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Development of Tandem Cells Consisting of GaAs Single Crystal and $CuInSe_2$/CdZnS Polycrystalline Thin Films

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Summary

The tandem cells consisting of GaAs single crystal and $CuInSe_2$ polycrystalline thin films are being developed under the joint program of the Boeing Co. and Kopin Corp. to meet the increasing power needs for future spacecraft. The updated status of this program is presented along with experimental results such as cell performance, and radiation resistance. Other cell characteristics including the specific power of and the interconnect options for this tandem cell approach are also discussed.

Introduction

Energy demands for future spacecraft are expected to increase significantly. The development of high-efficiency, light weight, and radiation resistant photovoltaic arrays is required to meet these demands. The Boeing Co. and Kopin Corp. have been jointly developing mechanically stacked tandem cells based on GaAs(AlGaAs) top cells and $CuInSe_2$(CIS) lower cells to address these requirements.

The thin film GaAs(AlGaAs) has been chosen as top cell due to its high efficiency and good radiation resistance. The CIS cell has been chosen as bottom cell due to its excellent radiation hardness, high optical absorption coefficient, and optimal bandgap value in combination with an AlGaAs top cell. Since both cells are incorporated as thin films, the specific power of this tandem is expected to be extremely high. In addition, this tandem cell approach provides interconnect flexibility to permit more efficient arrays since each cell is fabricated and tested independently and can be selectively matched. In this paper, we discuss the characteristics of these cells and present the current status of this program.

Tandem Cell Fabrication

The structure of the tandem cell under development is shown schematically in Figure 1. It consists of a double heterostructure GaAs/AlGaAs CLEFT top cell mechanically stacked on a CdZnS/$CuInSe_2$ thin film bottom cell. Fabrication of the cell is accomplished in a similar manner to the one described elsewhere [ref.1].

The very thin GaAs single crystal film (10 μm thick) is fabricated by the CLEFT technique [ref.2] and the layers of p^+ AlGaAs, p GaAs base, n GaAs emitter, n^+ AlGaAs window, and n^+ GaAs cap are grown by OMCVD [ref.3] to form a double-heterostructure. After the front face of the cell is processed, a support is mounted to the cell and the thin film is separated from the bulk GaAs. Grid deposition and anti-reflection coating, and etch removal of inactive GaAs film complete the top cell fabrication.

The CIS lower cell is fabricated by sequential deposition directly onto a glass substrate of a Mo electrode, $CuInSe_2$ absorber, and CdZnS window and metallic contact grid. The $CuInSe_2$ film is deposited by a simultaneous elemental coevaporation process and the CdZnS film is deposited by coevaporation of the CdS and ZnS binary compounds [refs. 4 and 5].

Mechanical stacking of the top cell and the bottom cell is accomplished using a space qualified optical adhesive to form the final structure consisting of a coverglass and the subcells. Interconnecting the top cell grids to contact pads on the CIS cell substrate completes fabrication of the tandem cell.

Tandem Cell Characteristics

Efficiency

The best performance of this tandem approach that we have achieved so far is 20.3%* (20.5%) AM0 for a four terminal 1 cm^2 cell design. The results of this cell are shown in Figure 2. The subcell efficiencies were 18.1% and 2.2%* (2.4%) for the GaAs top cell and the CIS bottom cell respectively. Measurements were conducted at 28°C, with a Xenon solar simulator intensity setting of 137.2 mW/cm^2. The external quantum efficiency measured with the same cell is shown in Figure 3. Exact optical loss mechanisms for the bottom cell are being investigated and the tandem stack is being further optimized. Details of this work will be published at a later date.

Earlier projections using the combination of bandgap values of AlGaAs(1.75 eV) and CIS(1.0 eV) predicted the maximum efficiency of 32.9% [ref.6]. Using a realistic tandem cell model, we expect to achieve 22.7% AM0 cells with our current cell structure(GaAs/CIS) in the very near future. When combined with a high quality AlGaAs top cell, further improvement of efficiency up to 26% AM0 is anticipated.

Radiation Hardness

Radiation resistance of this tandem cell is expected to be superb. In order to assess the radiation effects on these cells, bare CIS and bare GaAs solar cells were fabricated, and submitted for radiation experiments using facilities at Boeing Radiation Effects Laboratory(BREL).

