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TEMPERATURE RESPONSE OF SILICON SURFACE BARRIER SEMICONDUCTOR DETECTORS OPERATED IN THE DC—SHORT CIRCUIT CONFIGURATION

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Semiconductor detectors are finding increasing application in medicine as nuclear detectors, spectrometers and dosemeters. Their small size, with high sensitivity and ease of handling, render them specially well suited for clinical dosimetry in body cavities. An example of such an application is the measurement of bladder and rectal doses during intracavitary irradiation of gynaecologic carcinoma.

Several favourable reports have been published on the clinical experience gained in the use of these devices (JONES 1963, PARKER & JOHNSON 1969, PARKER 1970). However, problems are encountered with the temperature sensitivity of the p-n junction semiconductor detectors when used in the clinical environment in which a detector is subjected to a sudden ambient temperature change, i.e. from room to body temperature.

Temperature effects in semiconductor detectors used in spectroscopy have been intensively investigated and the technique is accepted of operation in stabilized ambient temperature.

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Little information is available, however, on this subject in semiconductor devices used as dosimeters in the dc mode of operation. Moreover the observations of various workers on temperature effect are not in agreement.

With detectors run in the short-circuit configuration, sensitivity to temperature was reported to be either completely zero (GULBRANDSEN & MADSEN 1962, SCHARF 1960) or of negligible magnitude (PARKER & JOHNSON 1969), whilst changes in the output current were observed in SCHARF's later work (1966) and on a large number of surface barrier coaxial probes by ALLSWORTH (personal communication).

In the work being reported here the response of the semiconductor detectors was investigated in the temperature range of 10° — 40 °C, being of interest in clinical dosimetry. Higher temperatures were not used to avoid damage to the devices which may occur due to thermal expansion of internal electrode connections and to avoid possible permanent deterioration of the detector performance. Measurements were made on silicon p-n junction surface barrier detectors of cylindrical geometry 6mm and 3mm in diameter, developed at AERE, Harwell (ABSON et coll. 1968) for clinical use and on planar devices of general application. Water bath of controlled temperature was utilized to vary the ambient temperature throughout these investigations. The output current was measured by means of a specially developed picoampere level amplifier of low input impedance providing also the facility of variable load resistance for the detectors investigated. In experiments involving radiation Cs-137 sources were used and care was taken to avoid any changes in scattering conditions.

Output signal of the semiconductor detector

The theory of operation of p-n junction detectors and the mechanism of radiation detection has been discussed by many workers (JONES 1963, SCHARF 1960, DEARNALEY & NORTHROP 1966, BERTOLINI & COCHE 1968) and will therefore be omitted. However, some points helpful in the consideration of the measurement of the output signal and of the temperature effect will be reviewed in much simplified form.

In the process of formation of a p-n junction a strong electric field is established in a narrow transition zone between the p-type and n-type layer, also called the depletion region, or space charge region. The depletion region is present even when no external bias is applied across the junction. The electric field is directed from the n-type to p-type layer, so that electrons and holes produced by radiation in the depletion region (or outside it, but diffused into it) are driven to the n-type or p-type material respectively. Thus when the

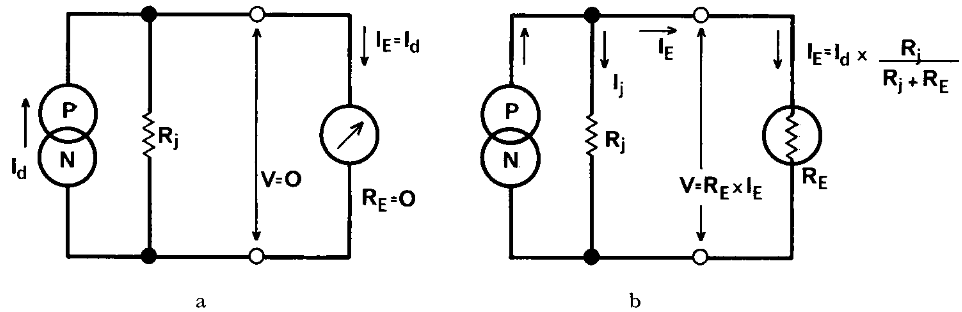

Fig. 1. Semiconductor detector connected in the short circuit, dc mode of operation; a) Pan ideal circuit. b) Practical circuit.

junction is irradiated with ionizing radiation a current is generated, flowing in the reverse direction in the detector.

According to Scharf (1966) the radiation induced current in a detector of p-type base can be obtained by the simplified relation:

$$I_R = eAg(w + L_n) \;/\; (\mu L_n + 1) \qquad (1)$$

where e = electronic charge; A = irradiated silicon surface area; g = electron-hole pair generation rate; w = width of the depletion region; μ = linear attenuation coefficient in silicon; L_n = diffusion length of electrons.

It is seen from eq. (1) that I_R is, for a given radiation, independent of crystal dimensions and mainly determined by the charge collection volume. I_R is proportional to the exposure rate, because of the dependence of the generation rate g on the exposure rate which is given by the relation:

$$g = \frac{86.9\ \mu_{en}}{\xi\ (\mu_{en}/\varrho)\ \text{air}} \triangle X/\triangle t$$

where μ_{en} = linear energy absorption coefficient of silicon; (μ_{en}/ϱ) air = mass energy absorption coefficient in air; ξ = energy required for the production of electron-hole pair in silicon; $\triangle X/\triangle t$ = exposure rate.

From the point of view of the output signal measurement there are two distinct modes in which the semiconductor detector can be run; with an external reverse bias voltage and without an external bias.

