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Steady-State Response of Silicon Radiation Detectors of the Diffused P–N Junction Type to X rays. II: Photodiode Mode of Operation[1]

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The response to x rays of silicon radiation detectors of the *p-n* junction type was investigated with special consideration of their dependence on the applied voltage. In agreement with theory, the photocurrent, I_g, was found to consist of a voltage-independent part mainly determined by the average diffusion length of minority carriers in the base layer, and a voltage-dependent part which is proportional to the width of the depletion region, w. Due to the voltage dependence of w, I_g increases with increasing voltage applied, but its relative change produced by different voltages is independent of exposure rate and quality of radiation. Exposure rate and energy dependence of I_g expressed in relative values are thus independent of applied voltage. Silicon radiation detectors, used as photodiodes can therefore be useful for monitoring of radiations at exposure rates larger than 1 R/min, taking advantage of the possibility to increase current sensitivity by increasing the voltage V and to increase the voltage signal by increasing the load resistance R_L. There are however limitations in increasing V and R_L because of the increasing noise with increasing dark current and some dependence of measured current signals on R_L. The temperature coefficient of I_g is positive and independent of R_L, but shows some small voltage dependence. In the temperature range between 25 and 50 °C, the average temperature coefficient is approximately 0.35 percent per degree centigrade. A value of the average diffusion length of minority carriers in the base layer has been derived from the measured voltage dependence of I_g.

Key Words: X rays, dosimetry, silicon, silicon junctions, diodes, semiconducting devices, photodiodes, radiation detectors.

1. Introduction

In a previous paper [1][2] (hereafter referred to as part 1) an investigation was reported of the steady-state response of silicon radiation detectors of the diffused $p–n$ junction type to x rays when operated as photovoltaic cells. This paper reports an investigation of the steady-state response of such cells to x rays when operated as photodiodes. Both investigations were carried out in order to examine the suitability of such cells for exposure rate measurements of x rays and to obtain information leading to the establishment of optimum conditions for design and operation of such cells when used for x- and gamma-ray dosimetry.

Under the photodiode mode of operation, as well as in the case where the detector is operated as a photovoltaic cell, a photocurrent is generated by irradiation in the reverse direction of the detector which, for a given quality of radiation determined by its spectral energy distribution, is proportional to the exposure rate. Under the photovoltaic mode of operation, no external voltage is applied to the detector. But under irradiation, the detector becomes biased in the forward direction, causing part of the generated photocurrent to leak back through the detector in the forward direction. The current measured in the external circuit is equal to the difference of the generated photocurrent and the leakage current, and is thus strongly dependent on the current-voltage characteristic of the detector and the external load resistance.

Under the photodiode mode of operation, the detector is biased in the reverse direction by an externally applied voltage. The total current measured under irradiation is equal to the sum of the dark current produced by the bias voltage without irradiation and the generated photocurrent. The full value of the generated photocurrent can thus be determined by measuring the increase in reverse current produced by irradiation. This is usually done by measuring the change in voltage drop over a known load resistance, and this voltage signal can be increased over a wide range by increasing the load resistance, thereby increasing the sensitivity of measurements. The photocurrent measured under the photodiode mode of operation is not determined by the junction leakage current, as is the case under the photovoltaic mode of operation. Its value and temperature dependence should therefore be independent of the size

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[1] Work supported in part by the U.S. Atomic Energy Commission.

[2] Figures in brackets indicate the literature references at the end of this paper.

of load resistance used. How far this ideal performance is obtained with silicon detectors will be discussed below. Special consideration is given in this paper to the voltage dependence of the generated photocurrent, which increases with increasing bias voltage, thereby increasing the radiation sensitivity of the detector.

Measurements were made of (a) the performance characteristics of silicon radiation detectors operated as photodiodes when irradiated with x rays, and of (b) the voltage dependence of the generated photocurrent at different values of exposure rate, detector temperature, and photon energy.

2. Theoretical Considerations

If a reverse voltage is applied to a p-n junction type silicon detector, the main part of the voltage drop inside the silicon wafer appears across the width of the depletion region. That means that, also under the photodiode mode of operation, the electric field in the base and surface layer outside the depletion region may be assumed to be negligibly small. Current carriers produced outside the depletion region are collected by the electric junction field by diffusion only and form, together with carriers produced by radiation inside the depletion region, the generated photocurrent I_g. One can, therefore, apply the relation for I_g (eq (1)), which was derived in part 1 for the photovoltaic mode of operation, considering a one-dimensional model of a p-n junction detector with a p-type base layer and an n-type surface layer (fig.1):

$$I_g=\frac{qA_Rg_s}{\mu}\exp(-\mu d_s)[1-(1-\mu L_n')\exp(-\mu w)+\mu L_p'] \text{ ampere} \tag{1}$$

where g_s is the carrier generation rate or the number of carriers produced per cm^3 per second at the irradiated silicon surface, and is given by the relation (eq (A16) in part 1):

$$g_s=\frac{86.9\mu_{en}}{\epsilon(\mu_{en}/\rho)_{\text{air}}}(\Delta X/\Delta t). \tag{2}$$

In eqs (1) and (2), q is the electronic charge in coulomb, A_R the irradiated silicon surface area in cm^2, μ and μ_{en} the linear attenuation and energy absorption coefficients respectively of x rays in silicon in cm^{-1}, $(\mu_{en}/\rho)_{\text{air}}$ the mass energy absorption coefficient of x rays in air in g^{-1}cm^2, d_s the thickness of the surface layer, and w the width of the depletion region in cm, ϵ the average electron-hole pair production energy in ergs, and $\Delta X/\Delta t$ the exposure rate in R/sec. The quantities L_n' and L_p' are the effective diffusion lengths defined in part 1 [1], which are functions of the attenuation coefficient μ, and of the electrical properties and geometrical dimensions of the silicon wafer used in the detector.

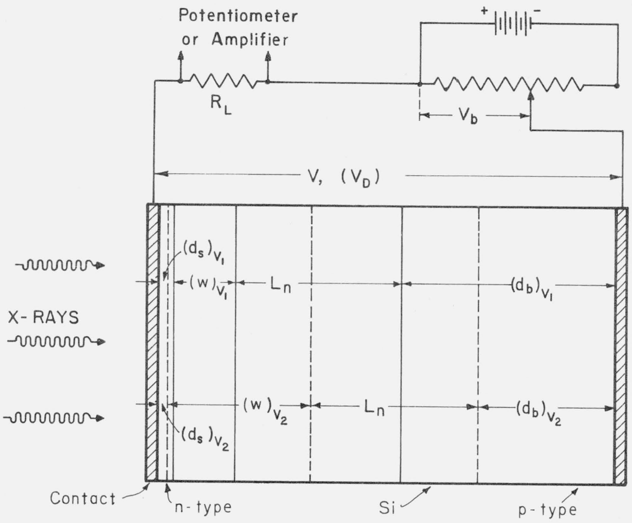

FIGURE 1 *Photodiode measuring circuit and geometry of* p-n *junction detector showing widths of surface layer* (d_s), *base layer* (d_b), *and depletion region* (w) *at two different voltages* V_1 *and* V_2 *applied at the detector.*

