SOLAR CELL RADIATION RESPONSE NEAR THE INTERFACE OF DIFFERENT ATOMIC NUMBER MATERIALS

E. A. Burke, J. R. Cappelli, L. F. Lowe, and J. A. Wall
Air Force Cambridge Research Laboratories (AFSC)
Bedford, Massachusetts 01730

The response of Co-60 irradiated N/P silicon solar cells was measured as a function of the atomic number of the medium adjacent to the cell and the direction of the gamma ray beam. The interpositioning of various thicknesses of aluminum between the adjacent material and the cell had the effect of moving the cell to various locations in an approximate monatomic numbered medium. Using this technique the solar cell response was determined at various distances from the interface for gold and beryllium. The results were compared with predictions based upon ionization chamber measurements of dose perturbations in aluminum and found to agree within five percent. Ionization chamber data was then used to estimate the influence of various base contact materials. The directional effect is most noticeable for gold contacts leading to a response when the beam enters the cell face which is 40% greater than for the opposite direction. The situation is reversed for beryllium which produces a response which is 17% greater when the beam enters through the base than for the reversed direction.

INTRODUCTION

The prediction of solid state device response to ionizing radiation requires a knowledge of the energy absorbed (the dose or dose rate) in active regions of the device. If the device is adjacent to materials (packaging or structural supports) with atomic numbers different than the device material and the primary radiation produces electrons with ranges that are comparable to device dimensions, ionization chamber studies indicate that the energy deposited can vary significantly from that absorbed in the absence of the surrounding materials. Methods commonly used for predicting the dose neglect the possible influence of adjoining materials. Similarly, the materials, dimensions, and encapsulation of dosimeters rarely corresponds to the test specimen so that experimental measurements can be misleading. Little experimental data exists concerning the nature and magnitude of the dose perturbations produced and as a result theoretical predictions have not been adequately tested.

The greatest amount of work on the problem of dose perturbations at interfaces has been done by those with an interest in the biological effects of radiation. They have been particularly concerned about the enhanced dose in soft tissue adjacent to bone under X irradiation. Experimental and theoretical work on this problem has been reviewed by Spiers[1].

In view of the large differences in the photoelectric cross sections for elements of different atomic number and the resultant large difference in the deposited energy it is not surprising to find dose perturbations near interfaces at x-ray energies. At gamma ray energies where the Compton cross section is dominant, energy deposition varies relatively little from one material to another and small perturbations might be expected.

The fact that significant changes in the dose can occur at gamma ray energies was first pointed out by Dutreix et al[2] and recently examined for typical device materials exposed to Co-60 gamma radiation by Wall and Burke[3]. Energy deposition profiles in aluminum adjacent to gold are shown in Fig. 1. The data was obtained using a multiple cavity parallel plate ionization chamber technique[3]. It shows that the dose in aluminum is enhanced when the gamma beam penetrates the aluminum before entering the gold. However, the dose is actually reduced below the equilibrium value for aluminum when the gamma beam is reversed. There is a strong directional effect. The effect is noticeable at a distance of 200 mg/cm^2 away from the boundary which means that it extends over typical device dimensions. For lower atomic number materials the effect is similar but somewhat reduced as shown in Fig. 2.

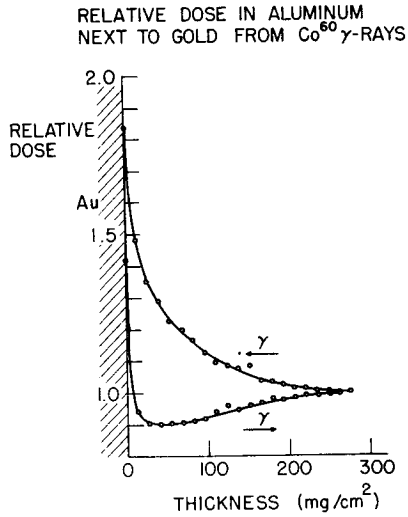


FIGURE 1. - Air Ionization Measurements of the Relative Dose in Lauminum next to Gold. Arrows indicate the direction of the gamma beam.