With the external bias applied, charge pulses are collected at the detector terminals, amplified and registered by means of a scaling counter or count-rate meter. A discriminating device is used to eliminate noise and spurious signals. This technique has limitations in the level of the dose rate to be measured due to a considerable leakage current of the order of microampere (thermally generated carriers, edge and surface leakage effect) resulting from the biassing voltage.

By operating the diode with no bias voltage, the leakage currents are reduced to picoampere level and lower radiation intensities can be detected. In these conditions there is a close similarity in the behaviour of the p-n junction detector to that of a photovoltaic light cell. As with the latter, the radiation-induced signal of the detector can be measured either in the open circuit configuration in terms of voltage signal, or in a short circuit configuration as the current induced in the outer circuit of the p-n junction. In both cases a relatively simple instrumentation is required for signal amplification.

It can be shown that the short circuit mode offers linear dose rate-detector current relation and is therefore more attractive than the voltaic configuration in which these quantities follow a more complex function.

Short circuit mode of operation. The electrical behaviour of a p-n junction radiation detector operated in the short-circuit mode can be deduced by considering the circuits in Fig. 1, in which the detector is represented by a current generator (I_d) and its parallel-connected internal resistance (R_j). I_d is the current generated in the detector flowing internally from n-type layer to p-type layer. In Fig. 1 a the terminals of the device are short circuited (the resistance of the external circuit $R_E = 0$). The whole of the detector current flows through the external circuit, in which it can be measured. As $R_E = 0$, there is no voltage potential across the terminals ($V = 0$) and the short circuit conditions are fulfilled.

It will be noted that the detector current I_d consists of two components, I_R = the radiation generated current and I_0 = the current which flows through the p-n junction even when no radiation is acting upon the detector and no external bias is applied (cf. p. 132). The latter will be further referred to as detector thermal current in order to distinguish it from the leakage or reverse current which is of similar origin but of much larger magnitude and flows under a completely different circuit arrangement.

In order to measure the detector current, an instrument must be connected into the external circuit, having a finite internal resistance, R_E. The circuit therefore takes the form shown in Fig. 1 b. The consequence of the presence of R_E is that the detector current now divides between R_j and R_E and therefore the current measured in the external circuit is smaller always by the fraction which flows into the internal resistance branch of the circuit.

$$\text{Hence } I_E = I_d - I_j \text{ and } I_E = I_d \times \frac{R_j}{R_j + R_E} \qquad (2)$$

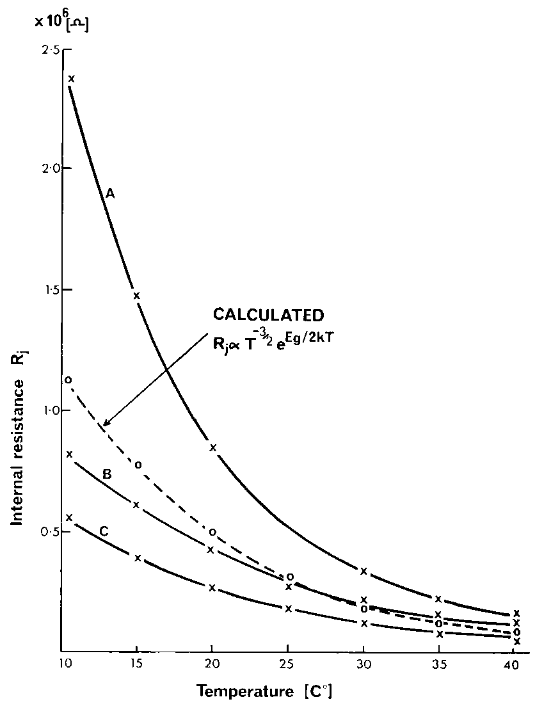

Fig. 2. Variation of the p-n junction internal resistance with temperature as found for several detectors. The dotted line illustrates the variation of the silicon resistivity according to relation $\varrho \propto T^{-3/2} \exp(Eg/2kT)$.

It is seen from eq. (2) that the magnitude of the external circuit current I_E follows the variation of $R_j/R_j + R_E$ with all other parameters fixed. As R_E is taken smaller to approach zero value, I_E approaches I_d and the circuit goes into the ideal short circuit configuration. Although in practice R_E is never zero, I_d can be determined by extrapolation of R_E towards its zero value.

A close approximation to the ideal situation is obtained in practical circuit by making R_E small compared with R_j. For example, if $R_j/R_E = 1\,000$, the current in the external circuit differs from the true detector current by 0.1 per cent, a discrepancy negligible for most practical purposes. However, the internal resistance of semiconductor detectors does not remain constant with variable ambient temperature.

Variation of the p-n junction resistance R_j with temperature

The investigation of the behaviour of the internal resistance of the p-n junction was carried out with the detector immersed in a water bath of controlled and adjustable temperature and with the detector connected in a