*Adjusted for white light response of the lower cell (suspected to be due to light trapping in the layers between cells)

The experimental results on the normalized power degradation for CLEFT GaAs and CIS cells as a function of irradiation fluence are shown respectively in Figure 4 and Figure 5. These results reaffirmed our previous report [refs.1 and 7] that the CIS cells have superior radiation hardness when compared to Si and GaAs solar cells. The illuminated I–V curves measured on the 1.0 and 2.0 MeV electron radiation samples of CIS exhibited a negligible degradation at all fluences. The CIS cells showed much more resistance to proton radiation than GaAs or Si cells as shown in Figure 6. We also observed a recovery of the CIS performance to near pre-irradiation values with samples stored at room temperature and ambient pressure. The results of radiation experiments on the GaAs cells showed comparable values to the ones that have been reported with bulk. We expect, however, somewhat better performance with CLEFT GaAs film on radiation hardness due to its n-on-p structure, the shallowness of junction in these CLEFT cells, and to the thinness of the film. Radiation results on GaAs cells from various reports are plotted for relative comparison in Figure 7. Since radiation effects depend on parameters such as cell structure, operating temperature, initial performance or device parameters and many others, direct comparison is not easily possible. Thus, we have to consider the present comparison of GaAs radiation hardness results as being more relative than absolute.

Based on these results combined with our enhanced solar cell modeling program, however, further improvement is expected with GaAs cell structure optimization. Even further improvement of radiation hardness is expected when an AlGaAs top cell currently being evaluated, is included in the tandem stack.

Weight

One distinct advantage of this approach is found in weight consideration. Compared to conventional approaches involving cell growth on a bulk substrate, this tandem utilizes the CLEFT technique to fabricate a very thin GaAs film. Combined with the thin-film CIS cell directly deposited onto thin glass, we expect the weight of a 4 cm^2 tandem cell including coverglass to be 190 mg, as shown in the Table 1. With the efficiency of 20.5% already achieved, this provides specific power of 590 W/kg. When a projected efficiency of 26% is used, we expect specific powers upto 750 W/kg in these cells.

Interconnect Options

Since this tandem cell is mechanically stacked, it provides considerable interconnection flexibility. Using the four terminal approach, each cell can be fabricated with high processing yields, optimized independently and then selected for array level optimization. Since it is not series-interconnected, degradation of each cell due to radiation and/or operating temperature would have less impact on the other, especially when the array is configured in voltage matching condition. It is known [ref. 8] that voltage matching offers advantages such as less sensitivity to radiation damage, and spectral variation and wider selection of bandgaps for optimal performance. It was found that a configuration of three series connected CIS cells in parallel with a GaAs cell is suitable for voltage matching and this configuration can be realized at either the module (tandem cell) level or array level.

Tandem Cell Optimization

In addition to our current effort toward improving the GaAs/CIS tandem cell efficiency by minimizing optical transmission losses, evaluation of AlGaAs/CIS tandem has been undertaken for the purpose of achieving higher EOL efficiency. Also being developed is a larger area(4 cm^2) tandem cell. Masks for both top and bottom cell have been fabricated and initial device fabrication has shown promising results.

Conclusion

The updated status of our GaAs/CIS tandem cell program has been summarized, and the characteristics of cells have been discussed. This tandem cell approach utilizing thin film GaAs single crystal and polycrystalline CIS thin film cells is viable, mature and nearing readiness for implementation in high-performance space power systems.