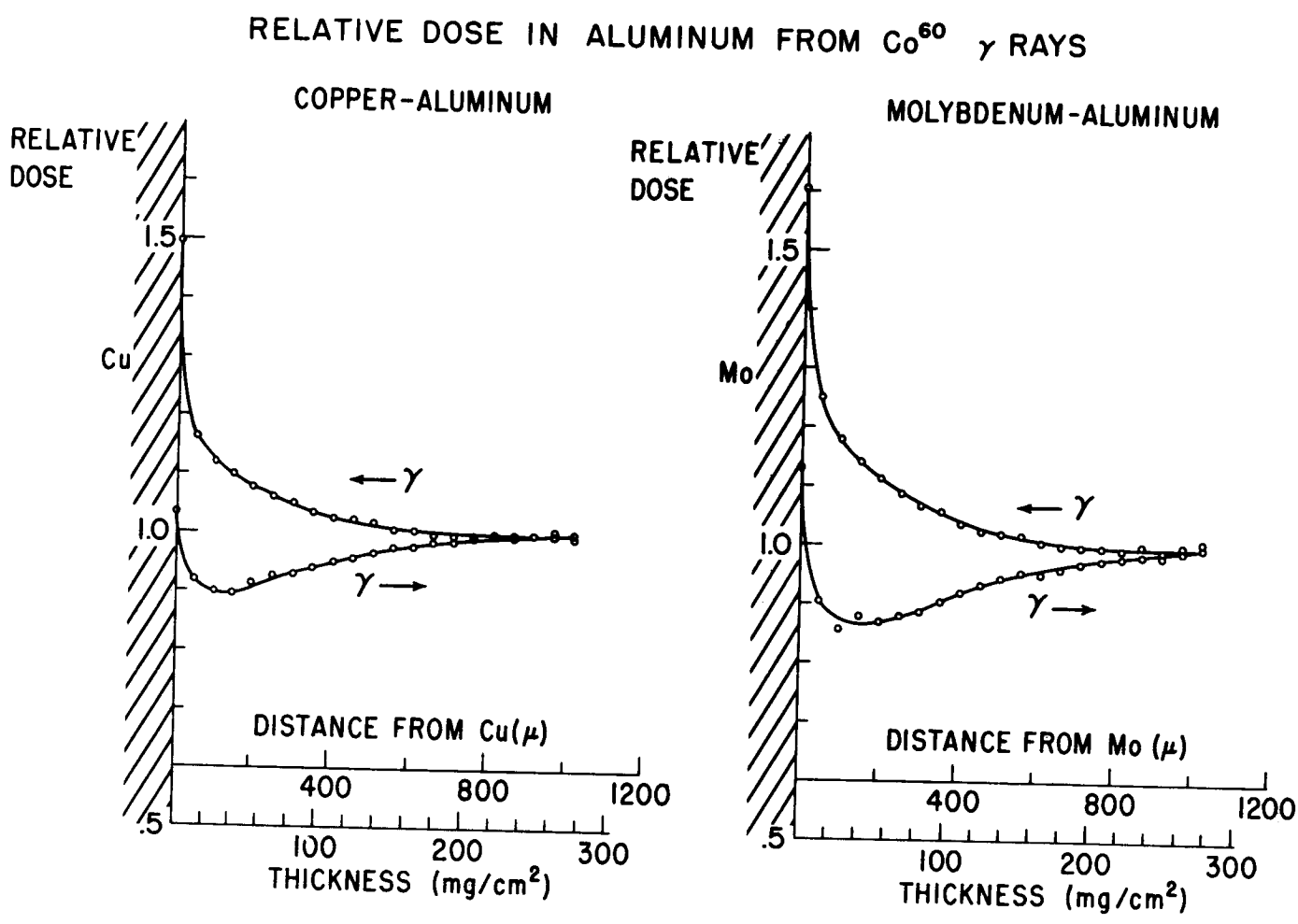


FIGURE 2. - Air Ionization Measurements of the Relative Dose in Aluminum Next to Copper and Molybdenum.

AFCRL PHOTO 120-406

Notice, however, that the minimum in the dose profile appears to be greatest for materials of intermediate atomic numbers such as molybdenum. It has also been found[3] that beryllium or carbon adjacent to aluminum reverses the effect, i. e. the aluminum dose is enhanced when the beam penetrates the beryllium first and reduced for the opposite photon direction. Finally, it has been found that micron layers of high atomic number materials produce a readily observable effect as shown in Fig. 3.

It is important to note that the results described were obtained with ionization chambers. We must be careful in assuming that other phenomena, such as electron-hole pair production in semiconductors will behave in the same way in the transition zone near an interface. If we are interested in applying ion chamber data to solid state devices it is desirable to show that the response of the latter can be predicted from the former. That was the primary objective of the work reported here.

