variation on the diode's response with orientation in the radiation field. This will be important depending upon the nature and energy of the radiation. A further difficulty connected with the use of miniature diodes comes from the increased importance of scattering from the electrical lead wires of the diode. This too is independent upon the character of the radiation being measured. In an attempt to minimize the effect of these factors, particularly with respect to measurements of cobalt-60 radiation, a pn junction with approximately azimuthal symmetry was fabricated. Evaluation of this device was interrupted by the appearance of a discontinuity in the lead wires potted into the polystyrene probe stem and is still not complete. However, since the probe structure is believed to be novel, a brief description is given.

The overall geometry of the device is similar to that of the cylindrical ionization chamber with its central collecting electrode. The diode, after fabrication, was mounted on a polystyrene rod and encapsulated entirely in polystyrene after lead wires were epoxied to the outer and central nickel electrodes. A schematic of the diode structure and photograph of the probe assembly appears in Figure XIII and XIV. The "wrap-around" configuration of the diode junction gives a total junction volume about four times as large as is found in the usual geometry of the same dimensions and can thus be expected to be proportionately more sensitive.

Actual fabrication of the diode was facilitated by use of a technique which permitted evaporation of lithium on all sides of the p type silicon in one step. This consisted of mounting the filament of silicon concentric with the shaft of a small greaseless motor which was mounted in the vacuum evaporator. The motor shaft was set at a 45° angle with the vertical above the lithium boat. Running the motor during the evaporation uniformly exposed all sides of the 20 mm long
filament to the evaporating lithium. The diode at the end of the polystyrene stem in the photograph (Fig. XIV) has 2 mm dimensions. This was a matter of convenience. Smaller dimensions can be made where called for. Silicon filaments have been ground and drilled here into 5 mm long shells with outside diameters of 1.25 mm and wall thicknesses of less than .010". Such a geometry will prove useful in situations where a minimum amount of silicon is allowable in the detector, say for cobalt-60 gamma-ray measurements.

B. Two Dimensional Diode Arrays

Arrays of lithium drifted diodes are pertinent to the construction of particle analysis and counting systems which require position indication. Work at Sloan-Kettering Institute aimed toward the fabrication of a matrix of diodes suitable for a two dimensional counting system has progressed beyond the goals established in last year's proposal. The three devices produced so far are discussed.

1. First matrix configuration (p side checkerboard)

In the first attempt at production of a matrix of diodes, the technique of partitioning the p side of a lithium drifted diode was employed. Although it was recognized that this geometry was not amenable to extension to large scale arrays, it was considered a reasonable initiation to the problems of "ganging" diodes on one substrate, a step required to avoid enormous packaging problems. Nine square, individual, 5 mm., sections of p material were defined on the integral p side of a cylindrical 2 cm. diameter lithium drifted diode by cutting into the intrinsic region. A 6 inch diameter, .020" thick diamond wheel, mounted on a grinding machine, was used to obtain an accurate geometry.

a) Diode characteristics

The diode used to form the matrix had a lithium drifted depth of 1.5 mm (as measured by copper staining) with a total wafer thickness of 4.6 mm. The starting material was 200 - 300 ohm-cm. float zone, p type silicon with lifetime greater than 500 microseconds. The leakage current versus bias characteristic was taken before partitioning of the p side and was found to be acceptable but unexceptional.

b) Matrix construction

Mounting wax was used to hold the diode on a carbon block prior to cutting. The carbon block was trimmed after mounting the diode so that the diode surface was levelled to within .003" with respect to the grinding machine carriage. The grooves in the p side were cut .128" deep. This carried the grooves .010" into the intrinsic region. Following this, the wafer was removed from the carbon block and the gold electrodes, which had been applied previously by electroless plating, were masked on both sides with thermosetting tape prior to etch polishing. The tape was cut at the grooves on the p side to give the etch solution access to the grooves. Total etch time was around 2½ minutes using 30 second intervals, with intervening de-ionized water rinses employed to prevent excessive temperature elevation. Following removal of the tape with electronic grade trichlorethylene, the matrix was ready for testing.
detected by the matric elements deviated widely from the prediction of rms voltage measurements by as much as a factor of two. For example, where the measured spread in the 976 KeV line was 57 KeV, 30 KeV was predicted by rms measurements. It appears that the disparity can be explained in terms of the scattering of the beta particles by the relatively thick (300 microns) entry window of the matrix elements. A surface barrier electrode should eliminate the bulk of this effect.