For the detectors investigated, it may be assumed that $d_b/L_n \gg 1$, and $d_s/L_p \ll 1$, if d_b and d_b are the widths of the base and surface layers respectively (fig. 1) and L_n and L_p the average diffusion lengths of the minority carriers determined by their lifetime τ and diffusion constant D $(L=\sqrt{D\tau})$. Assuming further negligible surface recombination on the base contact, one can substitute in eq (2)

$$L_n'=\frac{L_n}{\mu L_n+1};\; L_p'=\frac{d_s}{1+(s_pd_s)/D_p} \tag{3}$$

and obtain [1]

$$I_g=\frac{qA_Rg_s}{\mu}\exp(-\mu d_s)\left[1-\frac{\exp(-\mu w)}{\mu L_n+1}+\frac{\mu d_s}{1+(s_pd_s)/D_P}\right] \tag{4}$$

if s_p and D_p are the surface recombination velocity and the diffusion constant of holes in the n-type surface layers respectively and L_n the average diffusion length of electrons in the p-type base layer.

A characteristic feature to be considered under the photodiode mode of operation is the voltage dependence of I_g. Under the photovoltaic mode of operation [1], the voltage dependence of I_g was neglected because radiation-produced forward voltages were of the order of a few millivolts only. However, when operating the detector as photodiode, bias voltages of several volts are applied. With increasing voltage, the width w of the depletion region is increased, while the effective diffusion lengths of the minority carriers remain unchanged, provided the previously made assumption of field-free diffusion regions is valid.

The charge collecting volume is thus increased and extended deeper into the silicon crystal (fig. 1), and according to eq (4), I_g is increased as well.

The voltage dependence of the width of the depletion region is given by the relation [2]

$$w_V = w_1\,(V+V_0)^m \tag{5}$$

if w_V is the width of the depletion region at the voltage V applied at the detector during irradiation, V_0 the potential difference (barrier height) at the p-n junction at $V=0$, and w_1 the width of the depletion region at $(V+V_0)=1$ V. The power exponent m is dependent on the distribution of impurities in the transition region and has values between 1/3 and 1/2.

In diffused p-n junction detectors of the type investigated, w_1 is of the order of 10^{-3} cm. Therefore for x rays, except for very low photon energies and high bias voltages, one can assume $\mu w \ll 1$ and substitute in eq (4) as an approximation $\exp(-\mu w) = 1-\mu w$. Furthermore, it may be considered that the surface layer thickness d_s is of the order of 1 to 2μ, and is negligibly small compared with the diffusion length L_n of electrons in the p-type base layer, which is of the order of a few hundred microns. One can therefore neglect the absorption of radiation in the surface layer and the current contribution by carriers produced in this layer, which is further reduced by the strong surface recombination of minority carriers at the surface contact.

Under these assumptions one obtains from eq (4) and (5):

$$(I_g)_V = a + b(V+V_0)^m \tag{6}$$

if $(I_g)_V$ is the generated current at the applied voltage V and

$$a = (qA_R g_s L_n)/(\mu L_n + 1); \qquad b = (qA_R g_s w_1)/(\mu L_n + 1). \tag{7}$$

Equation (6) gives a simple interpretation of the voltage dependence of I_g, showing that I_g consists of a voltage-independent part a formed by carriers collected by diffusion, and of a voltage-dependent part $b(V+V_0)^m$ due to carriers produced inside the depletion region.

Both constants a and b are dependent on exposure rate and quality of radiation due to their dependence on g_s and μ, and are proportional to the irradiated surface area A_R. However their ratio

$$b/a = w_1/L_n$$

is independent of these parameters and only determined by the electronic properties of the silicon wafer. Equation (6) can therefore be written as

$$(I_g)_V = a k_V \tag{8}$$

if k_V is called the voltage factor at the voltage V given as

$$k_V = 1 + (b/a)(V+V_0)^m = 1 + (w_1/L_n)(V+V_0)^m. \tag{9}$$

For the detectors investigated one can assume $m=0.5$ [3] and obtains for the voltage dependence of I_g

$$\frac{dI_g}{dV} = \frac{qA_R g_s w_1}{2(\mu L_n + 1)}(V+V_0)^{-1/2}. \tag{10}$$

For a given radiation, the voltage dependence of I_g decreases with increasing voltage V.

The diffusion part a of the generated photocurrent may also show a voltage dependence if high bias voltages are applied, for the following reasons: By increasing V, the depletion region is extended, pushing the diffusion region deeper into the silicon wafer. The width d_b of the base layer remaining outside the depletion region is thereby reduced, and the ratio d_b/L_n is decreased (fig. 1). For values smaller than approximately $d_b/L_n=3$, the effective diffusion length L_n' will markedly decrease with decreasing values of d_b/L_n [1]. L_n' will become smaller than the value given by eq (3), and consequently I_g and dI_g/dV will be different from values obtained from eq (8) and (10). This effect, however, need not be considered in this investigation, because of the dimensions and electric properties of the detectors investigated and the moderate bias voltages applied.

3. Experimental Procedure

The silicon radiation detectors investigated were of the same type as those used in the measurements reported in part 1. They were commercially available encapsulated detectors of the diffused p-n junction type made of 1000 Ω-cm p-type silicon with an n-type surface layer on the irradiated side. The surface was protected by a one-micron-thick aluminum layer and was covered with additional aluminum sheets of a total thickness of approximately 325 μ, in order to approach electron-equilibrium conditions in the charge-collecting volume for the types of radiations used.

The x-ray sources were a 250-kV tube and a 50-kV beryllium-window-type tube with an inherent filtration of approximately 4.0 mm Al and 0.25 mm Be, respectively. The x-ray tubes were tungsten target tubes operated by stabilized constant voltage supplies. Different filtration was used as described in part 1 for obtaining different qualities of radiations. Exposure rates of x-rays were measured with calibrated R-meters, except in the case of low-energy radiations obtained from the 50-kV x-ray tube, which were measured with an NBS free-air chamber. If not otherwise stated, the x-ray beam was collimated as described in part 1, so that only the free sensitive surface of the detector was hit by the radiation.

Dark current and total current under irradiation were determined by measuring the voltage drop over a known load resistance (fig. 1) by a null method using a potentiometer. For measurements of small voltage signals obtained with small load resistances, a d-c amplifying microvolt-ammeter of known amplifying ratio was used in measuring the amplified voltage output by a null method. The photocurrent or current signal was determined from the difference of voltages measured with and without irradiation. Only moderate bias voltages were applied to the detectors in order to avoid the increased noise and instability of the dark current observed at higher bias voltages.

Capacity measurements were carried out with a standard-type capacity bridge.