Solar cells were selected for examining the possibility of predicting device response. The interface conditions studied were similar to those studied with ionization chambers. The results obtained indicated that ionization chamber data could be employed to predict device response. Calculations were then carried out for solar cells with base contacts of several different materials.

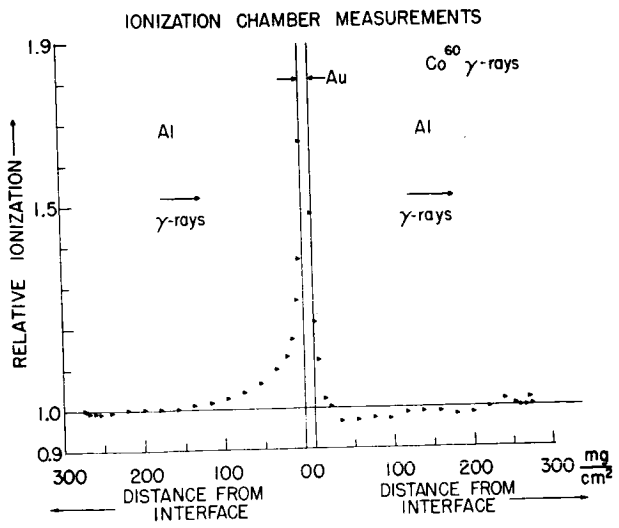


FIGURE 3. - Air Ionization Measurements of Dose Perturbations Near a Thin Gold Film.

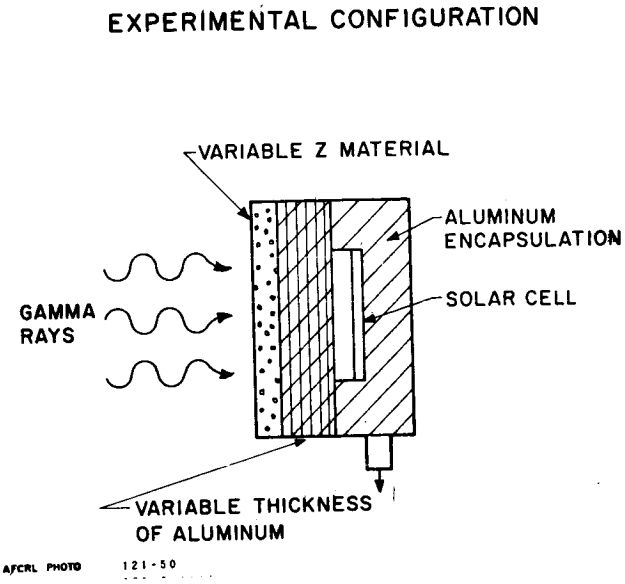


FIGURE 4. - Experimental Configuration Used in Solar Cell Measurements.

EXPERIMENTAL

The devices employed were 1 x 2 cm, N/P silicon solar cells with 0.5 μm junction depth and a 2.5 Ω-cm base resistivity. The diffusion length of minority carriers in the base was determined by exposing the cells encapsulated in aluminum (to establish equilibrium dose conditions) to a Co-60 gamma source and measuring the short circuit current. The dose rate was established with a calibrated ionization chamber and the minority carrier production rate calculated assuming that 3.6 eV are required to produce an electron-hole pair[4]. Typical diffusion lengths for undamaged cells were in the vicinity of 140 μm.

The sample holder employed in the solar cell exposure is shown in Fig. 4. The cell was mounted in a recessed aluminum plate whose thickness exceeded the range of the highest energy electrons generated by Co-60 gamma radiation. In the experiments reported here the base contact was adjacent to the aluminum plate. Aluminum foils of variable thickness could be placed between the face of the cell and the gold or beryllium plates used in the interface studies. Rotation of the sample mount through 180° permitted the response to be determined for both beam directions.

A 16 kilocurie Co-60 source was employed in the irradiations. Both collimated and uncollimated photon beams yielded the same results within the uncertainty of the measurements. In order to normalize the data the cell response was measured with aluminum replacing the gold or beryllium end plate.

COMPARISON OF CELL RESPONSE WITH IONIZATION CHAMBER RESULTS

The short circuit current as a function of aluminum foil thickness was normalized to the current observed with the cell completely encapsulated in aluminum. Results are shown for both gold and beryllium end plates and for two beam directions in Figs. 5 and 6. As can be seen the response is qualitatively similar to the ion chamber results. The difference can be attributed to the solar cell thickness (0.038 cm) which represents a significant fraction of the distance over which the dose perturbation occurs. If the ion chamber results are a true indication of the dose rate the carrier generation rate will not be uniform through the cell. We can make a quantitative comparison by adopting an approach similar to that used in calculating the spectral response of solar cells[5].

