BASIS FOR EQUIVALENT FLUENCE CONCEPT IN SPACE SOLAR CELLS*

A. Meulenberg
COMSAT Laboratories
Clarksburg, Maryland

ABSTRACT

The equivalent fluence concept is defined, and its use and potential problems are noted. Silicon and GaAs solar cells are compared in a radiation environment. The analysis indicates that valid equivalent fluence values may be easier to obtain in GaAs than in silicon.

INTRODUCTION

Solar cells have been modified continually to improve their performance and lifetime for various space missions. Since an accurate simulation of the space radiation environment is very difficult, a means was sought to conveniently irradiate cells and use this information to predict performance in space with reasonable accuracy. For reasons described below, 1-MeV electrons were chosen as the single irradiation source that was both convenient and capable of simulating (at least to some extent) damage caused by the various components of the space radiation environment. Various means have been used to compare the damage to silicon solar cells by different energy protons and electrons with the damage resulting from 1-MeV electron irradiation. The "1-MeV electron equivalent fluence" concept is used to compare the damage calculated or measured for isotropic monoenergetic irradiation with the damage measured for normally incident 1-MeV electrons.

The 1-MeV equivalent fluence concept has been used with silicon cells for years with mixed success. The greatest application has been in standardizing the test procedure for comparing the radiation response of different cell designs or fabrication procedures. The concept has been less successful in the prediction of degradation in space, as explained below. Many problems that are experienced in the equivalent fluence concept for silicon will also be problems for GaAs. Two major questions need to be examined when considering an equivalent fluence model for GaAs:

a. Was the concept really useful enough in the silicon solar cell field to warrant such a concept for GaAs?

b. Is there a convenient and acceptable radiation type that can be used as the basis for comparison of radiation degradation studies in GaAs?

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To answer these questions many factors must be considered. The following is an attempt to construct the appropriate framework for such an effort.

ASSUMPTIONS IN AN EQUIVALENT FLUENCE MODEL

The assumptions of an equivalent fluence model are 1) that a radiation type and energy level exist that, alone, can reproduce the extent and nature of radiation damage from the various space radiation environments; 2) that the space radiation components are known well enough (quantitatively and qualitatively) to substitute an equivalent fluence for the space radiation; and 3) that an equivalent fluence can be determined for all the major components and energies by a reasonable laboratory experiment. To the extent that the first assumption is valid, the model is useful. The third assumption may be false even if the first two are correct.

The major types of radiation damage to present space solar cells all involve displacement of atoms within the single crystal device. (Ultraviolet radiation damage to the solar cell coverslide assemblies is not considered here.) Electrons typically displace single atoms from their lattice site. Protons generally produce single displacements and multiple or "cluster" displacements. Neutrons (which can be ignored in the natural environment) primarily generate large clusters of displaced atoms. Population densities of the space electrons and protons normally decrease rapidly with increasing energy. This preponderance of low energy particles and the fact that they are generally isotropic means that the damage produced is much higher near an exposed surface of a device than in deeper regions within the cell. This nonuniform damage profile is the basis for effective shielding; however, it complicates the equivalent fluence model, which often assumes uniform damage to simplify mathematical analysis.

Different solar cells respond to the various radiation components in different ways. The nature of this damage depends upon the dominant damage mechanisms and the contribution to these mechanisms from each type of radiation. Since solar cells are minority carrier collection devices, reduction of the minority carrier diffusion length is generally the major damage mechanism. However, under certain circumstances, undoping (either by compensation or by coordination of a mobile defect with a donor or acceptor site) may be the primary source of solar cell power loss.

Each satellite orbit has a characteristic blend of electron and proton energies and densities. These energies and densities are not always well known and may even change from hour-to-hour or year-to-year. Under such conditions, the selected environment (the second assumption) will introduce a greater error in damage prediction than that caused by the uncertainties in equivalent fluences. As these environments become better defined by space experiments, the errors in equivalent fluence models can become critical. A major source for such errors is the laboratory experiment used to determine the equivalent fluence of a certain radiation type. Such errors (which influence the third assumption) have been observed to result from nonuniform damage, incorrect damage profiles, dose rate dependence, anneal characteristics, injection level effects, and inappropriate fluence levels. In many cases, the prediction of cell degradation in space by use of equivalent fluence models is very approximate unless the models have been verified or modified by space data for a particular environment. In some cases, the use of an equivalent fluence can be misleading, even for only a comparison of cells, because the critical damage mechanisms may be different for the cells.