4. Results and Discussion of Measurements

4.1. Performance Characteristics

The performance characteristics of a silicon *p-n* junction radiation detector when operated as a photodiode is shown in figure 2. The detector had a free surface area of approximately 5 mm^2 and was fully irradiated with 30-kV x-rays of 0.09 mm Al half-value layer (HVL) at different exposure rates.

When the detector is being irradiated, the generated photocurrent I_g is added to the reverse current I_D produced by the applied bias voltage V_b without irradiation, also called the dark current. The current-voltage characteristic is raised and the vertical distance between the current-voltage characteristic obtained with and without irradiation is equal to I_g, which is proportional to the exposure rate. The detector can therefore be used for exposure rate measurements by determining I_g or any other quantity linearly related to it. How far this can be achieved will be discussed first.

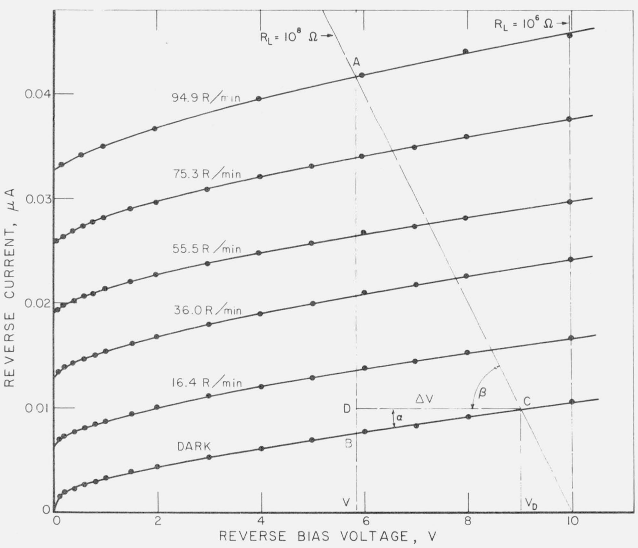

FIGURE 2. *Reverse current-voltage characteristics of a silicon radiation detector of the diffused* p-n *junction type measured without irradiation and when fully irradiated with 30 kV x rays of 0.09 mm Al HVL at different exposure rates with load lines indicated for two different load resistances.*

Irradiated cell surface area $A_R = 5.0$ mm^2.

At a certain bias voltage V_b, the voltage V applied at the detector is dependent on the load resistance and is, as indicated by the load lines in figure 2, at a certain current I

$$V = V_b - IR_L.$$

By irradiation, the reverse current is increased and V decreases by the additional voltage drop in the load resistance. This means that currents obtained with and without irradiation, are measured at different detector voltages.

For an ideal photodiode, it is assumed that the dark current reaches a voltage-independent saturation value at a voltage of a few volts and that I_g is voltage-independent. In this case, the current and voltage signals produced by irradiation are

$$\Delta I = I_g; \qquad \Delta V = I_g R_L. \tag{11}$$

By increasing the load resistance R_L, the voltage signal ΔV can be increased, theoretically without a limit, and this simple way of signal-amplifying is the main advantage in the use of photodiodes.

However, the assumptions made for an ideal photodiode cannot be applied to silicon *p-n* junction detectors. The dark current in a silicon detector does not reach a saturation value, but increases monotonously with increasing voltage, and the generated photocurrent shows a small voltage dependence. If $(I_R)_V$ is the total current measured under irradiation at the voltage V, and $(I_D)_{V_D}$ the dark current at the voltage V_D, then the current and voltage signals are

$$\Delta I = (I_R)_V - (I_D)_{V_D}; \qquad \Delta V = R_L \Delta I \tag{12}$$

but ΔI is now different from I_g, as seen from figure 2.

The relation between I_g and ΔI can be derived from figure 2. Assuming, for instance, $R_L = 10^8 \Omega$, and an exposure rate of 96 R/min, the values of V and V_D were obtained from the intersections of the loadline for $10^8\Omega$ with the respective characteristics measured with and without irradiation. Assuming further a linear voltage dependence of the dark current within the range of ΔV, a triangle ABC can be constructed (fig. 2) where $\overline{AB} = (I_g)_V$, $\overline{AD} = (\Delta I)_V$, $\overline{CD} = \Delta V$, $|\tan \alpha| = (\Delta I_D / \Delta V)_{V_D}$, and $|\tan \beta| = (R_L)^{-1}$. By trigonometrical analysis one obtains from the triangle

$$(I_g)_V = k_c (\Delta I)_V \tag{13}$$

if the factor k_c, which will be called the curve factor, is

$$k_c = [1 + R_L (\Delta I_D / \Delta V)_{V_D}].$$

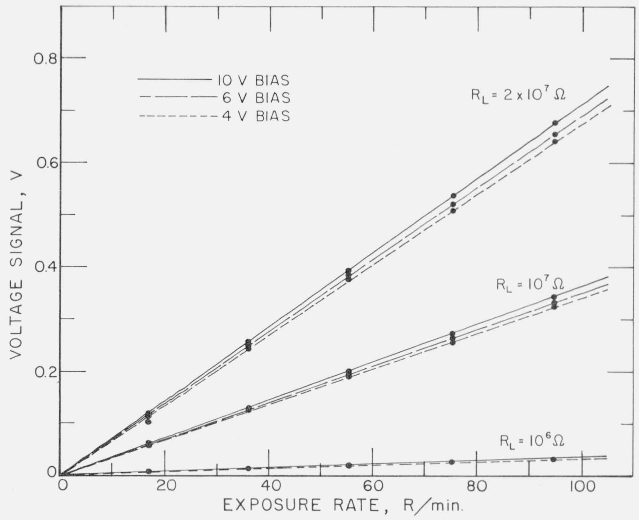

FIGURE 3. *Exposure rate dependence of voltage signals measured at different bias voltages and load resistances as derived from measurements shown in figure 2.*

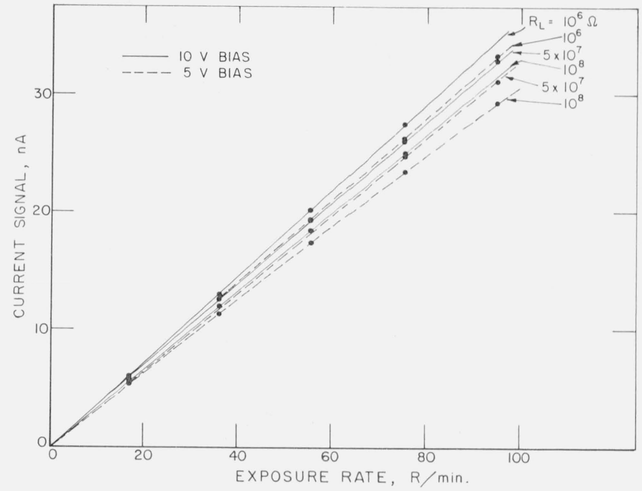

FIGURE 4. *Exposure rate dependence of current signals measured at different bias voltages and load resistances as derived from measurements shown in figure 2.*

At constant exposure rate and constant voltage V, i.e., at constant I_g, ΔI will be the smaller the larger R_L and the larger the slope of the current-voltage characteristic at the voltage V_D. Introducing the dynamic diode resistance $r_V = (dV/dI)_V$, eq (14) can also be written as

$$k_c = [1 + R_L/(r)_{V_D}] \qquad (14a)$$

provided that the slope of the dark current-voltage characteristic is constant within the voltage range ΔV. This condition will obviously be fulfilled if the bias voltage is not too low and the voltage signal is kept small by reducing the load resistance. Because of the voltage dependence of r_V, which increases with increasing V_D, the curve factor will show some voltage dependence.