g) Electrical resistance between diode elements of matrix

The electrical resistance between diodes of the matrix structure is a measure of the degree of electrical separation achieved on the common intrinsic silicon substrate. (The capacitance between elements on the units being considered can be neglected). The resistance will determine how efficiently charges liberated in the individual diodes will be collected at the electrodes of the individual diodes and consequently what fraction of each charge pulse produced by an incident particle will flow out of the boundary of the diode of origin to its neighbors. In addition, the interdiode resistance determines the effective boundary region of the diode. If the interdiode groove resistance is high enough the actual collection regions tend to "pinch off" part of the groove width separating each diode. This has been observed by others (24, 25) who have used a pair of concentric grooves on the n side of a lithium drifted diode to include a guard ring and anticoincidence structure in a diode telescope assembly.

The interelement resistance of this first matrix configuration was measured with no bias on the matrix and found to be on the order of 20 Meg ohms initially at 23 volts (Simpson meter). This figure declined in a period of months to 1.5 Meg ohms as expected since the matrix holder was not hermetically sealed. Appropriate surface treatment was found to restore the original resistance level. In the interest of obtaining the subsequent matrix configuration, no further tests were made on this unit. It was placed under 200 volts bias and stored.

2. Second matrix configuration (orthogonal p and n electrode strips)

The data and experience obtained in the construction of the first matrix were a basis for embarking on the fabrication of a second more demanding configuration but one which lends itself in a more practical way to use in aggregate to cover larger areas. For example, based on the first configuration, a \((10 \times 10) \text{ cm}^2\) array of diodes would require 2500 elements to resolve an area \((2 \times 2) \text{ mm}^2\). Furthermore, these elements would require individual monitoring which is economically unfeasible. A row and column method of address, on the other hand, allows, in theory, the same spatial resolution to be achieved with \(2N\) fewer amplifiers where \(N\) equals the number of rows (or columns) in a square array. Such a configuration can be achieved in a diode matrix. This required partitioning of both the p and n regions of a lithium drifted diode into electrically isolated strips by cutting parallel, linear, grooves that penetrate to the intrinsic region. The electrode strips of each side are parallel. Those on the n side, however, lay at right angles to those on the p side so that when a difference in potential is applied between the n and p side strips, the \((N \times N)\) regions of overlap constitute diode regions (Figure XX). Again, the interstrip resistance and depletion depth are important factors in determining the operational isolation and effective boundaries of the diode.
regions. A successful application of this geometry has been made (ref. 26) in
the production of a .2 mm thick silicon dE/dx counter. A disc of high resistivity
n type silicon was used in the formation of the latter matrix so that the
electric field in the overlapping electrode regions was extended to the n side
contact when the bias was high enough.

The formation of a lithium drifted diode into this type of matrix has apparently
not yet been attempted elsewhere. The data obtained from the two units fabricated
at S.K.I., while still incomplete, are adequate, it is felt, to indicate essential
success of the effort since the principal difficulty of obtaining sufficient
electrical resistance between electrode strips on both sides appears to have
been surmounted. This conclusion is, at the moment, chiefly founded on approxi­
mate figures of acceptability for groove resistance values for 2 mm depletion
layers (ref. 25).

a) First unit

1. diode characteristics

The diode used to form the first orthogonal strip matrix
was a circular wafer 17 mm in diameter. The lithium drift depth was 3.5 mm.
The starting silicon had the same properties as above. The diode junction
depth before drift was about 300 microns below the surface of the n side as
above.

2. matrix construction

The procedure devised for cutting grooves in the p and n
sides of the square diode allowed for the necessity of etch polishing the
damaged areas without injury to the strips of electrodes on both sides. Since
it would be unfeasible to mask the electrode strips individually after cutting
the grooves, thermosetting masking tape was applied to both electrodes before
cutting the grooves. The risk in this approach was that the tape could lift
off from one or more strips from the temperature elevation during etching. The
resulting damage, if serious enough, would require the application of new
electrodes. This would return the situation to the problem of individually
masking the strips. However, the procedure adopted worked well enough despite
some minor electrode damage in its two instances of use. The grooves, cut on a
grinding machine as before, yielded four electrode strips on each side with 16
potential diode regions. The grooves on the p side were cut to a depth of 1 mm,
on the n side to a depth of .5 mm. Following a total of about five minutes of
etch polishing, the tape was removed and testing of the matrix was begun.