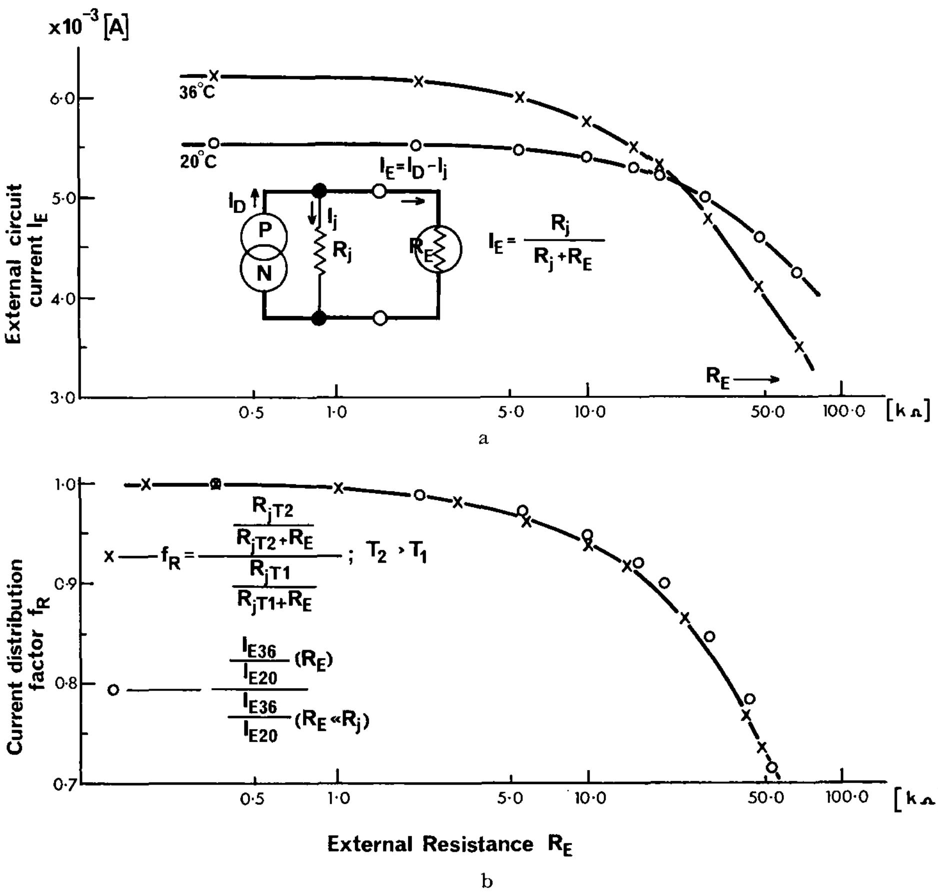

Fig. 3. a) Current in the external circuit at room and body temperature as a function of the external resistance. b) Comparison of the variation of the current distribution factor f_R with the measured variation of the external circuit current ratios at room and body temperature.

circuit used for measuring the current-voltage characteristic of semiconductor diodes. The external bias applied was very small, of the order of a millivolt, to secure operation on the straight portion of the characteristic. Indeed, for such low bias voltages, the characteristic is completely linear in both positive and negative bias directions. The current flowing through the device in this condition was measured with a low-input impedance picoammeter to avoid errors due to variable R_j/R_E ratio.

A strong dependence of R_j upon temperature was found (Fig. 2) in all the detectors investigated, R_j decreasing with rising temperature (silicon has negative temperature coefficient). Graphical analysis of the $R_{j(T)}$ curves revealed that the resistance change in the temperature range 10 — 25° C follows an exponential relation with the slope varying for individual detectors, being between 80 kΩ and 9 kΩ per degree centigrade. At higher temperatures, the $R_{j(T)}$ relation seems to obey a power law with an exponent of approximately $-3/2$. The transition from an exponential to a power relation is gradual and takes place between 25 and 30° C.

The theory of the semiconductor p-n junction diode suggests a purely exponential junction resistance-temperature relation. However, a semiconductor detector operated in a dc mode with a zero bias has the electrical characteristics of a temperature-sensitive resistor and it seems that the expression describing the temperature effect in a doped semi-conductor material may be more appropriate here. In this case the expression for the variation of resistivity with temperature comprises two terms of the type

$$\mathrm{R}_j \sim T^{-3/2} \exp\,(Eg/2kT) \qquad (3)$$

where Eg is the energy gap and k the Boltzmann constant.

Detailed comparison of measured values with R_j variations calculated by expression (3) gives good agreement, especially for higher temperatures for which the slope of the experimental curves and the calculated one are in accord.

The large separation between R_j values at low temperatures can be attributed to differences in the resistivity of the silicon used for the fabrication of these devices. Surface currents can also be expected to have some influence, but their contribution could not be determined.

In general, higher junction resistance values were found with the planar than with the cylindrical detectors.

It appears that R_j changes arise mainly from the effect of temperature on the bulk of silicon.

R_E—R_j interplay in the temperature effect. Fig. 3 shows the current measured in the external circuit of the detector, exposed to a dose rate of approximately 60 R/h, as a function of the resistance in the external circuit, R_E, and the ambient temperature. It is of interest to consider the behaviour of the detector in more detail.

It is seen that at a given temperature, the current in the external circuit increases with decreasing R_E because the ratio R_E/R_j becomes smaller so that a greater proportion of the detector current flows into the external circuit (cf. p. 127). At arbitrarily small values of R_E, approximation to ideal short circuit conditions is obtained and $I_E = I_D$.

The current curves taken at both room temperature and average body temperature show generally identical features. However, it will be noted that at high values of R_E, smaller current was measured in the external circuit at 36° C than at room temperature. This is due to the fact that the internal p-n junction resistance is smaller at the higher temperature. The ratio of resistances $R_j/(R_j + R_E)$ is therefore smaller at 36° C than at 20° C for the same value of R_E, resulting in the flow of the detector current I_D more into the R_j branch of the circuit. With arbitrarily small R_E, the variations of the p-n junction resistance have no effect on the distribution of current $R_j/(R_j + R_E) \approx 1$ in this condition) and the observed higher value of the external circuit current at body temperature is entirely due to the thermal changes in the detector current.

It follows that the result of the change of detector temperature, as observed in the external circuit, depends on the interrelation between the change in the detector current, the p-n junction resistance as well as the magnitude of R_E.

The expected change of the current in the external circuit after the thermal quiescent state is reached can be estimated by means of a factor formed by the ratio

$$f_R = \frac{R_{jT_2}}{R_{jT_2} + R_E} \Big/ \frac{R_{jT_1}}{R_{jT_1} + R_E}$$

where R_{jT_1} and R_{jT_2} are the values of the internal resistance of the p-n junction at considered temperatures, T_2 being the higher.