Figure 3 shows the exposure rate dependence of voltage signals at different bias voltages and load resistances, as derived from the performance characteristics shown in figure 2. Voltage signals are proportional to exposure rate and, at constant values of load resistance, increase with increasing V_b. Current signals derived from these voltage signals ($\Delta I = \Delta V/R_L$) show obviously the same dependence on exposure rate and bias voltage as ΔV (fig. 4), but decrease with increasing load resistance. This indicates that voltage signals increase with increasing load resistance at a smaller rate than R_L (eq (12)).

The dependence of ΔI and correspondingly of ΔV on circuit parameters like V_b and R_L can be explained by the dependence of the curve factor (eq (14)) on those parameters and by the voltage dependence of $(I_g)_V$. The larger R_L, the larger is k_c and, at constant V, the smaller is ΔI. For smaller bias voltages and very large R_L, e.g., $R_L = 10^8 \Omega$ at $V_b = 5$ V (fig. 4), the slope $(\Delta I_D/\Delta V)_{V_D}$ does not remain constant within ΔV. Equation (14) cannot be applied and the exposure rate dependence of ΔI and ΔV becomes nonlinear. In particular, a nonlinear exposure rate dependence may also be observed at moderate values of R_L, if the voltage applied during irradiation at the detector is in the low-voltage region where the dynamic resistance r_V is strongly voltage dependent. The increase of ΔI with increasing bias voltage is due to the increase of I_g with increasing V according to eq (8).

4.2. Voltage Dependence of I_g

In order to measure the actual voltage dependence of I_g, the influence of the curve factor was reduced as much as possible by using small load resistances. In this way the curve factor could be kept approximately at unity value, thus allowing the assumption $\Delta I = I_g$.

The voltage dependence of the current signal measured on a silicon radiation detector is shown in figure 5. The detector had a sensitive surface area of approximately 2.5 cm^2, and was fully irradiated with heavily filtered 100-kv x rays of 11.2 mm Al HVL at an exposure rate of approximately 2 R/min. The voltage dependence of the dark current of the detector was of the order of 10^{-8} A/V and the load resistance $10^4 \Omega$. The curve factor was therefore approximately 1.0001. The current signal shows a small nonlinear increase with increasing bias voltage, increasing only by about 11 percent when changing the bias voltage from 1 to 15 V.

In order to test the relation given by eq (6), the unknown quantities m and V_0 had to be determined by capacity measurements. By considering eq (5), one obtains the voltage dependence of the junction capacitance

$$C = \frac{\epsilon_{Si}\epsilon_0 A_c}{w} = \frac{\epsilon_{Si}\epsilon_0 A_c}{w_1}(V + V_0)^{-m} \qquad (15)$$

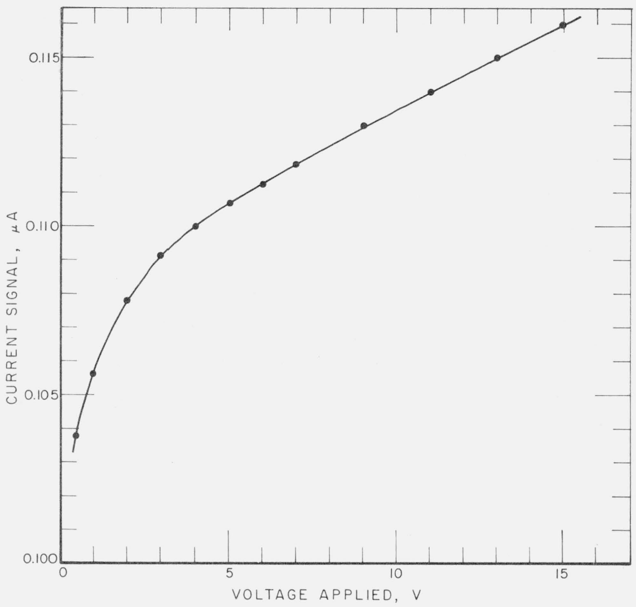

FIGURE 5. *Voltage dependence of current signals produced by heavily filtered 100 kV x rays of 11.2 mm Al HVL at an exposure rate of approximately 2 R/min.*

Surface area of detector is approximately 2.5 cm², $R_L = 10^4 \Omega$.

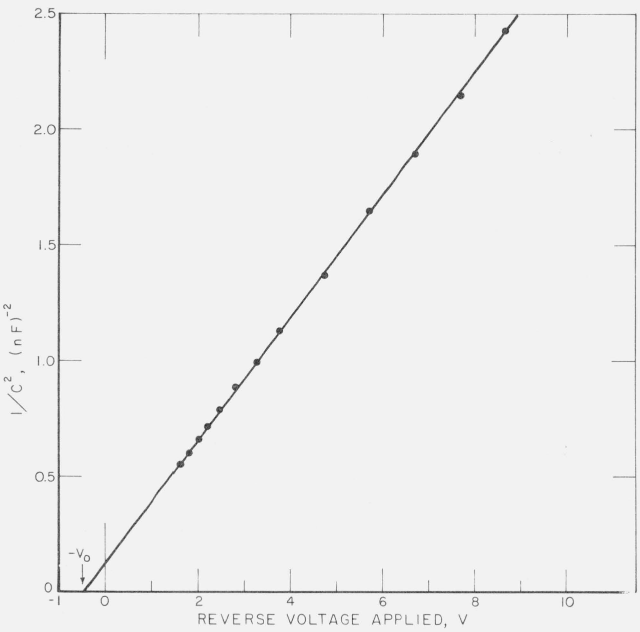

FIGURE 6. *Determination of zero-voltage junction barrier height* V_0 *and width* w_1 *of depletion region at* $(V+V_0)=1$ V *from intercept at voltage axis and slope of graph* $1/C^2$ *versus* V *derived from measurement of voltage dependence of capacity* C *of* p-n *junction type silicon radiation detector.*

if ϵ_{Si} is the dielectric constant of silicon ($\epsilon_{Si}=12$), ϵ_0 the permittivity of free space ($\epsilon_0=8.85\times10^{-12}$ F/m), and A_c the area of the surface contacts of the detector. From measurements of the voltage dependence of C, a value of m between 0.4 and 0.5 was obtained from a double logarithmic graph of C versus $(V+V_0)$ assuming tentatively $V_0=0.5$ V. Choosing the theoretical value of $m=0.5$ for an abrupt junction [2], one can derive from eq (15) the relation:

$$\frac{1}{C^2}=\left(\frac{w_1}{\epsilon_{Si}\epsilon_0 A_c}\right)^2 (V+V_0) \tag{16}$$

from which V_0 and w_1 can be determined. By plotting measured values of $(1/C^2)$ versus V, a straight line was obtained (fig. 6) confirming the value chosen for m. The value of V_0 is given by the intercept on the voltage axis and w_1 could be determined from the slope of this graph. Values of V_0 and w_1 evaluated by the method of least squares were for the detector investigated $V_0=0.477$ V and $w_1=14.5\times10^{-4}$ cm, $(\text{volt})^{-1/2}$.