3. matrix holder

In order to test a diode element of an orthogonal strip
matrix, contact must be made to the row and column whose overlap comprises the
diode electrodes (see Figure XX). A special mounting was constructed to permit
quick electrical access to all of the diode elements while the sensitive surface
area suffers a minimum exposure to ambient contaminants until some form of
surface passivation is used. Figures XXI and XXII are photographs of the matrix
test mount. The second larger matrix is shown in position in Figure XXI. The
metal strips between connector pins at the left side are used to put the upper
electrode strips in parallel. The upper and lower rows of contact "fingers" can
be lifted clear during insertion of the matrix into its seat. This can be seen in Figure XXII. By means of individual adjusting screws overhead, each finger can be raised or lowered to obtain good contact after the entire row has been pivoted down on the matrix surface. A fitting emplaced in the cover of the test box is used to flow dry nitrogen into the test box when desirable.

4. RMS noise (FWHM) and leakage current measurements

Noise and leakage current measurements were made regularly for several days following the formation of this first matrix. When stable and acceptable values of (FWHM) and leakage current values versus reverse bias were assured, it was decided to fix the surface conditions of the matrix.

5. varnish encapsulation

Commercially available polyurathane varnish was slightly diluted with trichlorethylene and used to encapsulate the first orthogonal strip matrix. The entire matrix was dip coated. After a short period of drying, the unit was laid flat on a clean disc of teflon and allowed to dry for several days in a dust free environment. Repetition of noise and leakage current measurements indicated that the varnishing procedure had been effective since these values had not deteriorated.

6. groove resistance

The resistance between the electrode strips was measured for the n and p side of the varnished matrix after "flattening" the lithium distribution for several days at room temperature under 450 volts bias. The typical n side groove resistance was found not to exceed 300 K-ohms even with 500 volts reverse bias applied to the matrix with all elements in parallel. At zero bias, the n side groove resistance dropped to about 150 K-ohms. These values were measured with 50 volts across the grooves. For the p side, the groove resistance was typically 250 Meg-ohms with 500 volts bias on the matrix. The former figure is of the order required to obtain adequate isolation between elements. No increase in the resistance of the n side grooves of this matrix could be effected by further flattening under 500 volts bias. The explanation for so low a resistance apparently lies in too shallow a groove depth since a deeper groove on the subsequent unit yielded higher values. This explanation raises the question of why a groove depth of .5 mm did not reach well into the intrinsic region since the latter begins at less than .3 mm from the n side surface according to measurements employing copper staining. This depth is consistent with the estimate of .3 mm for the junction depth before drifting. The anomaly has been observed elsewhere (ref. 25).

b) Second unit

1. diode characteristics

This unit had a lithium drifted depth of 3 mm. The starting material came from the same crystal as did that of the p side checkerboard matrix. After the lithium drift, a square diode 16 mm on a side was cut out of the circular diode. Noise and leakage current data for this diode were taken as usual before grooving both faces and found to be extremely good.
2. matrix construction

Using the same procedure as for the first unit, five grooves .5 mm wide were cut into each side of the square diode. The p side grooves were made 1.5 mm deep, those on the n side 1 mm deep. This resulted in thirty-six square diode regions (2 x 2) mm² (after etch polishing) on the single substrate. The 1 mm grooves on the n side were twice as deep as on the previous unit and eliminated doubt that the intrinsic layer had been reached. The finished matrix appears in Figure XXI, and XXII.

3. RMS noise and leakage current measurements

Noise and leakage current measurements made on this unit in air, argon and nitrogen were found to compare well with the values obtained for the original diode. Encapsulation in varnish was deferred to the end of further tests.

4. groove resistance

Before application of a flattening voltage to the matrix, the groove resistance on the n and p sides was measured for zero bias on the unit with a Simpson meter (23 volts). For the p side 20 meg-ohms was obtained as before for the two previous units. The n side groove resistances, however, for the same conditions were only 50 K-ohms. After a day of flattening under 500 volts bias, this figure rose to about 200 K-ohms. As expected, a substantial increase in both n and p side groove resistance was observed with the matrix elements under bias during the measurement. With 500 volts bias on the matrix, values of 500 meg-ohms and 250 meg-ohms groove resistance were found for the n and p sides respectively with 50 volts across the particular groove. A plot of resistance for one n side groove versus reverse bias on the matrix elements is shown in Figure XXIII for 50 volts across the groove. These data were obtained after extension of the flattening period under 500 volts bias. It can be seen that the groove resistance exceeds 1000 meg-ohms at 500 volts reverse bias.