EQUIVALENT FLUENCE MODELS FOR SILICON CELLS

In the early 1960's, the concept of 1-MeV electron equivalent fluence values became accepted for damage to silicon solar cells (ref. 1). The Solar Cell Radiation Handbook* has carried on this tradition and tried to update its use. Instead of a historical development of this concept, reasons for present acceptance and reservations will be briefly described.

Cobalt 60 gamma cells and 1.5 → 2.5 MeV electron accelerators are common and easily used without the need for introducing cells into a vacuum system. The ^{60}Co gamma rays generate electrons with maximum energies less than 1 MeV and an average of ~600 keV. This radiation environment would then reproduce the space electron environment damage quite well. However, protons generate defect clusters and the gamma cell does not provide electrons with enough energy to generate more than a minute quantity of non-single displacement defects. The 1-MeV electrons will generate nearly an order of magnitude more divacancies than the gamma cell dose for the same generated electron fluence, and these defects are common in proton irradiated silicon. Use of higher energy electrons will increase the generation of divacancies, but will not provide cluster and higher-order defects necessary to better simulate proton damage. The 1-MeV electron is therefore a good choice for use as the basis for an equivalent fluence when proton generated damage from complex defects is not a major contribution to the total cell degradation.

The relative damage between 1-MeV electrons and other radiation has been determined in two ways (ref. 2). One way is a comparison of cells at the 25-percent degradation point. Cells are irradiated by normally incident protons or electrons of various energies; the fluences required to degrade the AMO I-V characteristics by 25 percent are compared to the fluence of 1 MeV normally incident electrons required to give the same degradation. The main advantages are the simplicity of generating the data and the comparison of data under illuminated conditions as expected in space. One disadvantage is that, in solar cells heavily damaged by a single type and energy of radiation, the nature of the damage is often too different from that generated by a space or 1-MeV electron environment to be realistically compared. Another problem is that the results compare normal incidence vs normal incidence irradiation, not the isotropic vs the normally incident irradiation of the 1-MeV equivalent fluence definition.

A second and mathematically satisfying method of specifying damage is the comparison of minority carrier diffusion lengths at different levels of normally incident monoenergetic irradiation. This latter method has a disadvantage in that the diffusion lengths are generally determined at low injection levels rather than under space illumination levels. This problem can be rectified, but the experiment is thereby made more complicated. In proton irradiated cells, the injection level effect can be as high as 2.5. This means that the equivalent fluence determined at

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low injection levels will be 2.5 x higher than that determined at higher levels (ref. 2).

Both methods of comparing damage are inaccurate when the damage from one or both sources is nonuniform (such as from low energy protons). Another source of error is the annealing or recovery of a portion of the radiation damage. Electron damage typically anneals over several weeks at room temperature, however, proton damage anneals after several days. In space, the damage anneals as it accrues; therefore, data must be compared after annealing is complete when establishing equivalent fluences or predicting degradation in space.

The technique of determining equivalent fluence compares the damage from isotropic monoenergetic radiation to the normally incident 1-MeV electrons (ref. 1). This method requires mathematical manipulation of normally incident radiation data, to calculate isotropic damage (refs. 3-5), or it requires actual isotropic irradiation. The mathematical manipulation is difficult, if no simplifying assumptions are made, and generally incorrect, if they are made. Only a few attempts have been made to actually irradiate solar cells from different angles to simulate an isotropic irradiation (refs. 3, 6, and 7). More efforts in this area have been completed [M. W. Walkden, results to be presented at the Photovoltaic Generators in Space Conference, Bath, England, May 1982] and are planned for 1982.

The mathematical conversion of normally incident radiation damage to isotropic radiation damage requires an accurate description both of the cell damage along the radiation path length and the geometry of the cell and its coverslide assembly. An assumption of equal damage probability along the path length makes calculations easy, but is not valid for protons with energies below ≈40 MeV. In addition to generating the wrong equivalent fluence with this assumption, an incorrect fluence dependence would be calculated for the equivalent fluence. This fluence dependence (fig. 1) is more correctly a diffusion length dependence and simply indicates the portion of a cell over which carriers are collected.

Actual experiments with simulated isotropic monoenergetic radiation will reduce many of the problems associated with the mathematical transformation from normal incidence to isotropic irradiation. Nevertheless, severe problems remain in silicon because the damage is nonuniform throughout the active region, and the solar cell electrical characteristics are generally calculated based on uniform diffusion lengths throughout the base of the cell. To correctly calculate the damage coefficients for nonuniform damage, the nature and profile of the damage must be known and included in the exact diode equations without the assumption of uniformity (ref. 8). The type and/or number of experiments must be increased to fulfill these requirements.