These values were used in the evaluation of measurements given in the following sections.

a. Exposure Rate Dependence

The voltage dependence of current signals at different exposure rates, as derived from measurements shown in figure 2, is given in figure 7. The current signals were measured over a load resistance of $10^6\Omega$, but due to the small dark current of the detector, the curve factor differed only by approximately 0.1 percent from unity. The current signals ΔI can

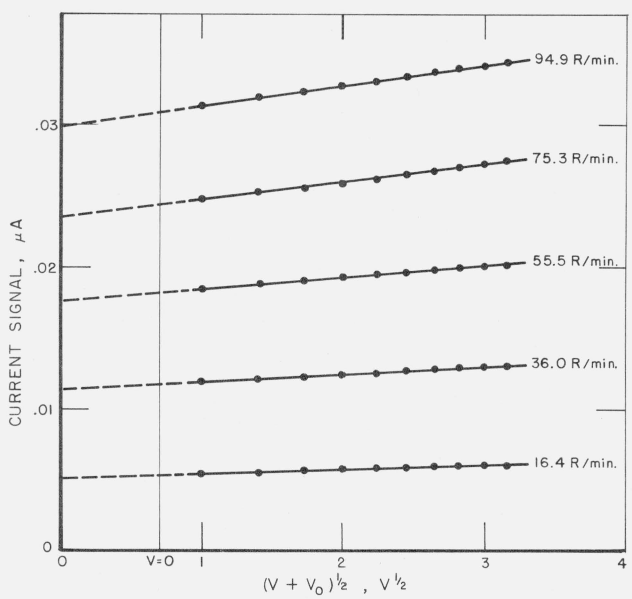

FIGURE 7. *Current signals measured at different exposure rates as function of* $(V+V_0)^{1/2}$.

Intercepts on current axis obtained by linear extrapolation of measured values, as indicated by dashed lines, are the voltage-independent diffusion parts of the current signals.

therefore be assumed to be equal to the values of the generated photocurrents I_g.

In agreement with eq (6), the current signal is at constant exposure rate a linear function of $(V+V_0)^{1/2}$ and increases with increasing voltage V, the slope b increasing with increasing exposure rate. By linear extrapolation of ΔI to $(V+V_0)^{1/2}=0$, one can separate the voltage-dependent and voltage-independent parts of the current signals, both parts showing proportionality with exposure rate. Or in other words, the current sensitivity of the detector, expressed in amperes per unit exposure rate, increases with increasing voltage, but the current signal measured at any voltage increases at the same rate with increasing exposure rate. This is indicated in table 1, showing that at different voltages ΔI increases at the same rate as the exposure rate. This means that the voltage factor (eq (8)) is independent of exposure rate and was in particular obtained from these measurements as $k_V=[1+0.05\,(V+V_0)^{1/2}]$.

TABLE 1. *Exposure rate dependence (fig. 7).*
Relative values of current signals measured at different voltages.

Exposure rate		Current signal (rel. value)		
R/min	Relative value	3V	6V	10V
16.4	0.173	0.175	0.176	0.175
36.0	.379	.378	.379	.379
55.5	.585	.582	.588	.584
75.3	.793	.788	.794	.795
94.9	1.000	1.000	1.000	1.000

b. Temperature Dependence

For measuring the voltage dependence of the current signal at different temperatures, the detector was placed inside a thermostatically controlled oven, and fully irradiated with 100-kV x rays filtered by 2 mm Al, and the nonmetallic oven wall at an exposure rate of approximately 50 R/min. The load resistance was $10^4\Omega$.

Figure 8 shows the current signals measured at different temperatures as function of $(V+V_0)^{1/2}$. The temperature dependence of V_0 was taken into account in determining the abcissa values. A reduction in V_0 of 2.8 mV per degree centigrade was assumed in accordance with calculations made by Baldinger et al., [4] for silicon detectors of a type similar to those used in this investigation. The values of V are the voltages applied at the detector as measured at different bias voltages and temperatures.

The current signal increases with increasing temperature and remains for voltages above approximately 1 V, proportional to $(V+V_0)^{1/2}$. The diffusion part a obtained by extrapolation of the linear part of the graph to $(V+V_0)^{1/2}=0$, increases with increasing temperature, while the slope b of the voltage dependent part decreases. By increasing the temperature from 23.4 to 51.1 °C, a increases by about 11 percent and b decreases by about 24 percent, thus reducing the ratio b/a. This means that the voltage factor (eq 9) is slightly temperature dependent, showing at 5 V a decrease from 1.06 to 1.04 when increasing the temperature from 23.4 to 51.1 °C. The voltage-dependent part is only a small fraction of the total current signal, and the temperature dependence of the current signal is mainly determined by the diffusion part, which increases with increasing temperature.

The temperature dependence of ΔI at constant applied voltages, as derived from these measurements is shown in figure 9. The curve factor was for the detector investigated for a load resistance of $10^4\Omega$ approximately 1.01 at 23.4 °C and $V=1.5$ V, slightly decreasing with increasing voltage and increasing with increasing temperature. These changes were of the order of 1 percent, so that the temperature

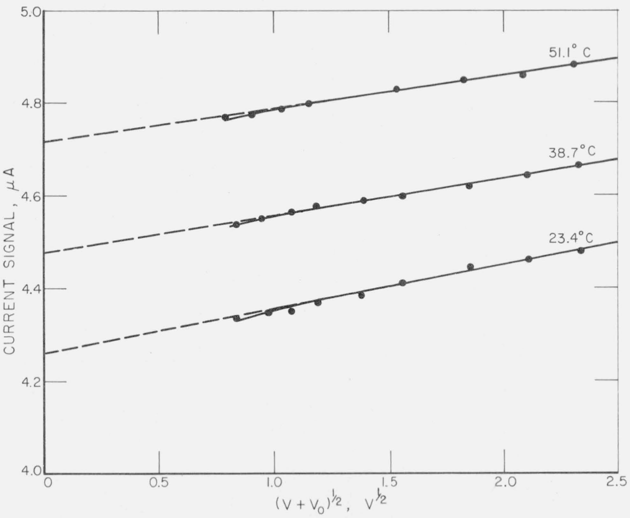

FIGURE 8. *Current signals measured at different temperatures as function of* $(V+V_0)^{1/2}$.
Linear extrapolation of measured values to $(V+V_0)^{1/2}=0$ is indicated by dashed lines.

