N91-30217

GaAs(AlGaAs)/CuInSe2 TANDEM SOLAR CELLS-- TECHNOLOGY STATUS AND FUTURE DIRECTIONS

N.P. Kim, and R.M. Burgess
Boeing Aerospace and Electronics
Seattle, WA. 98124

R.P. Gale, and R.W. McClelland
Kopin Corporation
Taunton, MASS. 02780

Mechanically stacked, high efficiency, light-weight, and radiation resistant photovoltaic cells based on a GaAs thin film top and $CuInSe_2$ thin film bottom cells have been developed under the joint research effort of the Boeing Co. and the Kopin Corp., and are considered one of the most promising devices for planar solar array applications. The highest efficiency demonstrated so far using the 4 cm^2 design is 23.1% AM0, one sun efficiency when measured in four-terminal configuration. In this paper, we present the current status of our GaAs(AlGaAs)/$CuInSe_2$ tandem cell program and describe future directions that will lead to cell efficiencies higher than 26% AM0. A new 8 cm^2 cell design developed for a two-terminal and voltage-matched configuration to minimize wiring complexity is discussed. Optimization of the GaAs structure for a higher end-of-life performance and further improvement of tandem cells by utilizing AlGaAs as an top absorber are described. Results of environmental tests conducted with these thin film GaAs/$CuInSe_2$ tandem cells are also summarized.

1. Introduction

The optimum power system for all spacecraft are the ones that incorporate high efficiency, light-weight, and radiation resistant photovoltaic cells. To meet these goals tandem solar cells have been developed under the joint research effort of the Boeing Co. and the Kopin Corp. The cells are mechanically stacked tandem cells based on a GaAs (AlGaAs) thin film single crystalline top cell and $CuInSe_2$ poly crystalline thin film bottom cell, and are considered one of the most promising devices for planar solar array applications (ref.1).

The top and bottom cells of GaAs (AlGaAs) and $CuInSe_2$ were chosen due to its high efficiency potential associated with its band gap combination (ref.2), relatively good radiation resistance of GaAs (AlGaAs) cells (ref. 3), and superb radiation resistance of $CuInSe_2$ cells compared to Si solar cells (ref. 3 and 4). The mechanical stacked tandem configuration was used to provide wiring flexibility and to minimize cell fabrication processing constraints associated with the monolithically integrated tandem approaches. Furthermore, this approach provides a potential for very high specific power since both cells are incorporated as thin films thus minimizing weight incurred from heavy semiconductor materials.

2. Technology Status

The schematic of the GaAs(AlGaAs)/$CuInSe_2$ tandem cell is shown in Figure 1, and consists of a double-heterostructure GaAs (AlGaAs) thin film top cell and a polycrystalline CdZnS/$CuInSe_2$ heterojunction thin film lower cell. The cross-section of the top and the bottom cells are shown in Figure 2 and Figure 3, respectively. The top GaAs(AlGaAs) thin film cell was fabricated by the CLEFT(Cleavage of Lateral Epitaxial Film for Transfer) technique (ref. 5) using MOCVD for cell structure growth. The CdZnS/$CuInSe_2$ (CIS) lower cell was fabricated using coevaporation method for semiconductor film deposition. Interconnection from the top cell bonding pads to glass substrate pads was conducted using gold ribbons to isolate the GaAs thin film from any stress caused by the next level interconnection. Details of cell fabrication process can be found in prior publications. (ref. 1,5, and 6) Electrical measurements were conducted in the four terminal configuration at one sun and

28°C with an AM0 power normalization of 137.2 mW/cm^2 using an XT-10 simulator and a JPL ballon flight calibrated GaAs/CIS reference cell unless noted otherwise.

2.1 Cell Efficiency and Cell Design

Cell efficiencies have continuosly improved from 17.4% to 23.1% since the Boeing and Kopin started their joint research work. Cell size also has progressed from the initial 1 cm^2 to the current 8 cm^2 during the same period. Figure 4 illustrates the major improvements of cell efficiency and size in the past five years (ref. 1,7,8, and 9). The highest efficiency demonstrated so far using the 4 cm^2 design was 23.1% AM0, one sun efficiency when measured in four-terminal configuration (ref.1). The best individual cells demonstrated in the completed tandem cells are 20.6% and 3.1% for the upper and the lower cells, respectively. A double layer AR coating of silicon oxide and silicon nitride on the GaAs top surface was incorporated into the base line process and significantly improved IR transmission toward the lower cell. A cell efficiency of 5.2% AM0 of the $CuInSe_2$ cell was demonstrated under a 1.7 eV band gap AlGaAs CLEFT filter, confirming the performance potential at the end-of-life (EOL) as well as at the beginning-of-life (BOL)(ref.9).