For an idea of the nonuniformities involved for proton damage in silicon, the displacement profiles for normally incident and isotropic irradiation can be examined. Nonpenetrating protons, normally incident on a silicon solar cell, will leave a region near the end-of-range which has a displacement density that may be orders of magnitude greater than in nearby parts of the cell (fig. 2a). An isotropic fluence of protons, with an energy spectrum representative of a solar proton flare environment at synchronous altitudes, would provide a factor of 5 to 10 difference in the displacement density from one side of the cell to the other (fig. 3). The narrow, heavily damaged region of the normally irradiated cell is somewhere within the cell bulk; its position depends upon the beam energy. The most heavily damaged region from the space environment is at the exposed surface; the damage gradient depends upon the coverslide thickness. To compound this problem, four types of proton damage in silicon have been identified (ref. 4) and each has a different energy dependence. These different types of damage can also affect the cells differently, depending on the injection level and Fermi level within the cell. It is, therefore, exceedingly difficult to compare a monoenergetic normally incident proton beam (fig. 2a) to a monoenergetic isotropic proton beam (fig. 2b); however, this comparison is required to calculate an equivalent fluence from laboratory data. Ironically, the damage profiles from the space proton and electron environments are more similar than those produced by the laboratory sources. Therefore, an equivalent fluence is more accurately provided by comparing cell degradation in space with degradation by 1-MeV electrons in the laboratory. Unfortunately, this technique does not provide a good basis for a significantly different environment.

Two cases are mentioned as examples of using the equivalent fluence for predicting proton degradation of silicon solar arrays. The August 1972 solar flare was observed to degrade a number of solar panels on the INTELSAT IV series. Analysis of the degradation indicated much higher proton fluences than were then recorded by experiments on board ATS-1. When final corrections to the ATS-1 data were published a year later, the results were in excellent agreement with the numbers predicted by analysis (which involved use of the 1-MeV equivalent fluences) of the array degradation made one month after the event.

The second case is the solar cell experiment (ref. 9) on NTS-1, which followed an inclined orbit at 13,529 km. The observed cell degradation was much greater than that predicted from laboratory data and the equivalent fluence model.

What accounts for the apparent success of the equivalent fluence model in the first case and the gross failure in the second? A series of mistakes, made from necessity, canceled themselves out in the successful case, but showed up in the failed case. What mistakes can be identified in retrospect in the analysis and why did they occur?

The following are possible reasons:

a. The only equivalent fluence values available were based on a simplistic model of radiation damage for 1 Ω-cm cells (but based on space data) from 1963 (ref. 1). The INTELSAT IV flight cells were 8-10 Ω-cm and fabricated nearly a decade later.

b. The proton energy spectrum for synchronous altitudes was based on limited data obtained for solar proton flares during cycle 19. These data are overly severe in the low energy region (<10 MeV), thereby increasing the predicted damage.

c. The third mistake, which compensated for the second, was in the modeling of the equivalent fluence which underestimated the equivalent fluence values for 1 Ω-cm cells. These mistakes canceled out in this case for synchronous orbit.

When the equivalent fluence model failed, conditions were different. The cells examined were ~2 Ω-cm; therefore, no significant uncertainty in the damage for different resistivities was encountered. The environment model did not have a bias in the most damaging proton energy range, which would increase the predicted damage. The equivalent fluence values were the same as those in the first case; but this time, there were no overestimated environment values to compensate for the incorrect model.

This incorrect model is still being used by many people because, for synchronous orbit, the results have not yet been proven false. Since the damage from protons for cells and coverslides >8 mils is less than that from electrons (even in the worst case), the errors in the model are not likely to be overly important. As cells, coverslides and back surface protection become thinner ($\lesssim$4 mils each), proton damage will begin to dominate. The environment is constantly being refined, and margins for error are constantly being reduced as spacecraft design is optimized. These trends indicate abandonment of the present equivalent fluence values and models unless someone is willing to pay for a corrected version. Many people who predict space degradation have in-house computer damage models and/or have an experimental base for their predictions. However, based on the above arguments, none of the published values or models for 1-MeV equivalent fluence values for single energy proton (and probably electron) damage to silicon appear to be correct (ref. 5).

GaAs VERSUS SILICON

It was pointed out in the previous section that for silicon, the concept of equivalent fluences, as presently defined, can vary from being a useful fiction to being a potentially dangerous trap. The situation may be different in GaAs for several reasons; some make it worse, some better.