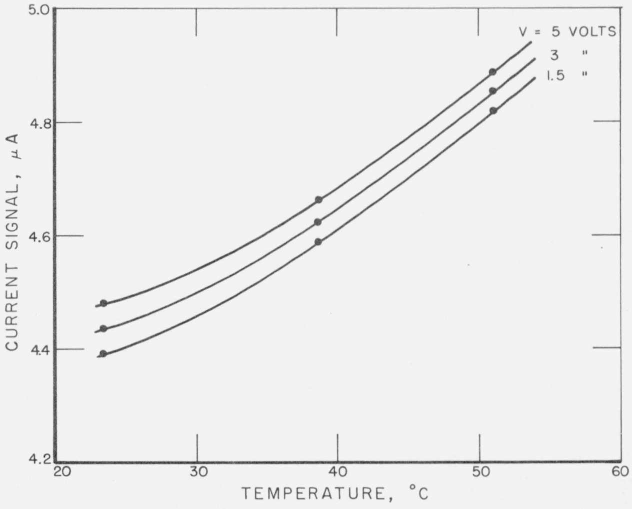

FIGURE 9. *Temperature dependence of current signals measured with different voltages applied at the detector.*

dependence given for the current signal may be assumed to be qualitatively the same for I_g. The temperature coefficient given as $\frac{1}{I_g}\left(\frac{dI_g}{dT}\right)$ increases with increasing temperature and decreases slightly with increasing voltage. At 51.1 °C the temperature coefficient has approximately the same value of 0.4 percent per degree centigrade for different voltages, but changes at 23.4 °C from 0.20 percent per °C at 1.5 V to 0.17 percent per °C at 5 V. Assuming linear temperature dependence between 25 and 50 °C

$$(I_g)_T=(I_g)_{T_0}(1+\gamma\Delta T)=(I_g)_{T_0}k_T \tag{17}$$

where k_T is called the temperature factor, the average temperature coefficient γ expressed in percent is 0.36 percent per °C at 1.5 V and 0.33 percent per °C at 5 V. These values are in good agreement with the value of 0.32 percent per °C, given in part I for the temperature coefficient of the short circuit current measured in silicon *p-n* junction radiation detectors operated as photovoltaic cells [1].

As previously stated [1], no definite explanation can be given for the positive temperature coefficient of the generated photocurrent I_g. However, the measurements given here support the assumption made [1] that the positive temperature coefficient of I_g is due to an increase with increasing temperature of the average diffusion length L_n of electrons in the base layer, which determines the size of the voltage-independent part collected by diffusion. A decrease in the pair-production energy ϵ could have only a small effect because a larger decrease in ϵ would cause an increase rather than a decrease in the temperature dependence of the voltage-dependent part of I_g (eq 2) that is not observed. A reduction in the internal series resistance with increasing temperature, sometimes assumed to be responsible for the positive temperature coefficient of I_g [5], would only have an effect on the dark current characteristic, because I_g is independent of the total load resistance. At a constant applied voltage V, a decreasing series resistance may cause an increase of the voltage applied at the junction (barrier height). But this increase would be very small because of the small series-to-diode resistance ratio. A decrease in series resistances may affect the curve-factor, due to a change of the slope of the dark current characteristic. However, considering the values of voltage- and curve-factors and their temperature dependence given above, changes of these factors cannot account for the increase of approximately 11 percent in the measured current signal.

The decrease in the slope of the graphs in figure 8 with increasing temperature may be due to a decrease of w and an increase of L_n (eq (9)). A negative temperature coefficient of the width w of the depletion region has been indicated by measurements of the temperature dependence of the capacitance of silicon diodes, which is inversely proportional to w. Baldinger et al. [4], and Antula [6] found in silicon diodes an increase of junction capacitance with increasing temperature and a decrease of the temperature coefficient of the capacitance with increasing bias voltage, that is in qualitative agreement with measurements discussed here.

c. Energy Dependence

The energy dependence of radiation-produced current signals measured at different applied voltages, including zero voltage (photovoltaic current) is shown in figure 10 for moderately and lightly filtered x rays, and in figure 11 for heavily filtered x rays. Load

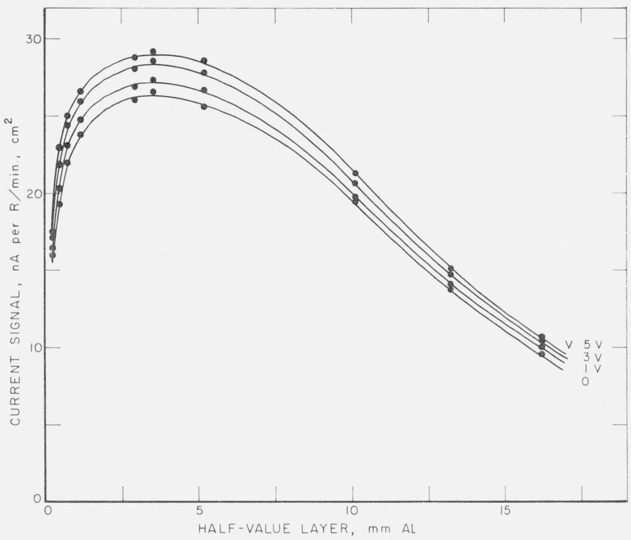

FIGURE 10. *Dependence of current sensitivity (current signal at an exposure rate of 1 R/min and 1 cm² irradiated surface) on quality of moderately and lightly filtered x rays as measured with different voltages applied at the detector.*

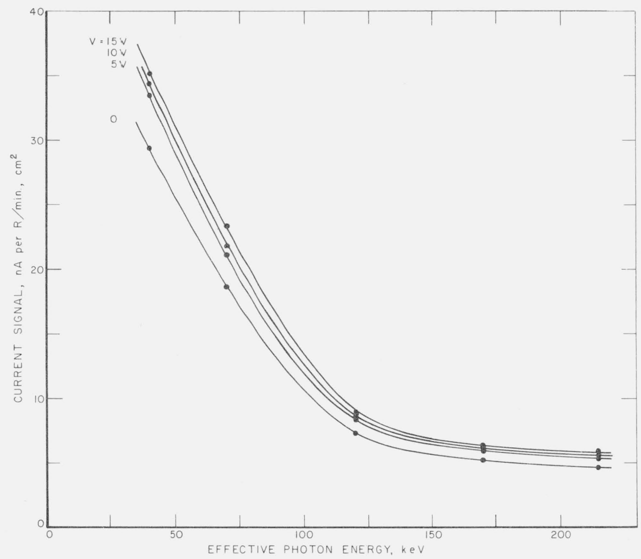

FIGURE 11. *Dependence of current sensitivity (current signal at an exposure rate of 1 R/min and 1 cm² irradiated surface) on effective photon energy of heavily filtered x rays (see table 1 in part 1) as measured with different voltages applied at the detector.*

resistances used were of such size that curve factors were approximately of unity value and current signals may be assumed to be approximately equal to generated photocurrents.

