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14. Abstract/Notes

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SIMULTANEOUS RADIATION DAMAGE AND THERMAL ANNEALING OF SOLAR CELLS

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ABSTRACT

A phenomelogical theory of the simultaneous radiation damage and first order thermal annealing of space solar cells has been developed. The effective electron fluence and thereby the efficiency reduction of GaAs and InP solar cells are calculated as a function of time for a rectangular pulse model of the space thermal cycle. It is found that the efficiency of GaAs solar cells reduces with time but InP solar cells do not show any reduction in their efficiency.

Solar cells, in space environment, are continuously irradiated by nuclear and electromagnetic particles (principally electrons, protons and photons). These radiations damage the solar cell by creating defects in its material and thereby reduce its efficiency. In addition to radiation damage, the solar cells, used in low earth orbit satellites, are subjected to thermal cycles (periodic temperature variation due to cyclic occurrence of the periods of eclipse and illumination).

Radiation damage of solar cells is an important consideration for almost all the space vehicles which stay in space for a long period of time. In order to increase the useful life of solar cells for these long missions, the study of annealing of radiation damage in space is needed. In space both annealing and radiation damage can occur simultaneously because of the very long duration of radiation compared to the annealing time. In laboratory, we cannot study this simultaneous effect because in laboratory annealing time is much larger than the duration of radiation exposure. Also radiation flux in space is much smaller than the available radiation flux in the laboratory. However, a theoretical study of their phenomena has been made by Heinochet et al[1]. In this paper, we extend this study by including the effect of space thermal cycle.

When the solar cells are bombarded by particle radiations, various types of defects can be produced inside the solar cell material. The number of i^{th} type of defects per unit volume $N_{im}(E)$, produced by the m^{th} type of particles with energy E, can be expressed phenomenologically as

$$N_{im}(E) = \sigma_{im}(E)\ N_a\ \phi_m(E) \quad , \qquad (1)$$

where N_a is the number of atoms per unit volume, $\sigma_{im}(E)$ is the production cross section of the i^{th} type of defects due to m^{th} type of particles with energy E and particle fluence $\phi_m(E)$.

We can express the production cross section $\sigma_{im}(E)$ in terms of the conventional production cross section σ_{ie} due to 1 MeV electrons and the multiplying coefficient A_m (E) as

$$\sigma_{im}(E) = A_m (E) \sigma_{ie} \quad . \tag{2}$$

By substituting Eq. (2) in Eq. (1) and summing over all types of particles and their energies, we obtain the total number of the i^{th} type of defects per unit volume as

$$N_i = \sigma_{ie} N_a \phi_e^{eq} \quad , \tag{3}$$

where

$$\phi_e^{eq} = \sum_{mE} A_m (E) \phi_m(E) \tag{4}$$

can be called the equivalent 1 MeV electron fluence. These defects are produced at the rate of

$$\frac{dN_i}{dt} = \sigma_{ie} N_a \Phi_e \quad , \tag{5}$$

where

$$\Phi_e = \frac{d}{dt} \phi_e^{eq} \tag{6}$$

is the equivalent 1 MeV flux. In space the production rate of defects given by Eq. (5) is reduced by thermal annealing which occurs because of the long duration of radiation exposure compared to the annealing time.

In general, thermal annealing is a complex process. In case of the simplest first order annealing process[1], Eq. (5) must be replaced by

$$\frac{dN_i}{dt} = \sigma_{ie} N_a \Phi_e - \omega_i(t) N_i \quad , \tag{7}$$

where

$$\omega_i(t) = \omega_{oi} \exp(-E_{ai}/ T) \tag{8}$$

is the annealing probability per unit time of the i^{th} type of defects. The quantities ω_{oi} and E_{ai} are the jump frequency and the activation energy,respectively. In Eq. (7) we have introduced the effect of space thermal cycle by taking into account the time dependence of $\omega_i(t)$, which from Eq. (8) appears because of the time dependence of temperature due to space thermal cycle. Eq. (7) is a nonhomogeneous first-order linear differential equation. For the initial boundary condition $N_i(t=0) = 0$, the solution of this equation is

$$N_i = \sigma_{ie} N_a \Phi_e \exp(-\int_0^t \omega_i(t_1)dt_1)\int_0^t \exp(\int_0^{t_1}\omega_i(t_2)dt_2)dt_1 \quad . \tag{9}$$