The active region for GaAs cells is generally 5-10 µm compared to the >200 µm beginning-of-life active region of a silicon solar cell. This means the following:

a. The influence on cell behavior from nonuniformities in normally incident proton damage observed in silicon is apparent at much lower energies in GaAs cells.

b. The damage difference from front to back of the active region of a GaAs cell in the space environment is negligible; therefore, an assumption of uniform damage is reasonable for GaAs cells, but not for Si cells.

c. The active region being limited to near the surface in GaAs cells implies that the average radiation within the active volume from the space environment is greater in a GaAs cell than in a silicon cell, even if the coverslide protection is identical.

The damage mechanisms for GaAs and Si cells are different:

a. The voltage and fill factor in GaAs cells are generally dominated by junction recombination ($n = 2$) (ref. 10), compared to the bulk recombination dominance in silicon cells ($n = 1$).

b. For uniform radiation damage, this dominance by the junction recombination in GaAs cells does not change (ref. 11).

c. The nature of damage in silicon has been found to be fluence dependent (ref. 12); the damage in GaAs has been found to be fluence dependent (ref. 11) and dose rate dependent [Li et al., and Loo et al., to be presented at the 16th PVSC, San Diego, California, September 1982).

d. Present GaAs solar cells generally have a different spectral response degradation under irradiation than silicon solar cells, which show only degradation from the red end. The fact that the GaAs cells degrade throughout the full spectral range [the extent in each region depending upon the junction depth (ref. 11)], further complicates the prediction of space degradation for these cells.

After a survey of the differences between GaAs and silicon solar cells, it seems that an equivalent fluence would be easier to define and properly use in GaAs than in silicon. The critical factor would appear to be the relative uniformity of the space radiation damage throughout the active region of the GaAs cell. It may well be that 1-MeV electrons are not the preferred basis for the equivalent fluence. The 1-MeV protons at low fluence might be a better choice, although the electrons at high flux might provide an adequate simulation of proton damage.

CONCLUSIONS

The 1-MeV electron equivalent fluence concept has been often used, and misused, in place of an understanding of space radiation effects in silicon solar cells. A large quantity of laboratory data is being generated on radiation characteristics of GaAs solar cells, but until more space data become available and integrated with the laboratory data, an equivalent fluence concept is premature. Unless these tests are correctly interpreted (and hopefully correctly conceived), the equivalent fluence values determined for GaAs will be an unmarked scale, only useful to compare observed space data with some arbitrary laboratory radiation type and energy. In answer to the questions posed in the introduction, the 1-MeV electron equivalent fluence concept has been useful in silicon space cells despite its shortcomings; and, at least for many environments, a convenient and acceptable radiation type can probably be found to provide equivalent fluences for GaAs solar cells in space.

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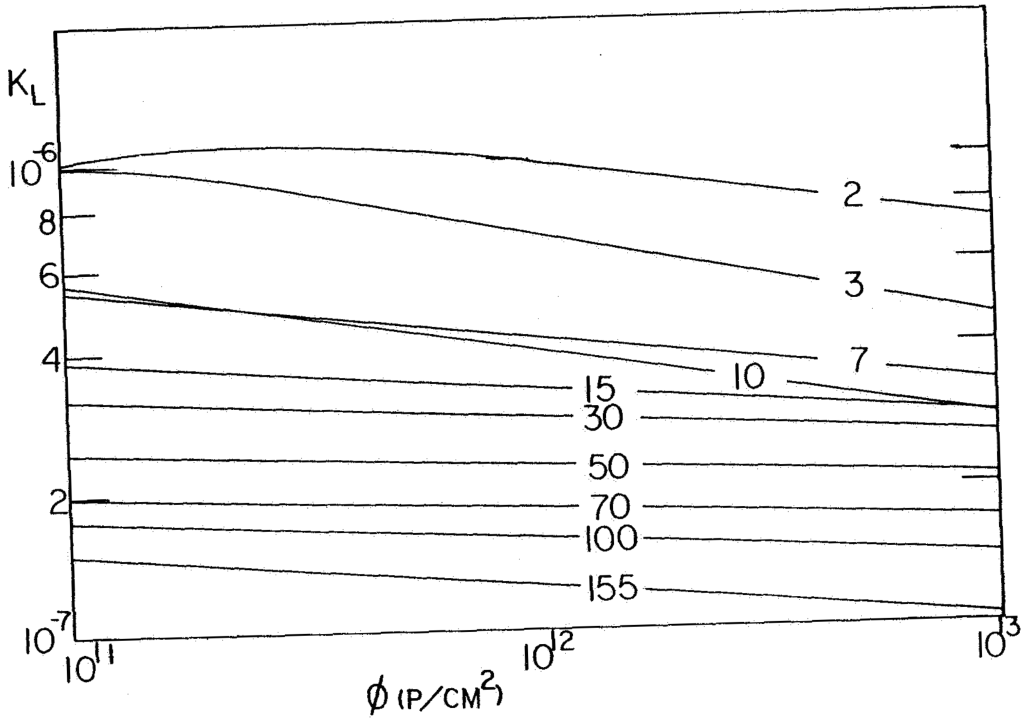

Figure 1. Diffusion Length Damage Coefficients vs Proton Fluence for Bare Cell Sets Measured at Low Injection Levels. The Curves are Labeled by the Incident Proton Energy in MeV.