For electrons in the p type base the form of the continuity equation applicable is

$$G_n - U_n + \frac{1}{q} \operatorname{div} \vec{J}_n = \frac{\partial n}{\partial t} \qquad (1)$$

where n is the excess minority carrier concentration in the base, $\vec{J}_n$ the current density, G_n and U_n are the minority carrier generation and recombination rates, and q is the charge on an electron. For steady state conditions, zero electric fields, low injection and one dimensional geometry Eq (1) simplifies to

$$G_n - \frac{n}{\tau_n} = - D_n \frac{\partial^2 n}{\partial x^2} \qquad (2)$$

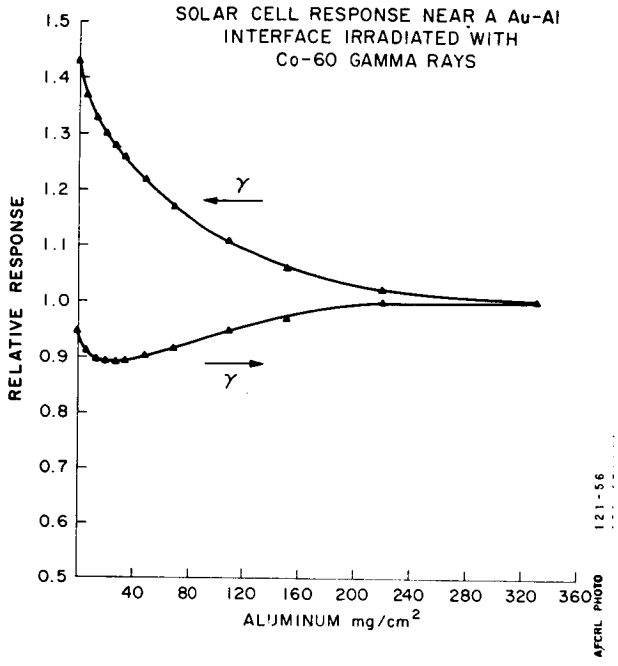


FIGURE 5. - Measured Solar Cell Response Near a Au-Al Interface.

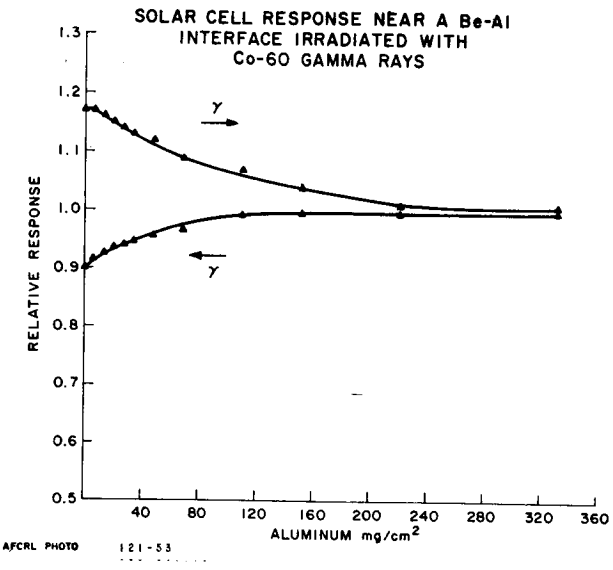


FIGURE 6. - Measured Solar Cell Response Near a Be-Al Interface.

where τ_n is the lifetime of minority carriers and D_n the diffusion coefficient. The normalized ionization chamber data can be fitted with an exponential series to within a few percent. If we assume that the generation rate is given by the same function we have

$$G_n = G_o \sum_m A_m e^{-\alpha_m (x + x_1)} \qquad (3)$$

where the values of the coefficients for beryllium, copper and gold are given in Table I, x_1 is the thickness of aluminum between the end plate and the face of the cell and x any point within the cell as measured from the cell face. The solution to Eq. 2 is

$$n = C_1 e^{x/L} + C_2 e^{-x/L} + G_o \sum_m B_m e^{-\alpha_m (x_1 + x)} \qquad (4)$$

where

$$B_m = \frac{A_m}{D_n} \left(\frac{1}{L_n^2} - \alpha_m^2 \right)^{-1} \qquad (5)$$