On summing the above Eq. (9) over the index i, we get the total number of defects per unit volume N as

$$N = \sigma_e N_a \phi_e^{eff}(t) \quad , \tag{10}$$

where

$$\phi_e^{eff}(t) = \Phi_e \sum_i \frac{\sigma_{ie}}{\sigma_e} \exp(-\int_0^t \omega_i(t_1)dt_1)\int_0^t \exp(\int_0^{t_1}\omega_i(t_2)dt_2)dt_1 \tag{11}$$

and $\sigma_e = \sum_i \sigma_{ie}$. On summing Eq. (3) over the index i and then dividing it by the resulting equation, it is easy to see that $\sigma_{ie}/\sigma_e \equiv C_i \equiv N_i/N$, the fraction of the i^{th} type of defects in absence of annealing.

The effective electron fluence ϕ_e^{eff}, given by Eq. (11), is the laboratory electron fluence which would produce the same number of defects in absence of annealing. It provides a means of comparing the damage produced by the simultaneous radiation exposure and thermal annealing in space to the damage produced in laboratory by 1 MeV electron radiations. To calculate the effective electron fluence, we need to know the equivalent electron flux Φ_e, the annealing probabilities $\omega_i(t)$ and the fractions C_i. The quantities $\omega_i(t)$ and C_i can be obtained experimentally and the Φ_e can be estimated from Eq. (4).

As an application of the above theory, we consider an equivalent 1 MeV electron flux Φ_e equal to 2.5×10^7 electrons $cm^2 sec^1$ which is an upper bound of the integrated trapped electron flux of energy greater than 0.1 MeV in geostationary orbit. This figure can be considered as a good representation of the upper bound of the equivalent 1 MeV electron flux in geostationary orbit, because in this orbit the radiation damage in solar cells is caused mainly by electrons. We have calculated the effective electron fluence for GaAs and InP solar cells studied by Yamaguchi et al.[2] who have obtained ω_{oi} and E_{ai} for the major defect having the fraction C_i equal to about 0.95. In our calculation, for simplicity, we have taken $C_i = 1$ and thus have neglected the effects of other defects which constitute only 5% of the total defects. For space thermal cycle, we have assumed a rectangular pulse model shown in Fig. 1. This model replaces temperature variations during periods of eclipse and illumination by a constant average values. For the period of eclipse, the temperature is taken as 200^oK, and for the period of illumination, three temperatures 300^oK, 330^oK and 360^oK are considered. Calculation is done for three thermal cycles: (1) a = 0, b = 24 hours; (2) a = 1.2 hours, b = 22.8 hours; (3) a = 30 minutes, b = 70 minutes. Here a and b are the periods of eclipse and illumination, respectively. First two thermal cycles correspond to geostationary orbit with and without eclipse and the thrird cycle correspond to the low earth orbit.

In Figure 2, we have plotted the effective electron fluence ϕ_e^{eff} for both GaAs and InP solar Cells. For GaAs solar cells no detectable change has been found due to variation in temperature and period of thermal cycle. On the other hand, for InP solar cells ϕ_e^{eff} reduces with the raise in temperature of the period of illumination.

In the low Earth orbit, Φ_e^{eff} is found to be higher than the geostationary orbit.

To calculate the efficiency of GaAs and InP solar cells as a function of time, we need to know the experimental results of efficiency as a function of 1 MeV electron fluence. Yamaguchi et al[2] have measured the efficiency of GaAs solar cells as a function of 1 MeV electron fluence and that of InP solar cells as a function of $^{60}Co\gamma$ rays fluence. In GaAs solar cells, they have also found that the damage caused by 1 MeV electron fluence is equivalent to about 2×10^2 times $^{60}Co\gamma$ rays fluence. Since for our calculation we need the efficiency of InP solar cells as a function of 1 MeV electron fluence, we assume that the relative damage caused by $^{60}Co\gamma$ rays fluence and 1 MeV electron fluence in InP solar cells is the same as that of GaAs solar cells. We believe that this assumption will not affect our qualitative discussion. On comparing our effective electron fluence with 1 MeV electron fluence of Yamaguchi et al[2], we found that for InP effective electron fluence is so low that no reduction in efficiency occurs during the period of 30 years. On the other hand, the efficiency of GaAs solar cells reduces to about 60% during the same period.