Operational testing of the individual diodes of this matrix remains to be done.

C. Approximation of the Efficiency of the Photoelectric Effect in Silicon and Germanium Diode

To obtain a notion of the gamma ray energies and depletion layer thickness which would pertain to the use of arrays of diodes in gamma counting applications, a first order calculation was made of the efficiency of the photoelectric effect for silicon and germanium diode structures with assumed window thickness of 150 microns. It is assumed that the diode dimensions are small enough so that each Compton scatter results in the loss of a photon out of the diode structure. Compton scattered photons can enter the diode structure from neighboring diodes and engage in possible photoelectric interactions. These will "smear" position indication in the counts registered by an array of diodes. The calculated efficiencies deal only with photoelectric interactions in the diode which are primary and therefore require eventual adjustment. In practice, a partial suppression of such pulses would result from a narrow electronic window width. It is recognized that such figures must eventually be obtained in terms of the characteristics of a specific situation, and that these, in part, would include gamma ray energy, diode geometry and depletion layer depth, electronic window width, etc. On the basis of these stipulations,
the curves of Figures XXIV, XXV, XXVI, and XXVII were constructed. These are essentially an evaluation of the following expression:

\[ \eta_{\text{photoelectric}} = \frac{\mu_{\text{pe}}}{\mu_t} \cdot e^{-\mu_t w} \left( 1 - e^{-\mu_t d} \right) \]

where:

\( \eta \) = Photoelectric efficiency (fraction of incident photons involved in a primary photoelectric interaction)

\( \mu_{\text{pe}} \) = photoelectric absorption coefficient (cm\(^{-1}\))

\( \mu_t = \mu_{\text{pe}} + \mu_c \)

\( \mu_c \) = Compton absorption coefficient (cm\(^{-1}\))

\( w \) = window thickness of diode (cm)

\( d \) = depletion layer thickness of diode (cm)

The Compton and photoelectric absorption coefficients for silicon and germanium were obtained from NBS circular 583. Those for germanium were calculated from the values for copper following Dearnaley and Northrop (27).

D. Evaluation of Thin Window Commercial Diode

A replacement for a Simtec Lmted. lithium drifted diode returned as defective was received and tested at SKI. It too was found to be substantially out of noise specifications (almost a factor of three). Test data returned with the unit were confirmed by the manufacturer. A third unit was received at the writing of this report. The diodes offered by the vendor have rugged boron p side windows of thicknesses less than .2 microns. Applications planned for this unit included measurements in a tissue equivalent medium under high energy electron irradiation specifically measurements of the secondary electron spectrum near the end of the primary range.
REFERENCES


Table 1  20 Mev Electron Summary: Calorimeter Extrapolation Chamber

<table>
<thead>
<tr>
<th>Carbon Depth $\text{gm/cm}^2$</th>
<th>Calorimeter</th>
<th>Extrapolation Chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rads carbon/Vm</td>
<td>% Dose</td>
</tr>
<tr>
<td>1.76</td>
<td>$56.38 \pm 0.85%$</td>
<td>100</td>
</tr>
<tr>
<td>3.35</td>
<td>$57.27 \pm 0.72%$</td>
<td>101.6</td>
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<tr>
<td>4.93</td>
<td>$53.70 \pm 0.78%$</td>
<td>96.2</td>
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<tr>
<td>5.89</td>
<td>$50.30 \pm 0.78%$</td>
<td>89.2</td>
</tr>
<tr>
<td>6.52</td>
<td>$47.77 \pm 0.72%$</td>
<td>84.7</td>
</tr>
<tr>
<td>7.48</td>
<td>$40.81 \pm 1.0%$</td>
<td>72.4</td>
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<tr>
<td>8.11</td>
<td>$36.67 \pm 0.92%$</td>
<td>65.0</td>
</tr>
<tr>
<td>8.59</td>
<td>$32.28 \pm 1.2%$</td>
<td>57.3</td>
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<tr>
<td>9.07</td>
<td>$25.20 \pm 2.1%$</td>
<td>44.7</td>
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<tr>
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<td>$19.21 \pm 1.5%$</td>
<td>34.1</td>
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<td>11.29</td>
<td>$4.49 \pm 2.4%$</td>
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<tr>
<td>12.88</td>
<td>$2.69 \pm 1.3%$</td>
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</table>

Errors indicated are root sum squares of experimental deviations, calibration deviations, estimated fixed errors, and the uncertainty in $W$ (1) where applicable.