This factor, further referred to as the current distribution factor, is useful in the analysis of the temperature effect. Its variation was numerically estimated for the detector of Fig. 3 and compared with the experimentally determined ratios of the external circuit (I_{E36}/I_{E20}) at room and body temperatures. These were normalized to the short circuit value and are shown in Fig. 3 b. A good agreement is seen between the predicted and the measured current variations, thus confirming the considered $R_E - R_j$ interrelation.

The two current curves seen in Fig. 3 cross over at a certain value of R_E. At the point of intersection a situation is reached at which the increase in the detector current $\triangle I_d$ is equal to the change of current distribution into R_j due to decrease in the latter. In these circumstances the detector appears to be insensitive to the variation in ambient temperature. The value of the resistance at which this happens will be called a cross over point resistance R_c.

The effect of interplay between the variation of the p-n junction resistance and the external circuit resistance, in the devices exhibiting an increase of short circuit current, can be used to advantage in order to stabilise the detector

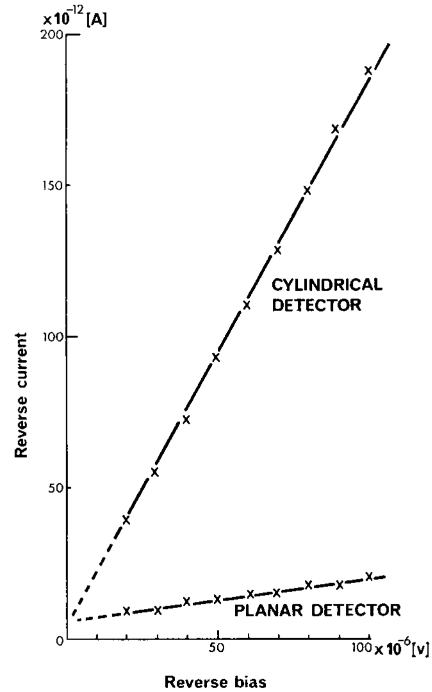

Fig. 4. Surface barrier p-n junction reverse current at ultra low bias voltages.

response to temperature. To accomplish this, the external resistance R_E should be made equal to the value indicated by the cross over point ($R_E = R_c$).

Detector thermal current I_O

All junction devices show currents even when not exposed to radiation.

These currents arise from several sources: diffusion, space charge generation and surface. The first contribution is due to the diffusion of the minority carriers from the field-free region into the depletion region. It is a function of specific resistivity of the material, life time of minority carriers, diffusion length, mobility of minority carriers and carrier density.

The second current is due to recombination centres in the space charge region. Here the centres generate electrons and holes at a rate depending on the cross-section, density of such centres and their location in the forbidden energy gap. It varies with the mobility, life time, the resistivity, and the width of the depleted region.

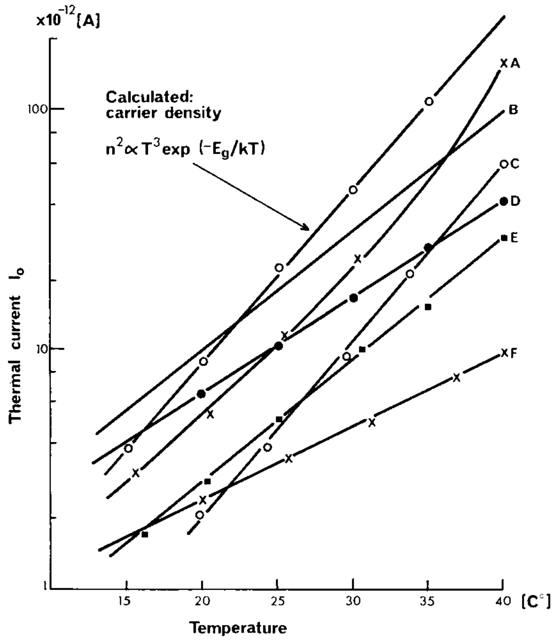

Fig. 5. Dependence of the detector thermal current I_0 on the ambient temperature. The dotted line illustrates the variation of the carrier density with temperature according to $n_i^2 \propto T^3$ exp $(-Eg/kT)$.

In general, the detector current is greater than the sum of the two components mentioned above, due to the surface current. This current is the least predictable in the junction device, being subject to change as the surface chemistry at the edge of the junction varies with time, bias and temperature.

Changes of temperature will introduce variations in the factors which influence the magnitude of these individual currents. By far the most important of these changes is the increase in diffusion and space charge generation currents. In each of these the carrier density n_i varies as exp $(-Eg/2kT)$, (Dearnaley & Northrop 1966, Bertolini & Coche 1968). Carrier life time changes exponentially, also, through changes in n_i. The dependence of the non-radiation current on the exponent Eg/kT explains why semiconductors with narrow energy gap will never be satisfactory at room temperature.

The physical origin and contribution of the various currents to the total reverse current have been investigated widely and a theory developed allowing prediction of their magnitude. However the reverse current measured is often found one or two orders of magnitude higher than the one calculated (Langmann & Meyer 1966). In a biassed device the reverse current is of the order of 10^{-7} to $^{-6}$A, with the space charge generation current being the major contributor. It decreases when the voltage bias is decreased approaching nanoampere at millivolt level. At bias voltages below a millivolt, the current-voltage function takes a linear relation of the type $I_0 = V_{bias}/R_j$, thus the slope is determined by the internal resistance of the detector at the given temperature.

Fig. 4 illustrates the behaviour of the reverse current at ultralow bias voltages as found for a planar and cylindrical device at room temperature in a circuit with $R_E \ll R_j$. With microvolts only applied to the p-n junction the current amounts to approximately 10^{-10}A and shows considerable noise.