A new cell design was developed to enable easy application of these cells by optimizing their configuration for a specific space power application at the cell level and thus minimizing wiring complexity at the array level. The design is based on the 2 cm x 4 cm cell area and features an improved two-terminal configuration with voltage-matched monolithic subcell units, different from the previous four-terminal devices.The configuration of two-terminal and voltage matching was achieved by stacking one GaAs CLEFT cell on top of four $CuInSe_2$ subcells monolithically interconnected in series to form a single cell unit. The ratio of one to four has been determined based on array level circuit analysis conducted at Boeing. The unit was optimized for low-earth-orbit application where operating temperatures are higher than those for other applications. However, the design still provides the flexibility of forming four-terminal devices for various characterization purposes through minor modifications in the intra-cell interconnect. All the unnecessary contact buss area included in the previous design has been eliminated, and contact pads of minimum size are utilized at the four corners of the cell, thus improving cell packing factor significantly.

A recently developed monolithic interconnection method in the GaAs (CLEFT) fabrication process (ref. 10) has been utilized to provide thick buss lines in the GaAs cell to minimize any IR drop. This new technique combines with the $CuInSe_2$ monolithic interconnection capability to allow ratios other than the present one to four and therefore optimization for a wide range of orbital conditions. Fine line lithography has been incorporated into the base line CIS fabrication process to achieve monolithic interconnection of the subcells with minimum area loss. Details of other tandem cell fabrication process have been reported and are found in prior publications (ref. 1,5, and 6). The initial fabrication results using the improved process are encouraging, and the photograph of the GaAs CLEFT and $CuInSe_2$ cells for the voltage-matched, two terminal tandem solar cell are shown in Figures 5 and 6.

The effects of operating temperature on performance of this new device have been analyzed using demonstrated cell performance data and temperature coefficients measured in our laboratory. Two-terminal tandem cell efficiencies of 22.8, 22.3, 21.3, and 20.7% are projected at 28°, 40°, 55°, and 70°C, respectively as shown in Table 1.

2.2. Cell Weight

One distinct advantage of our cell design is found in the reduced total cell weight. Compared to conventional approaches involving cell growth on a heavy bulk semiconductor substrate, this tandem approach utilizes the CLEFT technique to fabricate a very thin (approximately 5 um thick) GaAs or AlGaAs film. Combined with the thin film CIS cell directly deposited onto thin glass, the optimized weight of a 4 cm^2 tandem cell including 2 mil thick coverglass is expected to be about 190 mg (ref.11). Light-weight GaAs/CIS tandem cells were demonstrated on 2 mil thick substrate glasses with efficiencies as high as 20.8% (ref.1). The cell weighed 258 mg using a 1-mil thick coverglass without optimal substrate trimming and adhesive thickness, yielding 442 W/kg cell-coverglass spcific power. When adhesive thickness and substrate trimming is optimized, cell-coverglass specific powers up to 630 W/kg are projected for the GaAs/CIS tandem cell, and up to 700 W/kg is achievable when an AlGaAs top cell is incorporated.