References

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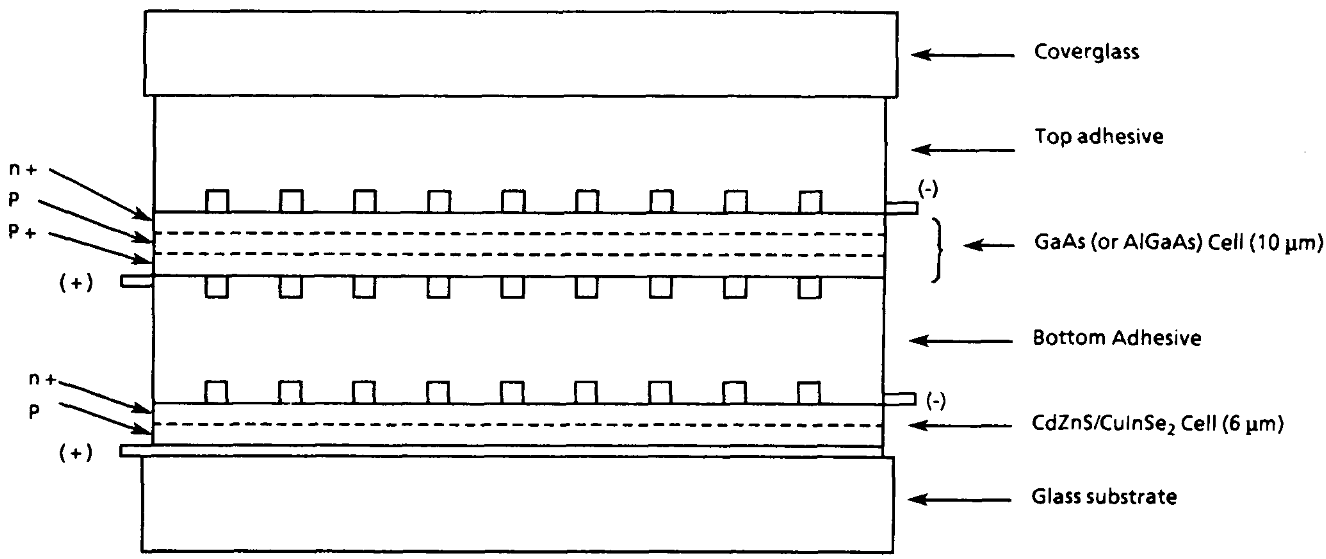
Table 1. Weight of Tandem Cell (4 cm²)

Component	Thickness	Weight
Coverglass	2 mil	53.1 mg
Top adhesive	2 mil	21.6 mg
GaAs CLEFT	10 um	21.2 mg
Bottom adhesive	2 mil	21.6 mg
$CuInSe_2$	6 um	13.0 mg
Glass substrate	2 mil	53.1 mg
Others		3.0 mg
Total		188.0 mg



Vertical dimensions not to scale
(see Table 1 for details)