(1) $33.73 \pm 0.44\%$  NBS Handbook 85, 1964.
MEAN STOPPING POWER RATIO VS DEPTH IN CARBON FOR 20 MEV ELECTRONS

- Solid circles (●) = Experimental
- Open squares (□) = Calculated by Kessaris
- Open triangles (△) = Calculated from Harder formula: $E_m = E_0 (1 - d/R_p)$

Fig. I
RELATIVE RESPONSE/RAD (carbon)

- LiF type 700: (Powder)
- LiF type 700: (Teflon Matrix)

Fig. II
RELATIVE RESPONSE/RAD (carbon)

CaF$_2$: Mn Teflon Dosimeters

Fig. III
CENTRAL AXIS DEPTH DOSE 6 MEV
ELECTRONS 9x9 cm FIELD

- ○ TI-53 silicon diode
- ● Silicon micro diode
- △ Cavity ion chamber

Fig. V
CENTRAL AXIS DEPTH DOSE 20 MEV ELECTRONS
9x9 cm FIELD

○ TI-53 silicon diode
△ Cavity ion chamber

Fig. VI
RELATIVE RESPONSE/RAD (carbon)

Micro-Semiconductor
MC - 150A Diode

Mean Electron Energy MEV

Fig. VII
$G(\text{Fe}^{+++})$ VS DEPTH IN CARBON FOR 20 MEV ELECTRONS

Fig. VIII
HeLa CELL SURVIVAL - 20 MEV ELECTRONS

Fig. IX
CALORIMETER MEASUREMENT OF BEAM ENERGY DENSITY PER PULSE

Tube number A004

Fig. X
DEPTH DOSE DISTRIBUTION

600 KEV Field Emission Electron Source

% dose

100
90
80
70
60
50
40
30
20
10
0

G/cm²

0
.04
.08
.12
.16
.20
.24

Fig. XII
"WRAP-AROUND" JUNCTION GEOMETRY

USUAL JUNCTION GEOMETRY

Fig. XIII
Fig. XVI
FWHM AND LEAKAGE CURRENT VS REVERSE BIAS FOR A SINGLE ELEMENT OF MATRIX #1

Leakage current vs bias

FWHM vs bias

Reverse bias (volts)

Leakage current (μA)

FWHM (keV)

0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300

0 1 2 3 4 5 6

0 12 15 18 21

Fig. XVII
FWHM AND LEAKAGE CURRENT VS REVERSE BIAS FOR MATRIX #1 WITH ELEMENTS IN PARALLEL-TWO MONTHS AFTER FABRICATION

Fig. XVIII
FWHM AND LEAKAGE CURRENT VS REVERSE BIAS FOR MATRIX #1 WITH ELEMENTS IN PARALLEL-FOUR MONTHS AFTER FABRICATION

Fig. XIX
Fig. XX
ORTHOGONAL ELECTRODE STRIP MATRIX
EFFICIENCY OF PHOTOELECTRIC EFFECT VS GAMMA RAY ENERGY FOR Si DIODE
Assumed Window Thickness = 150 μ

Depletion depth (in cm)

- Zero window, d=∞
- d = .15

Gam %a ray energy (kev)

Fig. XXIV
EFFICIENCY OF PHOTOELECTRIC EFFECT VS GAMMA RAY FOR Ge DIODE

Assumed Window Thickness = 150μ

Depletion depth (in cm)

- Zero window, d = ∞
- 0.8
- 0.7
- 0.6
- 0.5
- 0.4
- 0.3
- 0.2
- d = 0.15

Fig. XXV
EFFICIENCY OF PHOTOELECTRIC EFFECT VS DEPLETION LAYER THICKNESS FOR Si DIODE:

Assumed Window Thickness = 150μ

Fig. XXVI
EFFICIENCY OF PHOTOELECTRIC EFFECT VS DEPLETION LAYER DEPTH
FOR Ge DIODE

Assumed Window Thickness = 150μ

Fig. XXVII