The noise arises due to the dynamic nature of the charge balance across the p-n junction and statistical fluctuations in the number of carriers leading to changes in conductivity (shot noise). Thermal noise is generated as well, due to fluctuations in the spatial distribution of carriers arising from thermal diffusion. Noise increases with temperature and its contribution becomes more significant with decreasing bias voltage (MASUDA & TAKEDA 1967). It manifests in the form of current fluctuations in amplitude and direction and because of its presence the determination of the current value below 20μV of bias voltage becomes uncertain.

Without an external bias applied, thermal generation of carriers is responsible for the detector current. Its magnitude is small, of the order of 10^{-11}A, with considerable noise superimposed ($\pm$ 5pA). Similar values of the thermal current I_0 were observed in all of the devices investigated.

It is, however, not the magnitude of the I_0 current that matters but its variation with the ambient temperature. This correlation was investigated using a technique as follows.

With the detector subjected to an arbitrarly weak exposure the ambient temperature was changed from 20° to 40° C. After the time needed for the detector to reach thermal equilibrium the exposure was removed. The value to which the detector current dropped in these circumstances was then determined with the device still at 40° C. Possible drift of the measuring system was checked, and corrected, if necessary, by cooling the detector down and noting the process of returning to zero. The experiments were recorded on a chart recorder and repeated for the temperatures of interest. From the knowledge of the detector sensitivity and the exposure the mean value of this residual thermal current I_0 was estimated. Fig. 5 illustrates the results. It is seen that the thermal current increases considerably with the temperature, and seems to follow the changes in the carrier density n_i^2. An increase of peak-to-peak noise was also observed but its quantitative evaluation was not made.

At this stage of the work being reported it was not possible to determine, nor to make distinction, in the contribution of the diffusion, generation and surface current to the thermal current I_0. However, in view of the lack of an external bias, hence small width of the depletion depth, the space charge generation

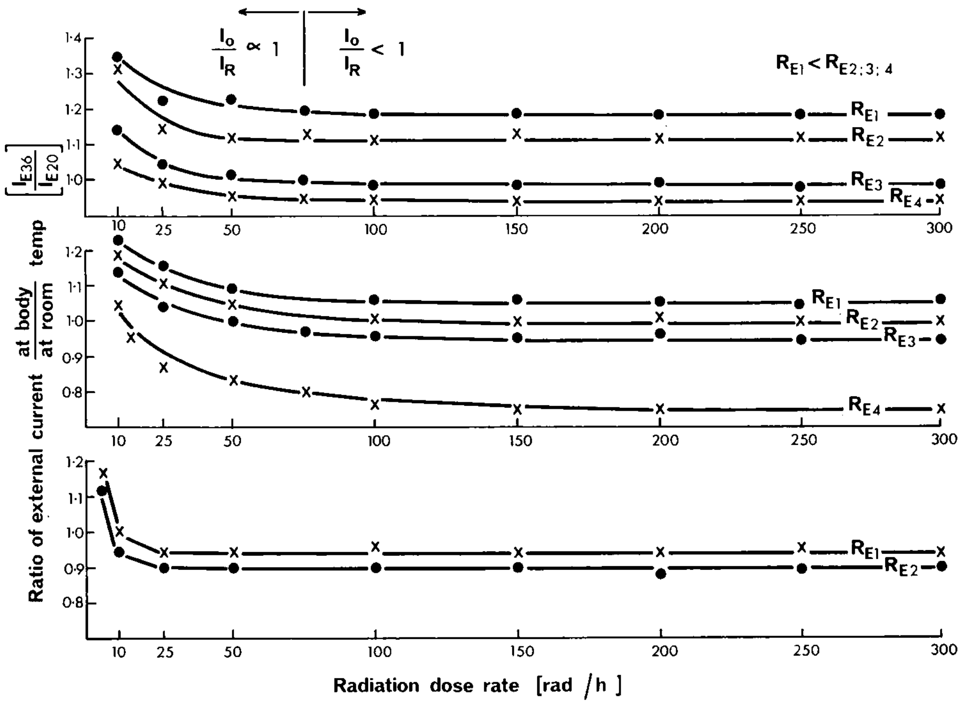

Fig. 6. Temperature response curves illustrating the various patterns of behaviour as found with silicon surface barrier detectors. $R_{E1} = 0.33$ kΩ, $R_{E4} = 100$ kΩ.

current is probably smaller than the diffusion current contribution. Considerable variability of I_0 with time at room temperature was observed which may perhaps be attributed to some surface effects. The degree of sensitivity of I_0 was found to differ with individual detectors. An attempt was made to correlate this with the basic characteristic of a p-n junction, but without success.

Temperature response curves

The investigations described in the previous sections provide some evidence that the temperature effect in a semi-conductor detector has several components, and the current change observed in an external circuit depends on all these factors and on their inter-relation. An experiment was therefore devised which allowed the component factors to come into play in such a way that their individual contributions could be determined. Detectors were irradiated at

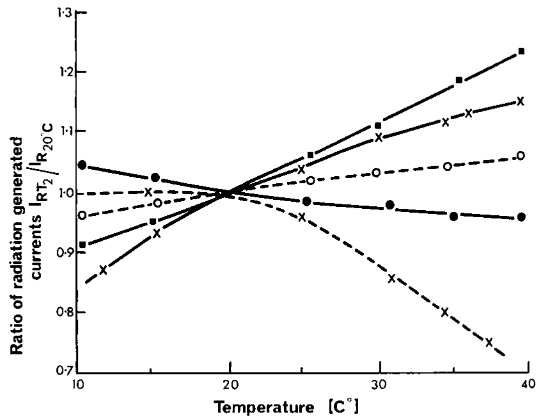

Fig. 7. Relative changes of the radiation generated current I_R due to temperature as found with various detectors, measured in a circuit with $R_j/R_E \gg 1$ and radiation exposure for which $I_R/I_0 \gg 1$.

constant (but variable) exposure rate and, whilst under irradiation, subjected to a sudden change in temperature, from 20° to 36.6° C. The external current I_E was measured at both temperatures and hence the ratio I_{E36}/I_{E20} found. Measurements were carried out at various exposure rates and with values of external resistance R_E ranging from 0.33 kΩ to 100 kΩ. The results, for three detectors, illustrating the possible type of response which a p-n junction may give are illustrated in Fig. 6.