and L_n is the diffusion length which is equal to $\sqrt{\tau_n D_n}$. If we assume that the excess minority carrier concentration is zero at the junction and at the base contact, i.e., n = o at $x = \ell$ and x = b, then

$$C_1 = \left(e^{b-\ell/L} - e^{\ell-b/L} \right)^{-1} \cdot \qquad (6)$$

$$G_o \sum_m B_m \left(e^{-\alpha_m (x_1 + \ell) - b/L} - e^{-\alpha_m (x_1 + b) - \ell/L} \right)$$

and

$$C_2 = -\left(e^{b-\ell/L} - e^{\ell-b/L} \right)^{-1} \cdot \qquad (7)$$

$$G_o \sum_m B_m \left(e^{-\alpha_m (x_1 + \ell) + b/L} - e^{-\alpha_m (x_1 + b) + \ell/L} \right)$$

The diffusion current from the base is given by

$$J = q D_n \left. \frac{dn}{dx} \right|_{x = \ell} \qquad (8)$$

TABLE I. Coefficients for the Empirical Fit to Ionization Chamber Measurements of Energy Deposition Profiles in Aluminum Adjacent to Beryllium, Copper, and Gold.

$$\text{Relative Dose} = \sum_m A_m e^{-\alpha_m x}$$

In all cases $A_1 = 1.0$ $\alpha_1 = o$

Beam Direction High Z → Low Z

End Plate	A_2	A_3	A_4	α_2	α_3	α_4
Be	-0.159	-0.075	0	0.0213	0.137	0
Cu	-0.183	0.192	0	0.0094	0.0749	0
Au	-0.262	0.255	0.284	0.0097	0.0408	0.351

Beam Direction Low Z → High Z

End Plate	A_2	A_3	A_4	α_2	α_3	α_4
Be	0.283	-0.836	0	0.0122	0.0325	0
Cu	0.204	0.293	0	0.0172	0.334	0
Au	0.526	0.231	0.249	0.0144	0.0998	0.346

When $\ell \ll L$ the ratio of the diffusion current $J(x_1)$ to that for uniform ionization J_o, is given by

$$\frac{J(x)}{J_o} = \frac{D_n}{L^2} \frac{1}{(\beta+\alpha)} \cdot \sum_m B_m e^{-\alpha_m (x_1+\ell)} \left[\beta - \alpha e^{-\alpha_m (b-\ell)} - \alpha_m L \right] \qquad (9)$$

where $\beta = \coth (b/L)$
$\alpha = \operatorname{csch} (b/L)$

The results obtained from Eq. (9) are compared with the normalized solar cell response of a cell which had a measured diffusion length of 140 ± 15 μm in Figs. 7 and 8 for gold and beryllium the normalized results agree within a few percent. The calculated relative sensitivity of the result to the diffusion length for these cases is shown in Figs. 9 and 10.

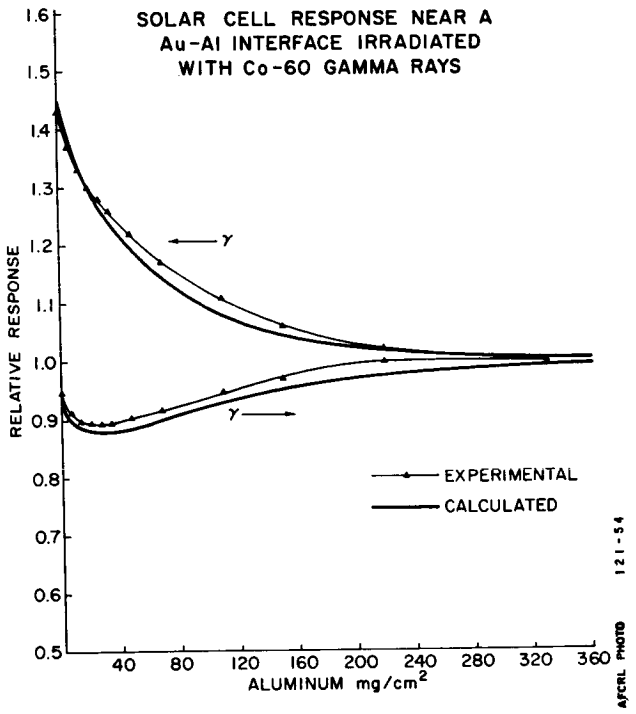


FIGURE 7. - Comparison of Measured Solar Cell Response Near a Au-Al Interface and Calculations Based Upon Ionization Chamber Measurements.