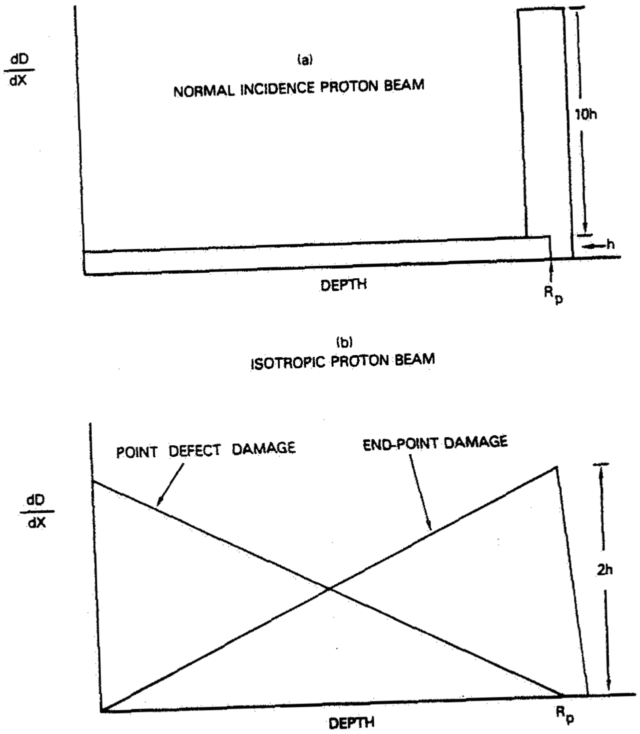

Figure 2. Damage Depth Profiles for Normally and Isotropically Incident Protons. The Proton End-of-Range is Denoted by R_p.

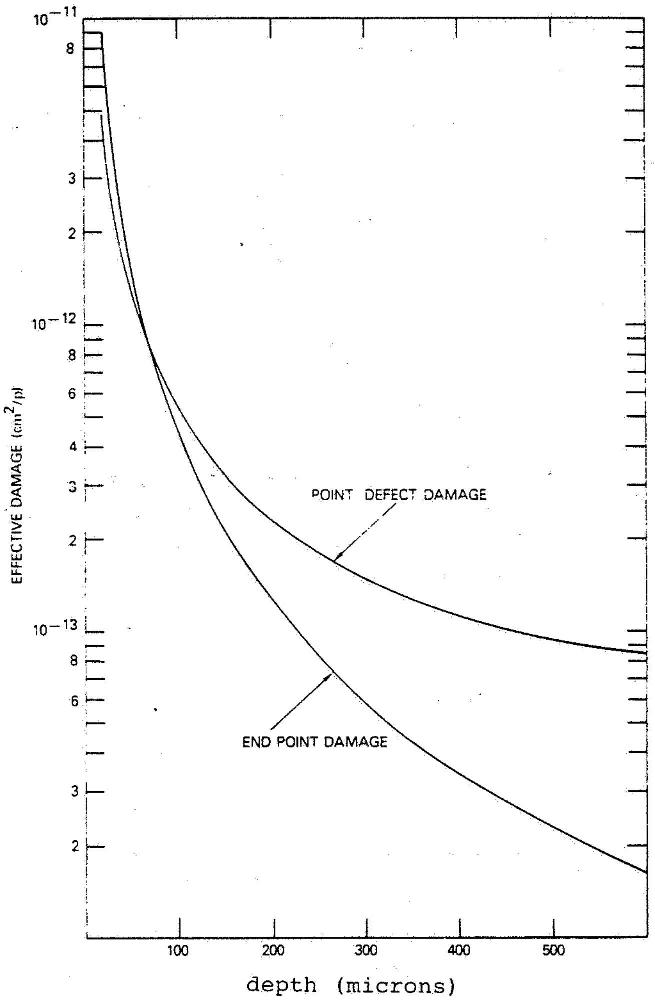

Figure 3. Components of Damage (Low Injection Level) from Solar Flare Protons at Synchronous Altitudes vs Depth into Silicon. The Relative Magnitude of the Components is Not Yet Determined (see text)