The features of Fig. 6 which require explanation are: (1) at arbitrarily high exposure rates, the ratio I_{E36}/I_{E20} is almost independent of exposure rate and may be $>$ or <1.0; (2) at low exposure rates the ratio is >1.0, i.e. the external current increases with increasing temperature and the effect is most marked at low value of R_E. This is because the detector thermal current, I_0, is large compared with the radiation induced current I_R and its change adds to the radiation current changes. Thus, I_{E36}/I_{E20} depends on the contribution of thermal change in $I_0 + I_R$. With increasing exposure rate, I_R/I_0 increases rapidly and the thermal change in I_0 becomes insignificant compared with the thermal change in I_R. The curves indicate that the temperature coefficient of I_R is independent of the precise value of I_R and hence is independent of the exposure rate. This has been found to be true of all the detectors tested in the present investigations. The apparent negative temperature coefficient at high values of R_E (i.e. $I_{E36}/I_{E20} < 1.0$) is compatible with the observations mentioned on page 128 and is attributable to the change in the current distribution factor f_R, with R_E and $R_{j(T)}$.

The slight slope of the curves in Fig. 6 in the medium range of exposure rates depends on the steady increase of I_R/I_0 with increasing exposure rate. A detector which has thermal current inherently large in value and very sensitive to temperature would produce curves with larger slopes and for such a device a much larger exposure rate is required before the condition $I_R \gg I_0$ is reached.

To summarize: the relative response of a detector to temperature clearly has two domains, an $I_R/I_0 \approx 1$ region in which the thermal change in I_0 is important and the overall temperature effect is exposure rate dependent; and an $I_R/I_0 > 1$ region in which I_0 is insignificant and the temperature effect is independent of exposure rate. In both domains R_E is important in determining the effective temperature coefficient.

A family of temperature response curves is useful for the derivation of essential information about a particular detector. The magnitude of the thermal current can be estimated from the data available at low exposures and the true temperature coefficient is clearly seen. The judgment of the possibility of using a detector in a temperature compensated circuit can be made and the approximate value of the cross-over resistance can be estimated. The spacing between the particular curves taken at various R_E, being the function of the current distribution factor, gives the ability to assesss the internal resistance of the p-n junction.

Temperature response pattern of the radiation generated current I_R

The results shown in Fig. 6 suggest the experimental conditions for studying the variation of the radiation generated current, I_R, in p-n junction detectors with changes in the ambient temperature. These conditions are that the radiation exposure rate should be large enough to render fluctuations of I_0 with temperature negligible, i.e. $I_R/I_0 \gg 1$; and that all of the current generated in the detector should flow into the external circuit, i.e. $R_E/R_j \ll 1$. An experimental determination of $\triangle I_{R(T)}$ was carried out under these conditions within the temperature range 10° to 36° C. The results are shown in Fig. 7 in terms of the ratios

$$I_{R(T_2)}/I_{R(20°C)}$$

Data on several detectors are included to illustrate the variety of the response pattern observed in the devices investigated. It is seen that both negative and positive current coefficients were observed in the room to body temperature range. The $I_{R(T)}$ relation does not seem to follow any uniform pattern. Seven out of ten devices have shown an increase of current between 2 and 23 per cent, (20° to 36° C); with three detectors, a negative response was noted.

No straightforward explanation of the experimental results emerges from the theory of p-n junction devices. Several factors can influence the thermal response of a detector. Some appear directly in the formula for the radiation generated current (1), others have an indirect effect.

The possible contributors are reviewed below and an attempt made to outline their significance:

Carrier mobility μ—appears in the expression for diffusivity $D = \mu kT/e$. It depends on both temperature and impurity concentration (Ludwig & Watters 1956). In silicon the mobility at temperatures higher than 150° K is similar for holes and electrons and a decrease of μ by approximately 0.79 per cent/° C can be expected. However, this is partially offset by an increase of T by about 0.35 per cent/° C in the room temperature region.

Diffusion length L—is given by $(D\tau)^{\frac{1}{2}}$ and represents the distance a carrier can travel by diffusion in a time equal to the lifetime τ. The variation of diffusion length which affects the collection efficiency of carriers is due to both diffusivity and the carrier lifetime.

Carrier lifetime τ—variation of τ is expected if the levels responsible for recombination are deep; their population could be considerably changed by variations of temperature and hence of Fermi level. With the known variation of the capture cross-section of the recombination centres with temperatures $\mu \times \tau = T^{n-3}$, when $2 \leqslant n \leqslant 4$ (Baldinger et coll. 1962) the carrier lifetime is expected to vary significantly. "Effective carrier lifetime", which depends not only on recombination but also on trapping, shows an increase for increasing temperature (Coleman & Swartzendruber 1966). This effect is not clearly understood, but can probably be attributed to the influence of temperature on the behaviour of trapping centres and on the rate of thermal excitation of the carriers out of the trapping centres (detrapping). An increase in carrier lifetime results in improved charge collection efficiency and hence increase in radiation generated current.