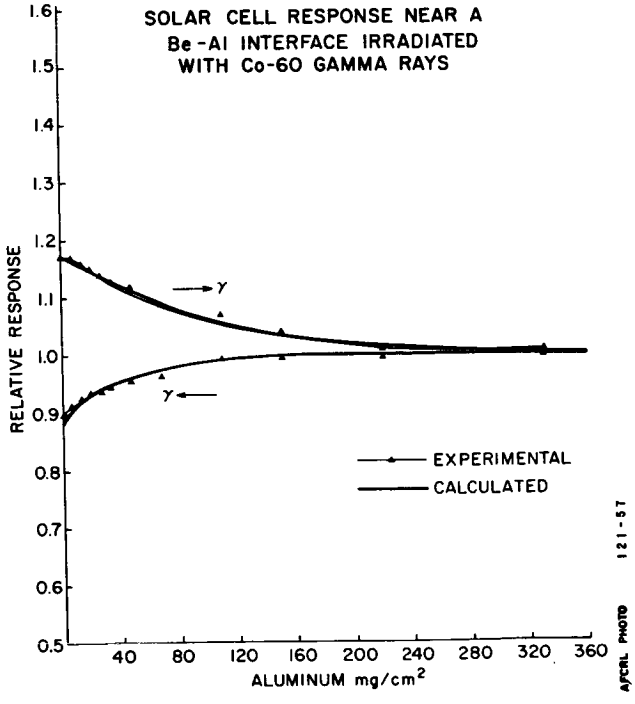


FIGURE 8. - Comparison of Measured Solar Cell Response Near a Be-Al Interface and Calculations Based Upon Ionization Chamber Measurements.

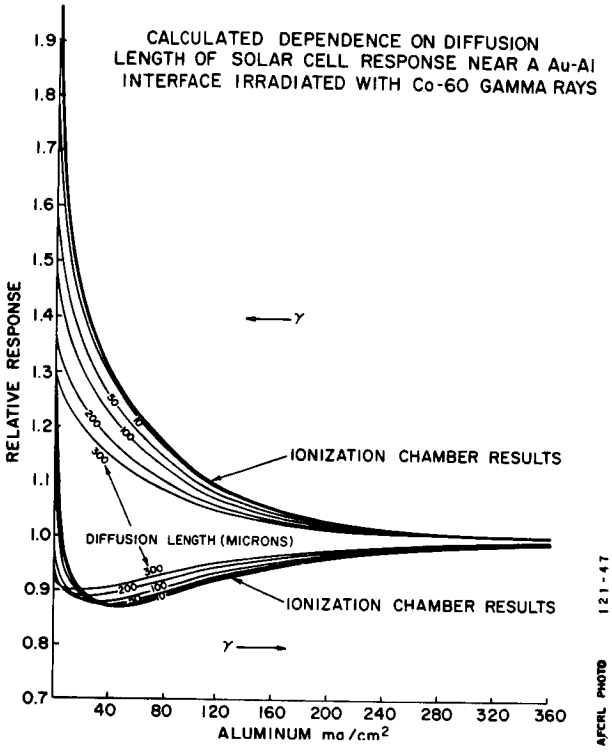
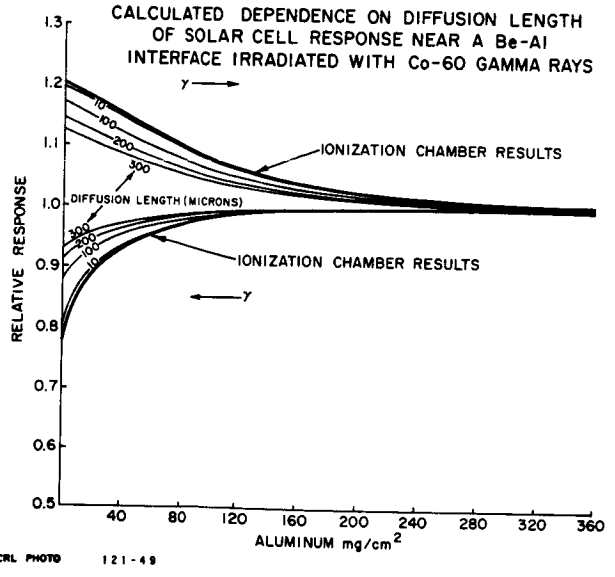


FIGURE 9. - Calculated Influence of Diffusion Length Upon Solar Cell Response Near a Au-Al Interface.