The current sensitivity, expressed here by the radiation-produced current signal measured at 1 R/min and 1 cm² irradiated surface area, increases with increasing voltage V, but the shape of its energy dependence remains similar at different applied voltages. For a certain increase of V, the increment in current signal shows an energy dependence similar to that of the total current signal. It first increases with decreasing HVL, reaches a maximum at a HVL of approximately 3.5 mm Al and then decreases with further decreasing HVL.

The voltage dependence of ΔI can better be analyzed by plotting ΔI as a function of $(V+V_0)^{1/2}$ as shown in figure 12. The linear dependence of ΔI on $(V+V_0)^{1/2}$ is maintained for different types of radiation, but the slope b on the voltage-dependent part of ΔI, increases and decreases in the same way as the total signal ΔI changes with quality of radiation. This behavior is in agreement with eq (7) showing that the slope b and the voltage independent part a of the current signal are both proportional to $g_s/(\mu L_n+1)$. With decreasing photon energy, a and b are first increasing because of the increase of g_s. But due to the energy dependence of the attenuation coefficient μ, which increases with decreasing photon energy at a greater rate than g_s, both a and b reach a maximum and then decrease at lower energies.

If at different radiation qualities a and b increase and decrease at the same rate, then the ratio b/a, and consequently the voltage factor k_V (eq (9)), must be independent of radiation quality. The voltage factor

$$k_V = I_g/a \tag{18}$$

was evaluated by assuming $\Delta I = I_g$ and determining a by linear extrapolation of the measured current signals to $(V+V_0)^{1/2}=0$. Voltage factors obtained from measurement with heavily filtered x rays at exposure rates of the order of 1 R/min are shown in figure 13. For x rays of different HVL, values of k_V are proportional to $(V+V_0)^{1/2}$, but show at constant voltage a certain spread without indicating any definite trend in energy dependence. At $V=15$ V, the highest voltage applied, the deviation of k_V from an average value is approximately ±2 percent that is within the experimental error of these measurements. The error in k_V is dependent on the error in measuring I_g, which was at the small exposure rates obtained with heavily filtered x rays about 10 to 15 times smaller than the dark current, and by the error in determining the value a by the extrapolation method. One may therefore conclude from these measurements that k_V is independent of radiation quality, and photocurrents increase with increasing voltage at the same rate at different qualities of radiation. If $(I_g)_1$ and $(I_g)_2$ are the photocurrents measured at photon energies $h\nu_1$ and $h\nu_2$, then their ratio at constant V

$$\frac{(I_g)_1}{(I_g)_2} = \frac{a_1(k_V)_1}{a_2(k_V)_2} = \frac{a_1\left[1+\frac{w_1}{L_n}(V+V_0)^{1/2}\right]}{a_2\left[1+\frac{w_1}{L_n}(V+V_0)^{1/2}\right]} = \frac{a_1}{a_2} \tag{19}$$

is independent of V, which means that the energy dependence of I_g given in relative values is the same

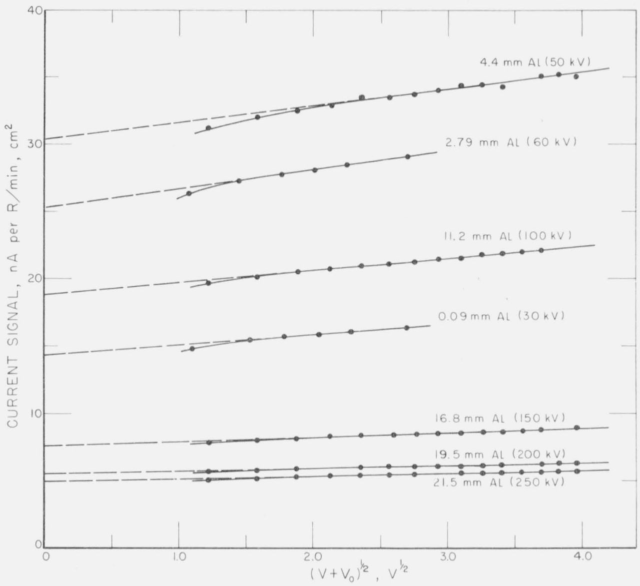

FIGURE 12. *Current sensitivity measured with x rays of different qualities as function of* $(V+V_0)^{1/2}$.

Qualities of x rays are specified by HVL in Al and operating voltage of x ray tube as indicated.

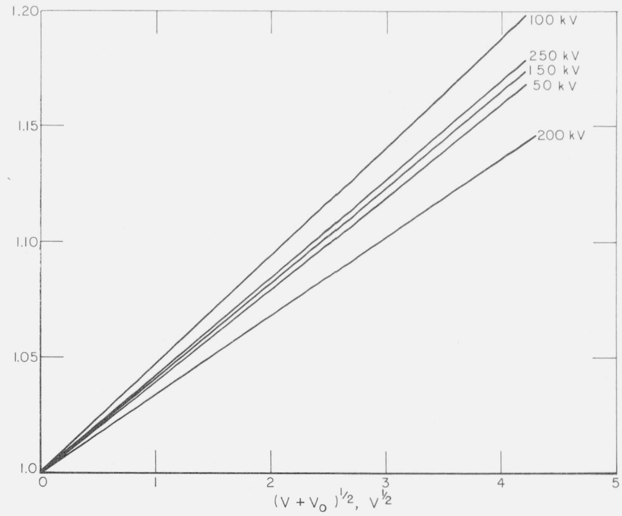

FIGURE 13. *Voltage factor as function of* $(V+V_0)^{1/2}$ *as derived from measurement of voltage dependence of current signals produced by heavily filtered x rays obtained at operating voltages as indicated (see table 2).*

for different applied voltages. This is shown in table 2 giving relative values of I_g at different applied voltages as measured with heavily, moderately, and lightly filtered x rays. The relative values at different voltages differ by about ±1 percent from their average values. Somewhat larger deviations are obtained for photovoltaic short-circuit currents at $V=0$, which were, however, not directly measured, but determined by extrapolation to $V=0$.

TABLE 2. *Energy dependence (figs. 10 and 11)*

Relative values of current sensitivities measured at different voltages. (Sensitive detector surface was covered with 325 micron thick Al-layer.)

X rays		Current signal per R/min, cm² (rel. value)			
kVcp	Approx. HVL mm Al	V=0	5V	10V	15V
		Heavily filtered x rays [a]			
50	4.4	1.576	1.590	1.577	1.578
100	11.2	1.000	1.000	1.000	1.000
150	16.8	0.392	0.397	0.397	0.399
200	19.5	.281	.285	.282	.282
250	21.5	.252	.256	.257	.257

X rays		Current signal per R/min, cm² (rel. value)			
kVcp	Approx. HVL mm Al	V=0	1V	3V	5V
		Lightly and moderately filtered x rays [a, b]			
30	0.30	0.601	0.600	0.600	0.600
30	.55	.728	.730	.736	.738
50	1.20	.880	.909	.910	.912
60	2.97	.980	.982	.981	.984
75	3.53	1.000	1.000	1.000	1.000
100	5.20	0.987	0.977	0.975	0.980
150	10.1	.730	.725	.724	.730
200	13.2	.519	.518	.516	.517
250	16.2	.370	.367	.366	.368

[a] For filter combination used see table 1 in part 1 [1].
[b] The additional filtration by the 325 μ thick Al cover was taken into account.