"*Built-in voltage*"—decreases with increasing temperature (Vul & Zavaritskaya 1960); an approximate estimate indicates a change of the order of 0.75 per cent/° C. The space charge region is proportional to the square root of the built-in voltage and thus the radiation sensitivity of the detector may change accordingly.

Mean energy required for hole-electron pair creation ξ—ionization energy for gamma rays appears to be a linear function of temperature. (Pehl et coll. 1968),

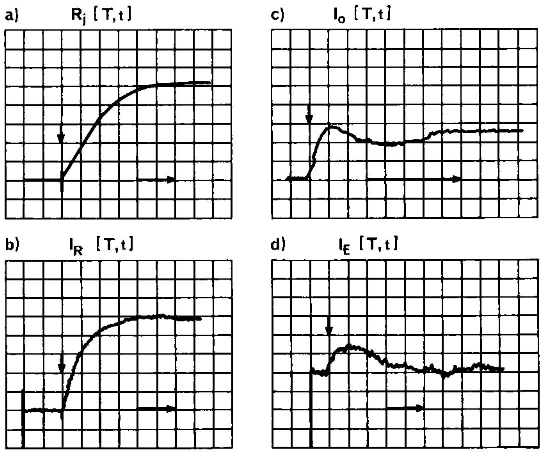

Fig. 8. Thermal transient versus time illustrating the variation of: a) internal resistance R_J; b) radiation current I_R; c) thermal current I_0 with superimposed thermal e m f generated in the internal connections of the detector; d) external current I_E for a detector operated in a temperature compensated circuit. Length of horizontal arrow represents 1 minute. The vertical arrow indicates the instant of temperature change 20° to 36.6° C. Vertical scale in relative units.

ξ decreases with the increase of temperature with a slope of approximately 0.027 per cent/° C. BOLDINGER & CZAJA (1961) have also shown that the ionization energy is proportional to the width of the energy gap. The effect of temperature on ξ is therefore marked twice, directly and through the decrease of the energy gap.

Forbidden energy gap Eg—since the electron levels depend on the spacing between atoms, *Eg* may be expected to depend on temperature (SMITH 1959). As the temperature increases, Eg decreases with a slope of 2.4×10^{-4} ev/° C, resulting in a decrease of *Eg* by approximately 0.025 per cent/° C.

Thermal transient

The results reported so far deal with the detector response to temperature changes after a thermal quiescent state is reached. A transition from one temperature to another takes some time during which the various factors participating in the process which leads to the changed response come into play. The thermal transit is of particular interest when the detector is used in a temperature-compensated circuit.

In clinical dosimetry the question arises as to whether a measurement can be taken immediately after the detector has been inserted into a body cavity or should it be allowed to reach thermal equilibrium first. To answer this question a more detailed investigation of the thermal transient was carried

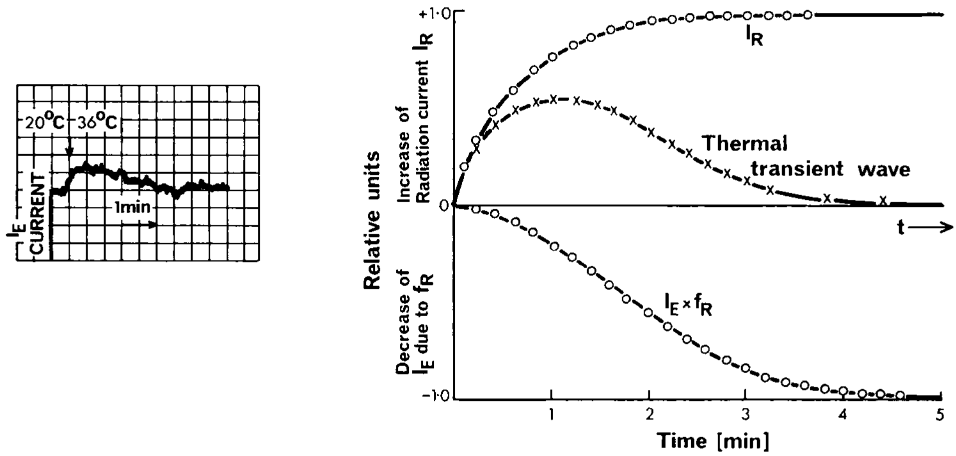

Fig. 9. Thermal transient wave in the external circuit for a detector run in a compensated configuration ($R_E = R_c$), obtained by graphical summation of the changes in the radiation generated current and the external circuit current (cf. Fig. 8 d). The time scale starts when the detector's ambient temperature is suddenly increased from 20 to 36 ° C.

out and an attempt made do determine the behaviour of the particular factors involved. This was done by subjecting the detectors to a sudden temperature change in water (20° to 36.6° C) at constant irradiation conditions and the response was recorded on a chart recorder of appropriate transfer characteristic. The thermal response time t_t was then determined as the time interval between the 10 % and the 90 % values of the response curve.

An example of a thermal transient curve recorded for a detector operated in a compensated circuit ($R_E = R_c$) is shown in Figs 8 d and 9.The curve reveals variations of the amplitude of the current during the transition of heat through the detector. The transient current wave disappears after thermal equilibrium is reached throughout the device, and only then does the ratio $I_{E36}/I_{E20} = 1$. The existence of the transient wave can be explained by the fact that the contributions of the factors participating in the temperature effect are not synchronized in amplitude and time. More detailed analysis has shown that the changes in the main quantities R_j and I_R have different time constants. The decrease of R_j, being due to the bulk effect, takes longer to complete, while the radiation generated current I_R, associated mainly with the phenomena within the sensitive volume of the detector, responds quicker to heat which has easy access to the surface barrier layer. These points are illustrated in Fig. 8, in which the thermal transients of R_j, I_R are shown for one of the cylindrical detectors. The corresponding time constants were found to be 2.2 min and 2.5 min for I_R and R_j respectively.