16-10 1302-307

FIGURE 10. - Calculated Influence of Diffusion Length Upon Solar Cell Response Near a Be-Al Interface.

CALCULATED SOLAR CELL RESPONSE FOR VARIOUS BASE MATERIALS

Since calculations of solar cell response based upon ionization chamber data agreed well with measurements when the interface was adjacent to the cell face, they were extended to the more realistic situation where the material was adjacent to the base contact. This requires a modification of Eq. (9) as follows

$$\frac{J(x)}{J_o} = \frac{D_n}{L^2}\,\frac{1}{(\beta+\alpha)}\cdot$$

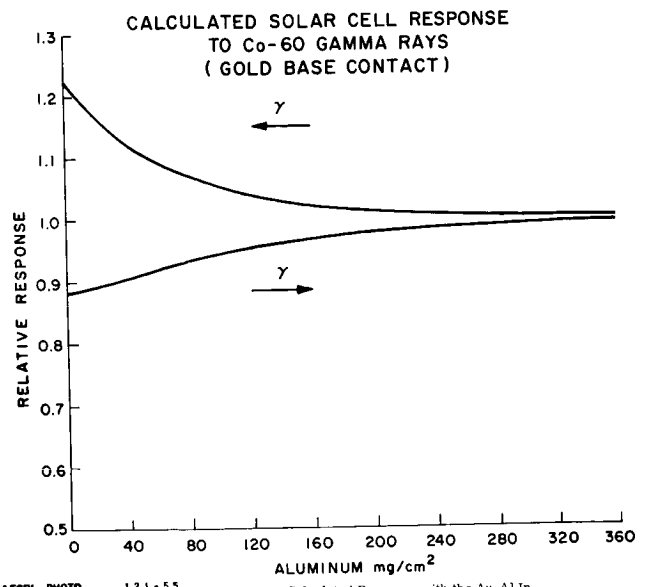
$$\sum_m B_m e^{-\alpha_m(x_1+b-\ell)}\left[\beta - \alpha e^{-\alpha_m(\ell-b)} - \alpha_m L\right] \qquad (10)$$

In this case x_1 is the thickness of aluminum interposed between the base contact and the interface. All other quantities are the same as those employed in Eq. (9).

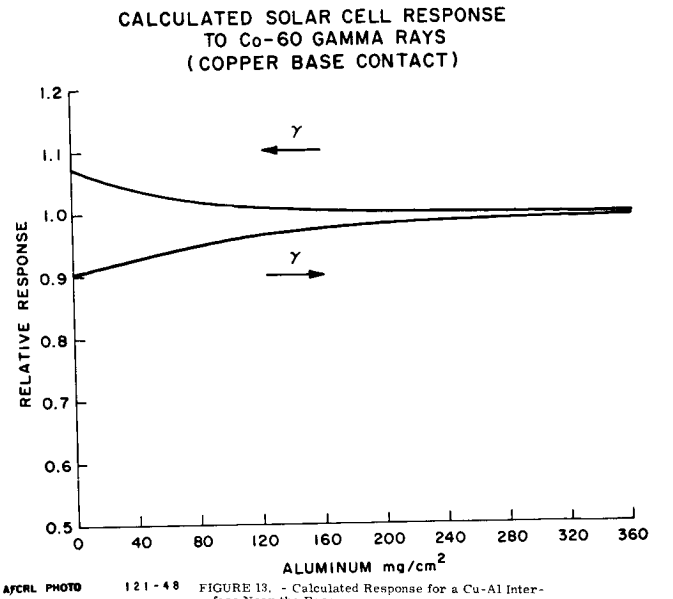
Calculations based on Eq. (10) are shown in Figs. 11-14. As might be expected the perturbation is largest for a thick (> 0.02 cm) gold base. When the beam enters through the cell and exits from the gold the response is 23% larger than it would be for an aluminum base contact. The reversed beam yields a result which is 12% lower than it would be for aluminum. Even 6 μm of gold produces an effect. The influence of copper and beryllium are smaller than for thick gold but readily noticeable. It is interesting to note that when the beam enters through the beryllium contact the response is approximately 12% greater than it would be for an aluminum base contact. Low atomic number elements can enhance the response if the beam traverses them before entering the device.