Figure 1. Schematic of Tandem Cell Structure

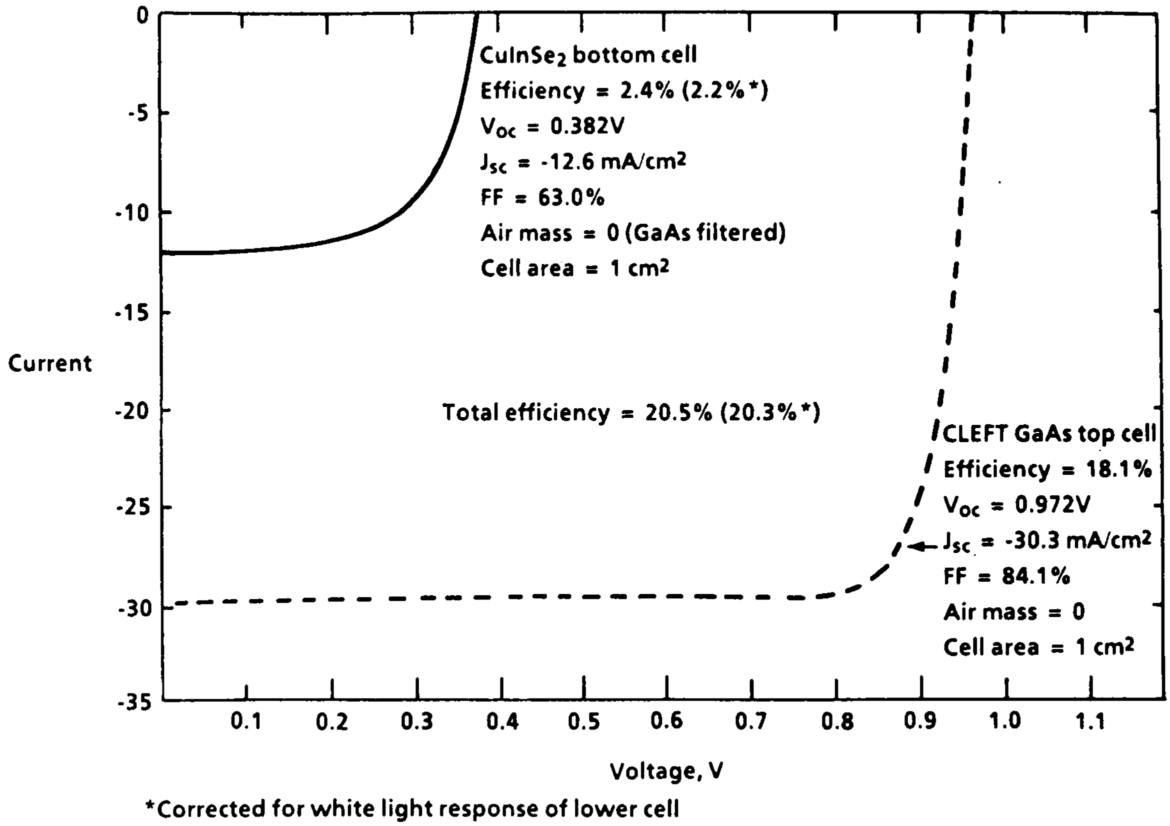


*Figure 2. I-V Measurements of Tandem Cell (*corrected for white light response of lower cell)*