The slope of the straight lines in figure 13 should, in accordance with eq (9), be equal to (w_1/L_n). If w_1 is determined by capacity measurements as shown above, then L_n can be obtained from measurements of the voltage factor of I_g. Using the average value of (w_1/L_n) obtained from these measurements (fig. 13) of $(w_1/L_n)=0.041$, and assuming a value $w_1=14.5$ μ as given above, the average diffusion length L_n is obtained as $L_n=354\pm 43$ μ. This value is of the right order of magnitude, but approximately 25 percent smaller than that obtained by solving eq (4) for L_n for a certain voltage. However, for solving this equation, one has to make assumptions about the quality of radiation, and exposure rate inside the charge collecting volume, and the effective irradiated surface area must be known, whereas the evaluation of L_n from the voltage factor is independent of these parameters. How far these values of L_n are correct, could not be decided, because lifetimes and diffusion lengths of minority carriers in the silicon wafer of the detector were not known.

5. Summary and Conclusions

It has been shown that if the detectors are operated as photodiodes the photocurrent produced by x rays in silicon radiation detectors of the *p-n* junction type may be considered to consist of two parts, a voltage-independent part which is determined by the average diffusion length of minority carriers in the base layer, and a voltage-dependent part which is proportional to the width of the depletion region, both parts being proportional to exposure rate. The voltage dependence of the generated photocurrent I_g was expressed by a voltage factor k_V (eq (8)), which for the detectors investigated, was a linear function of $(V+V_0)^{1/2}$, if V is the voltage applied at the detector during irradiation and V_0 is the zero-voltage barrier height of the junction. Due to the nonsaturating current-voltage characteristic of silicon radiation detectors, the measured current signal, or the radiation-produced change in reverse current, is different from the generated photocurrent by a factor k_c which was called the curve factor. The curve factor as defined by eq (13) is a linear function of the ratio of the load resistance and the dynamic resistance at the voltage applied under "dark" condition. Due to its dependence on the dynamic resistance, k_c is voltage and temperature dependent. Thus, assuming constant temperature, one obtains from eqs (8) and (13) for the photocurrent generated at the voltage V

$$(I_g)_V=ak_V=(k_c)_V(\Delta I)_V \tag{20}$$

or for the current signal

$$(\Delta I)_V=\frac{(I_g)_V}{(k_c)_V}=a\,\frac{k_V}{(k_c)_V} \tag{21}$$

if a is the voltage-independent diffusion part of I_g which cannot be measured directly, but is obtained by extrapolation of the current signals to $(V+V_0)^{1/2}=0$. It may sometimes be preferable to relate $(\Delta I)_V$ to a current signal $(\Delta I)_{V_1}$ obtained at a reference voltage V_1. In this case

$$(\Delta I)_V=(\Delta I)_{V_1}\,\frac{k_V(k_c)_{V_1}}{k_{V_1}(k_c)_V}. \tag{22}$$

By proper choice of R_L, the curve factors may be kept approximately at unity value, so that the ratio (k_V/k_{V_1}) can experimentally be determined by measuring the ratio $(\Delta I)_V/(\Delta I)_{V_1}$, as function of V at constant exposure rate of x rays of any quality.

The generated photocurrent I_g and correspondingly ΔI increase with increasing temperature, but while a increases, k_V decreases slightly with increasing temperature. The temperature dependence is nonlinear, and due to the temperature dependence of k_V, slightly voltage-dependent. However, within a temperature range between 25 and 50 °C, one may assume from these measurements, as an approximation, a voltage-independent linear temperature dependence determined by a positive temperature coefficient of approximately 0.35 percent per °C. The temperature dependence of I_g cannot satisfactorily be explained and further investigation will be required to establish the temperature dependence of different parameters as width of the depletion region, and lifetime and diffusion lengths of minority carriers.

In particular, the following conclusions can be drawn from this investigation with regard to the use of silicon radiation detectors as photodiodes for exposure rate measurements of x rays:

The photocurrent $(I_g)_V$ produced under the photodiode mode of operation shows qualitatively the same exposure rate and energy dependence as the short-circuit current produced under the photovoltaic mode of operation [1]. The increase of $(I_g)_V$ with applied voltage is rather small due to the small ratio of width of depletion region to diffusion length of minority carriers in diffused *p-n* junction type detectors. The advantage of increasing $(I_g)_V$ by increasing V, is offset by the accompanying increase in dark current, which becomes noisy and unstable at higher voltages. Large bias voltages should therefore be avoided.

Load resistance and applied voltage should be chosen in such a way that within the range of exposure rates considered, the curve factor k_c remains constant and approximately at unity value. If the dynamic resistance of the detector cannot be considered as being constant within the voltage signal measured across the load resistance, eq (14a) for k_c will not be applicable any more. The current signal will in a different way be related to $(I_g)_V$, resulting in a nonlinear exposure rate dependence. This situation may arise at low bias voltages or large voltage signals obtained with large load resistances and high exposure rates. The requirement of constant curve factor k_c, imposes a limitation on the size of the load resistance which can be used for amplification of the voltage signal.

The voltage factor has been shown to be independent of exposure rate or quality of radiation. This means that though current sensitivity will be different at different voltages, the ratio of two signals measured at different exposure rates or with x rays of different quality, but at constant voltage, will be the same independent of the voltage applied. Silicon radiation detectors operated as photodiodes may therefore specially be useful for monitoring of radiations, when only relative values of exposure rates are of interest. For measuring exposure rates in roentgens per unit time, detectors will have to be calibrated for the respective type of radiation with the same voltage and load resistance as used for the exposure rate measurements.

Compared with the photovoltaic mode of operation, the use of silicon radiation detectors as photodiodes has the advantages that their exposure rate and temperature dependence is, through the curve factor, only slightly dependent on the load resistance, and that it is possible, though within certain limits, to amplify voltage signals by increasing the load resistance. However, more elaborate circuitry is necessary for the operation of detectors as photodiodes, and the dark current, which shows some instability and strong temperature dependence, has to be measured or balanced out for each signal reading. For small exposure rates, the current signal may become much smaller than the dark current, limiting the measuring range to exposure rates larger than approximately 1 R/min. In this investigation, current signals produced at an exposure rate of 1 R/min were determined with a precision of ± 1 percent by measuring the amplified voltage drop over a known load resistance of moderate size with a potentiometer.

Finally, it should be pointed out that the discussion of measurements reported here was based on eq (6) which was derived under certain simplifying assumptions. If these assumptions are not fulfilled, deviations from the voltage dependence of $(I_g)_V$ reported here may be observed.

6. References

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