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FIGURE CAPTIONS

Figure 1 - Schematic diagram of the rectangular pulse model of the space thermal cycle. Temperature T is plotted as a function of time t; a and b are the periods of eclipse and illumination, respectively.

Figure 2 - All the curves for the GaAs solar cells corresponding to temperatures $300^{o}K$, $330^{o}K$ and $360^{o}K$ of the period of illumination and the space thermal cycles (1), (2) and (3) as described in the text, coincide with the curve A. Curves B, B'; B_1, B_1'; B_2, B_2' are for InP solar cells corresponding to temperatures $300^{o}K$, $330^{o}K$ and $360^{o}K$ of the period of illumination, respectively. The curves B, B_1, B_2 and B', B_1', B_2' correspond to the low Earth orbit (space thermal cycle (3)) and the geostationary orbit (space thermal cycles (1) and (2)), respectively.

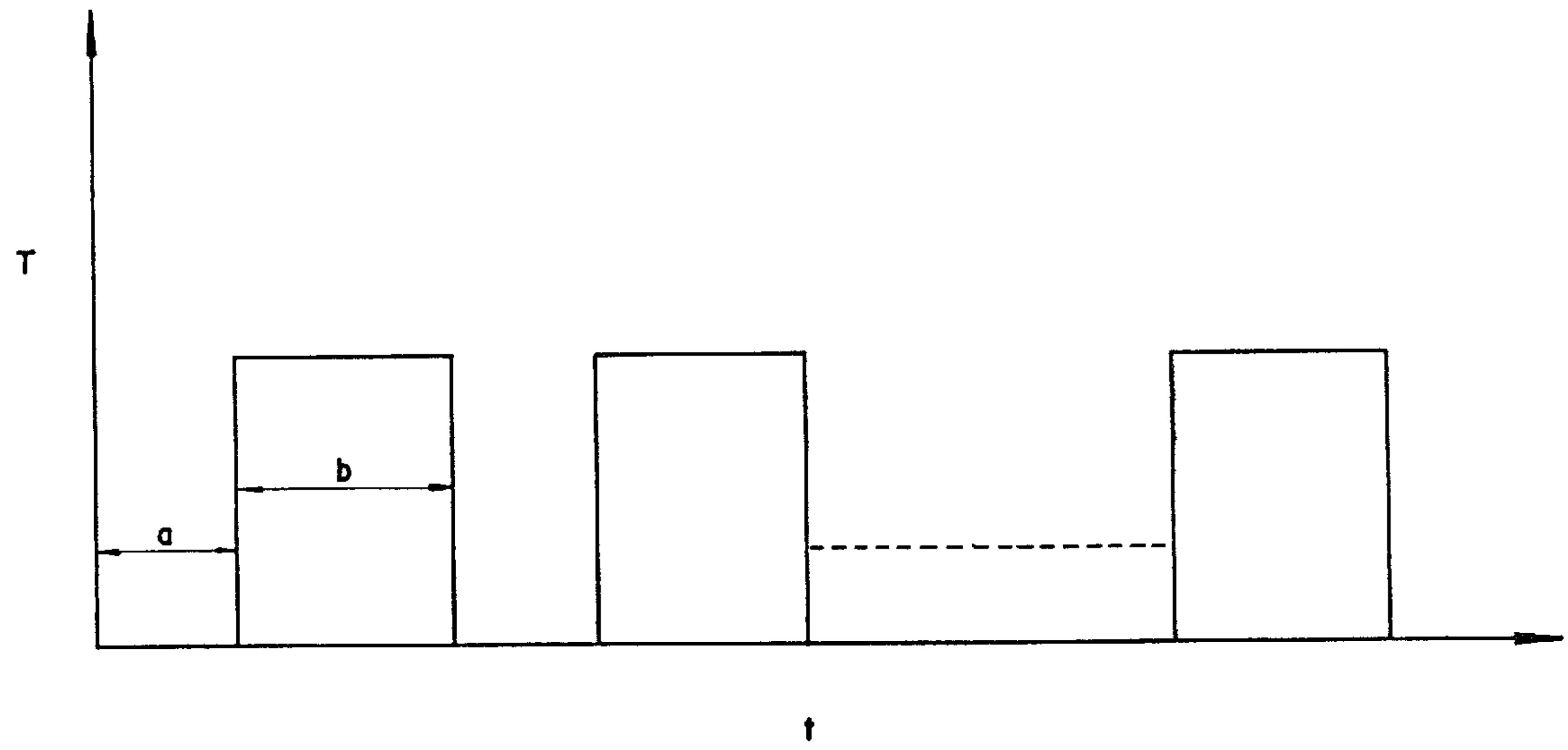
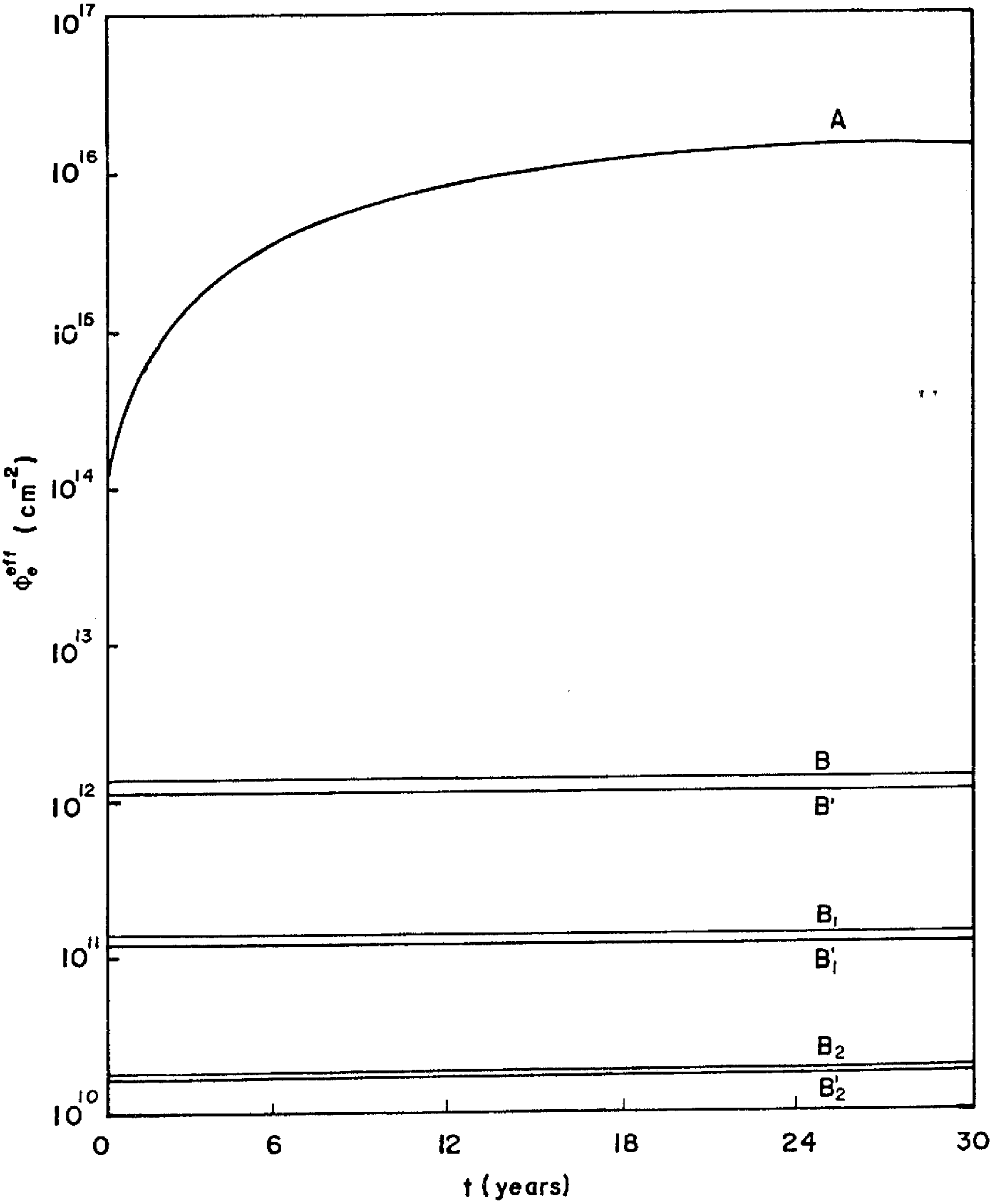


Fig. 1 - R. Kishore.



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