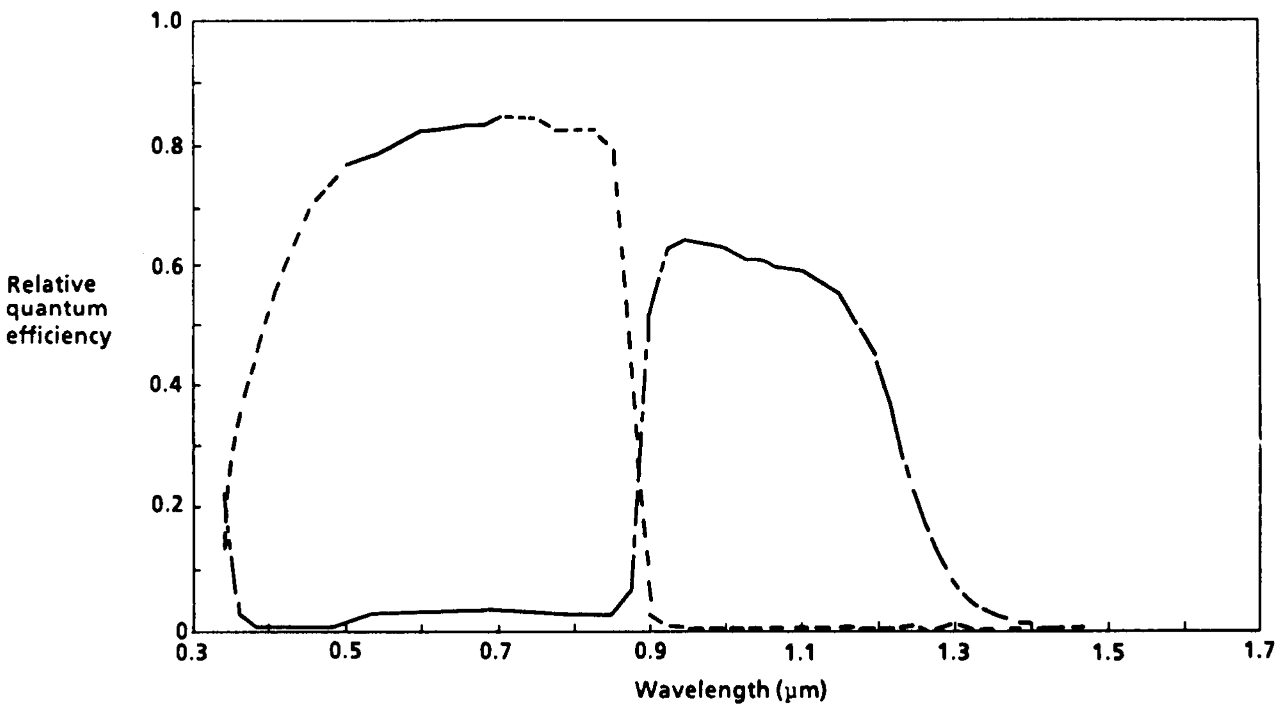


Figure 3. Spectral Response of Tandem Cell

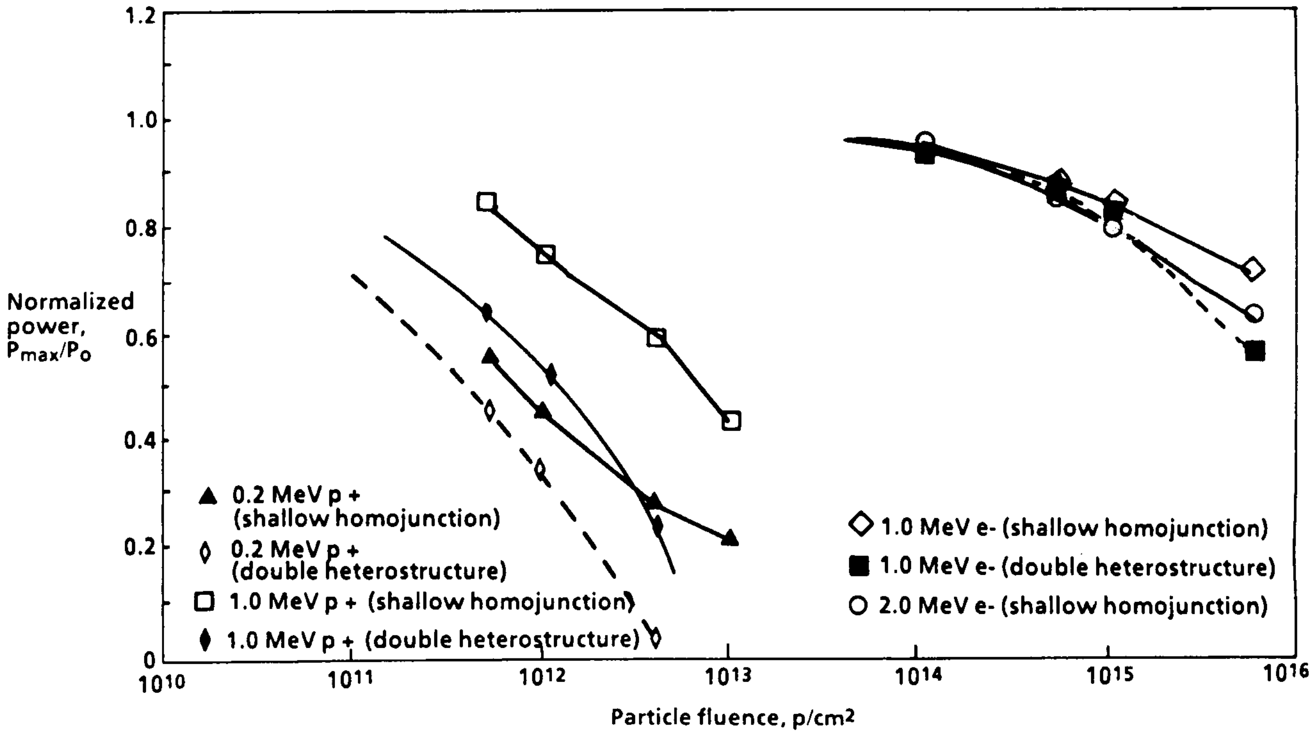


Figure 4. *Normalized Power Versus Particle Fluence Results of Irradiations of CLEFT GaAs Solar Cells by Protons and Electrons*