It is not, however, due to the longer time constant that the variation of R_j affects the transient wave but by its contribution to changes in the current distribution factor and hence the current in the external circuit.

From knowledge of the time constants and the magnitude of the quantities involved, the thermal transient wave was constructed by graphical summation, and is shown in Fig. 9. It is seen that the empirical transient is in very good agreement with the experimentally recorded curve providing proof for the above considerations.

The transient curve was observed with all of the detectors which qualified for operation in a compensated circuit. Differences in individual devices occur in the magnitude and duration of the current wave which can be explained by differences in sensitivities and masses of the detectors involved. However, the time displacement between the temperature effect on I_R and R_j was observed in all the measured devices, both of planar and cylindrical geometry. The amplitude of the transient is directly related to the detector temperature sensitivity.

An additional contributor to the transient wave appears when a detector is used for detection of small exposures ($I_R/I_0 \approx 1$ domain). In this case, the contribution of the variation on the detectors thermal current I_0 becomes apparent, resulting in the enlargement of the transient wave. Some of the detectors investigated have shown the presence of a very fast varying component (Fig. 8) superimposed on the thermal current transient I_0 which is attributed to the thermo-electric e m f induced in the internal connections of the detector (ALLSWORTH, personal communication).

Conclusions

In the course of the experiments carried out so far, three quantities R_j, I_0 and I_R were found to contribute to the temperature effect observed in the external curcuit of a p-n junction detector.

The internal resistance and the thermal current change follow relatively well the theoretically predictable pattern of behaviour. However, both positive and negative temperature coefficients of the radiation induced current were observed in different detectors. No explanation of this effect is forthcoming from the theory of the p-n junction detectors and further work is necesssary to correlate the relevant quantities contributing to the temperature effect with the experimental findings.

The external circuit impedance contributes to the form of the temperature effect observed in the external circuit to such an extent that it can alter the effect from positive to negative.

Thus the response measurable in the external circuit depends on the R_E/R_j and I_R/I_0 relations and it is therefore essential when referring to the temperature effect to state these quantities. It seems that the temperature coefficient can take two values; a real and an apparent one.

The real temperature coefficient of the radiation generated current can be measured in a circuit configuration in which $R_E/R_j \ll 1$ and with irradiation such that $I_R/I_0 \gg 1$. In any other situation the observed temperature response is an apparent one and it may differ considerably from the real one not only in magnitude but in direction as well.

In clinical measurements in which the detector is faced with variable ambient temperature a compensated external circuit configuration should be used. Only detectors with positive response to temperature in the exposure range of interest qualify for this application. The compensation is achieved by setting the operating point at the cross-over point of the temperature characteristic ($R_E = R_c$). However, the presence of the thermal transient wave must be taken into consideration.

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SUMMARY

The response to temperature of silicon p-n junction surface barrier devices used as dosemeters in dc-short circuit mode of operation was investigated, and an analysis of their performance in a temperature compensated circuit made. It was found that detectors of both planar and cylindrical geometry have similar temperature characteristic and it was shown that there are three contributors to the temperature effect: the variations in the radiation generated current and changes in the thermal current and the internal impedance of the p-n junction. Their behaviour and contribution were studied. The p-n junction detectors can have both positive and negative temperature coefficient, an effect not very clearly explicable by the theory of the p-n junction. The detectors showing an increase of current with increasing temperature qualify for operation in the compensated external circuit and are therefore useful for application in clinical measurements.

ZUSAMMENFASSUNG

Es wurde die Temperaturabhängigkeit von Silikon PN-Übergangs-Oberflächensperrschicht-detektoren, die als Dosimeter in einer Gleichstrom Kurzschluss-Schaltungs-Arbeitweise verwendet wurde, untersucht und eine Analyse deren Funktion in einer Temperatur-kompensierten Schaltung vorgenommen. Es wurde gefunden, dass Detektoren von sowohl planer als auch zylindrischer Geometrie ähnliche Temperatureigenschaften haben und es wurde gezeigt, dass drei Faktoren zum Temperatureffekt beitragen: die Veränderungen in dem durch die Strahlung hervorgerufenen Strom und dem Wärmestrom und der internen Impedance des PN-Übergangs. Deren Verhalten und Beitrag wurden untersucht. Die PN-Übergangsdetektoren können sowohl positive als auch negative Temperatur-Koeffizienten haben, ein Effekt, der sich nicht vollständig durch die klare Theorie des PN-Übergangs erklären lässt. Die Detektoren, die einen Anstieg des Stroms mit steigender Temperatur zeigen, sind für die Arbeit in der kompensierten äusseren Schaltung günstig und deshalb für die Verwendung bei klinischen Messungen anwendbar.

RÉSUMÉ

La réponse en fonction de la température de dispositifs à barrière de surface avec jonction p-n aux silicones utilisés comme dosimètre dans la technique de court-circuit dc a été étudiée; l'auteur a fait une analyse de leur fonctionnement dans un circuit à compensation de température. Il a constaté que les détecteurs de forme plane et de forme cylindrique ont des caractéristiques de température similaires et il a montré qu'il y a 3 facteurs de l'effet de température: les variations dans le courant produit par la radiation, les modifications dans le courant thermique et l'impedance interne de la jonction p-n. Il a étudié leur comportement et leur importance. Les détecteurs à jonction p-n peuvent avoir un coefficient de température positif ou négatif; cet effet n'est pas très clairement explicable par la théorie de la jonction p-n. Les détecteurs qui présentent une augmentation du courant quand la température augmente sont adaptés au fonctionnement dans le circuit externe compensé et sont pour cette raison utiles pour l'application dans les mesures cliniques.

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