SUMMARY

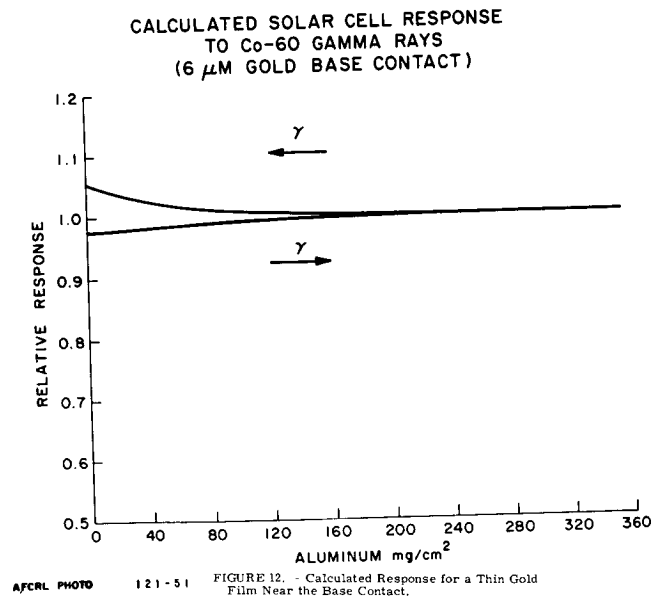
It has been found that ionization chamber measurements of dose perturbations in aluminum adjacent to gold and beryllium can be used to predict the response of silicon solar cells near the same materials. The influence of gold, copper, and beryllium base contacts was then calculated for N/P silicon solar cells exposed to Co-60 gamma rays. Strong directional effects are evident in all cases. The response can be enhanced by both high and low atomic number materials depending upon the direction of the gamma beam. For the cells examined here the response as a function of beam direction varied as much as 40%. Ionization chamber measurements indicate that at Co-60 gamma energies (~ 1.25 MeV) the interface effects could be as large as a factor of two.



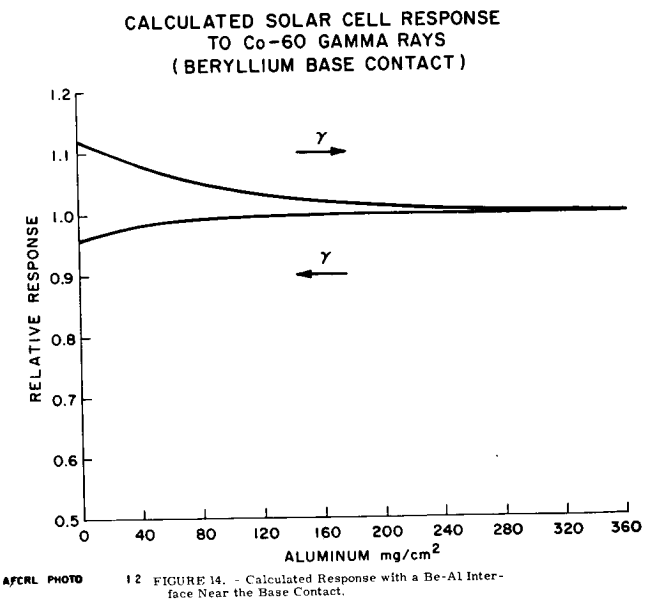
AFCRL PHOTO 121-55 FIGURE 11. - Calculated Response with the Au-Al Interface Near the Base Contact. The thickness of aluminum indicated lies between the gold and the base. Arrows indicate the beam direction relative to the cell face.



AFCRL PHOTO 121-48 FIGURE 13. - Calculated Response for a Cu-Al Interface Near the Base.



AFCRL PHOTO 121-51 FIGURE 12. - Calculated Response for a Thin Gold Film Near the Base Contact.



AFCRL PHOTO 12 FIGURE 14. - Calculated Response with a Be-Al Interface Near the Base Contact.

REFERENCES

1. SPIERS, F.W., in Radiation Dosimetry Vol. III, Ahix, Roesch and Tochilin, editors (Academic Press, Inc., N.Y. (1969) p 809-867.

2. DUTREIX, J. and BERNARD, M., Br. J. Radcol. 39, 205 (1966).

3. WALL, J.A. and BURKE, E. A., IEEE Trans. Nuc. Sci., NS17, 305(1970)

4. KLEIN, C. A., J. Appl. Phys. 39, 2029, (1968)

5. RAPPAPORT, P. and WYSOCKI, J. J., in Photoelectronic Materials and Devices, Larach, S., editor D. Van Nostrand Co., Inc. (1965) p. 239-275