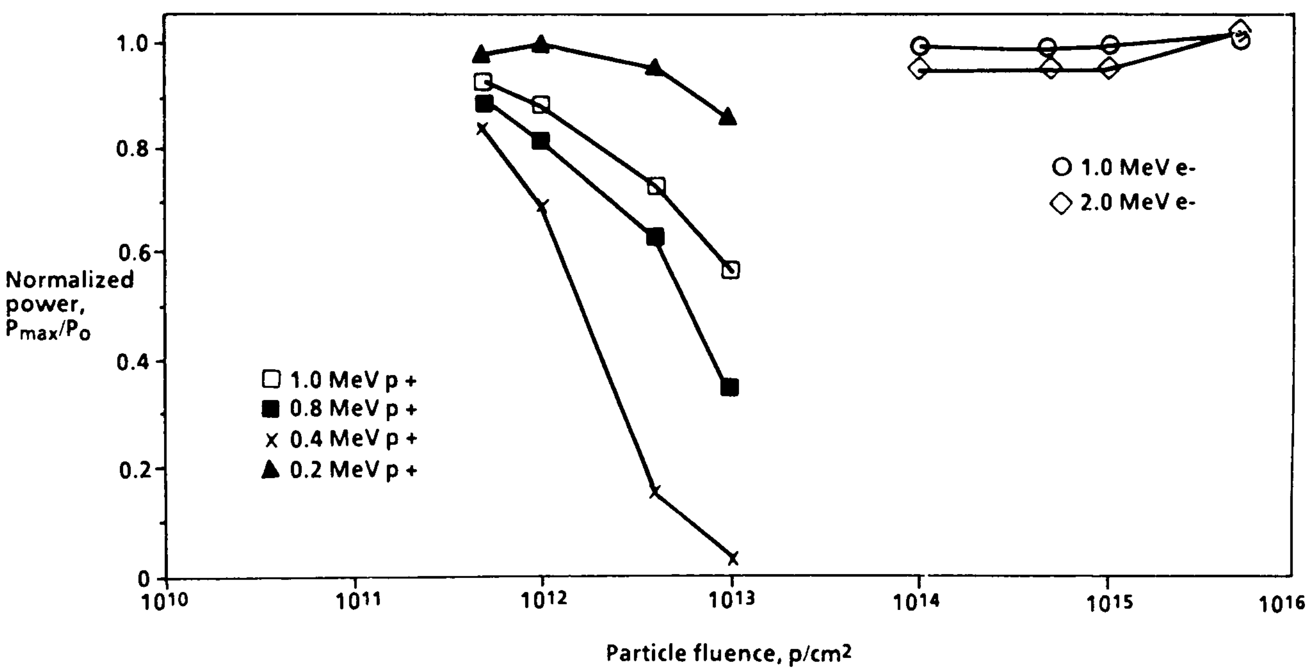


Figure 5. *Normalized Power Versus Particle Fluence Results of Irradiations of $CuInSe_2$ Cells by Protons and Electrons*

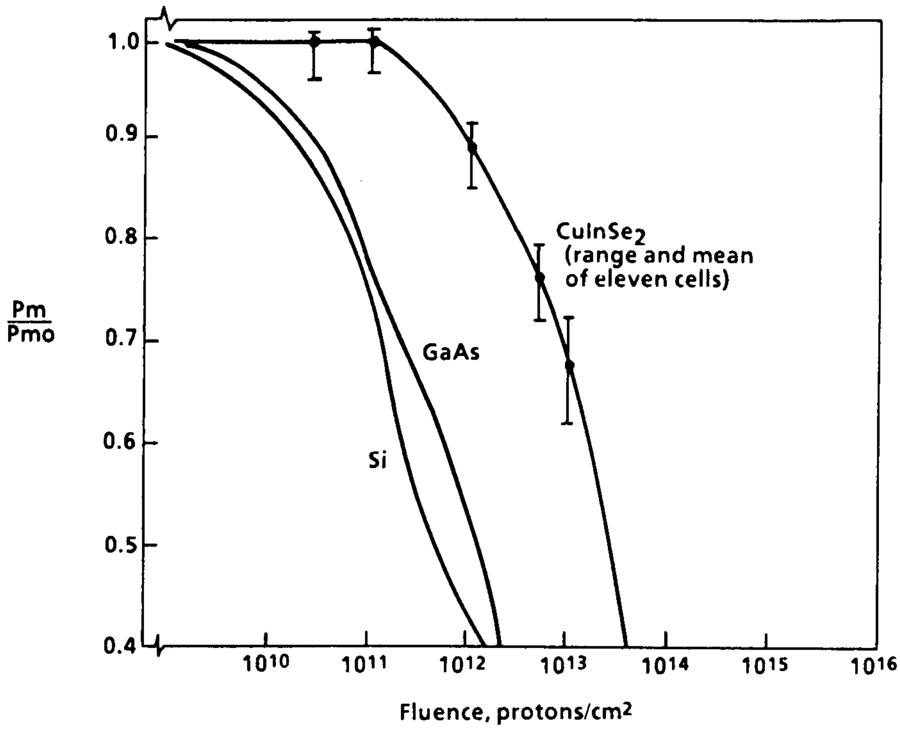


Figure 6. Degradation of Thin-Film CdS/CuInSe$_2$ Solar Cells as Function of 1 MeV Proton Fluence (ref. 7)

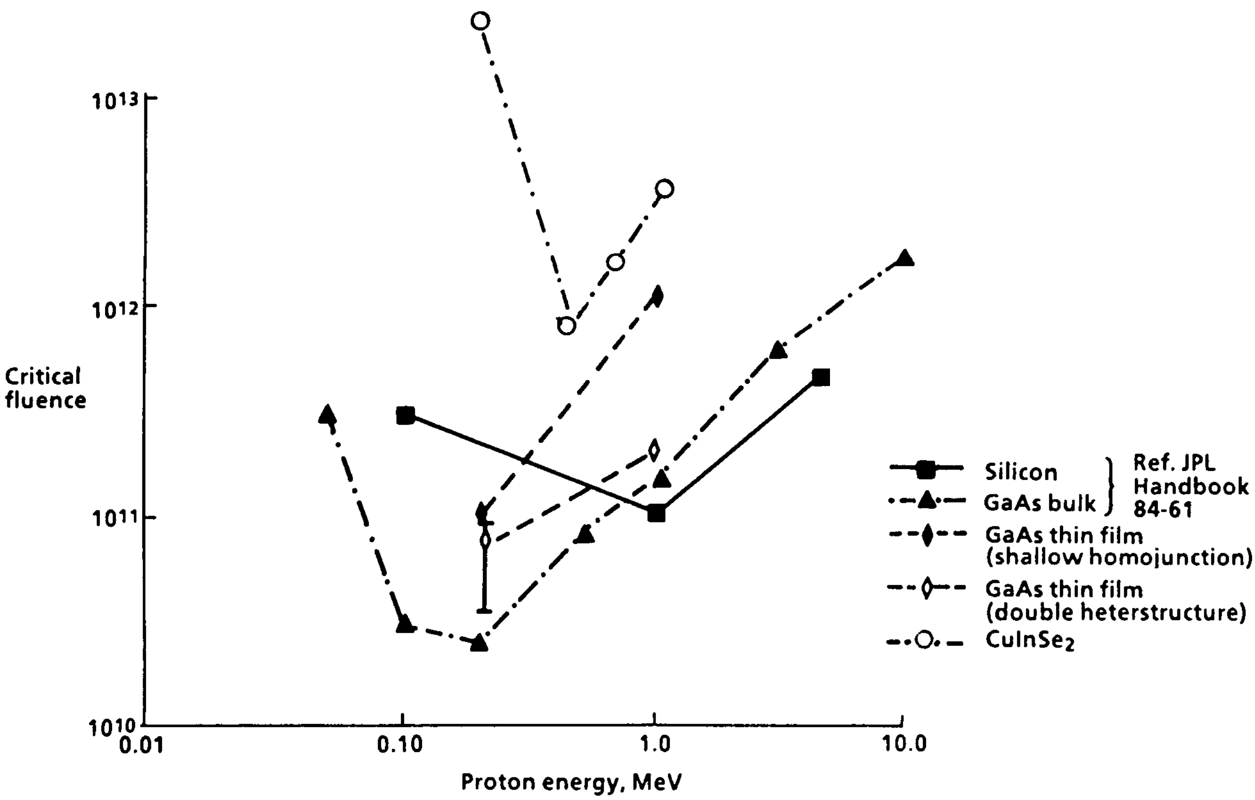


Figure 7. Critical Fluence vs. Proton Energy for Various Semiconductors