2.3. Environmental Effects

Since the main contributor to the performance degradation of space solar arrays is proton and electron radiation, the effects of these particles on individual cell devices and structures have been extensively studied. These studies have reaffirmed the superior radiation resistance of CIS solar cells when compared with GaAs and Si at comparable proton and electron energies and fluences. CIS solar cells show no measurable degradation occurs when irradiated with 1.0 and 2.0 MeV electrons to a total fluence of 5×10^{15} cm^{-2}. In addition, CIS solar cells are a factor of ten more radiation resistant to proton radiation between 10.0 and 0.2 MeV energies as compared to GaAs solar cells. These same studies (ref. 3) on the GaAs CLEFT solar cells indicated that the double heterostructure structure is as radiation resistant as the GaAs bulk cells with 1.0 MeV protons, and are slightly more radiation resistant at both the 1.0 MeV electron and 200 keV proton energies. A recent experiment was designed and conducted to optimize the GaAs double heterostructure for a particular mission's end-of-life (EOL) criteria. The designed experiment consisted of a systematic variation of the doping levels and/or thicknesses of the base and emitter layers. The cell efficiencies for the entire experimental matrix are plotted as a function of proton fluence in Figure 7. The EOL efficiencies required for the particular mission are indicated by stars in the figure and were met and exceeded by the optimized cell structure. The degradation curve indicated in the figure corresponds to this cell structure and is representative of the parameters currently used for the devices being fabricated. It was observed from this study that the lower doping in the base structure of the GaAs CLEFT cell improved the radiation resistance while the doping level in the emitter had little effect.

Thermal cycling tests were conducted on these tandem solar cells to confirm the survivability of the devices during the eclipse phase of a given mission. The performance of the tandem solar cells showed negligible degradation when cycled from +80°C to -100°C up to 850 cycles. (ref. 1) Humidity tests performed on the tandem solar cells and unencapsulated CIS solar cells show no degradation when exposed to 80°C and 80% relative humidity for a total of 175 days. These tests results along with addition environmental tests performed on these cells which include UV illumination, off-angle tests and vacuum stability, are summarized in Table 2.

2.4 Array level analysis

On-orbit array level circuit performance analysis was conducted to compare the impacts of the different cell technologies for three generic orbit applications (low earth orbit (LEO), med-earth orbit (MEO), geosynchronous earth orbit (GEO)) and showed that this tandem approach provides significant array weight and area savings over other cell technologies such as silicon or GaAs(Ge) (ref.3). Electrical performance test of demonstration panels fabricated was conducted to confirm optimized circuit configuration. A 30 cell string panel demonstrated 21.7% AM0 efficiency at 28 °C based on the nominal cell area including grid lines using the parallel-connected circuit unit of three series-connected CIS cells and three parallel-connected GaAs cells. The I-V characteristics and the picture of the panel are shown in Figure 8 (ref.12). The temperature coefficient for this string was calculated to be 2300 ppm/°C.

2.5. Manufacturing process development

Most of our recent effort has been focused on high throughput cell fabrication process development. A major cell fabrication cost reduction is expected to be achieved through the reuse of expensive GaAs substrate material. Substrate reuse has been demonstrated by fabricating GaAs CLEFT devices on reused and re-polished wafers. Performance of devices fabricated on reused substrates was comparable to the controls built on the fresh GaAs wafers. Using an optimized GaAs CLEFT structure for the EOL performance with the base lined double layer AR coating on the front, we were able to fabricate more than 50 tandem cells averaging a BOL efficiency of 21.1% with a standard deviation of 0.7%. These results in addition to the ones of tens of watts of tandem cells fabricated in the past confirmed the producibility and consistency of our current process even though our effort to reduce cell fabrication cost still continues.

3. Future Direction

Much higher performance improvement is expected when the current GaAs top absorber is replaced by high quality AlGaAs material since the band gap of the $CuInSe_2$ cell is better matched to the band gap of the AlGaAs than the GaAs. A 26% AM0 efficiency is projected for the beginning-of-life (BOL) for this device without any further structural change (ref.1). Furthermore, this AlGaAs/$CuInSe_2$ tandem cell offers significantly more EOL power output than other cell technologies (ref.6). Figure 9 shows the calculated power output as a function of 1.0 MeV electron fluence based on the reasonable BOL efficiencies assumed for the different cell technologies (14.5% for thin Si, 19% for GaAs, 2.5% for CIS under GaAs, 5.2% for CIS under AlGaAs, and 17% for AlGaAs). Radiation characteritics of different cells used in this analysis are found in the literature (ref. 4,13, and 14).

Tandem cell fabrication cost can be significantly reduced utilizing an even larger two-terminal cell design. After confirming two-terminal device configuration using the current 2 cm x 4 cm cell design, new cell designs of 4 x 4 cm^2 and 7 x 7 cm^2 are planned for the 3 inch and the 4 inch GaAs wafer substrate, respectively. These future cell designs will be for high voltage applications and further optimized for the end system use because monolithic interconnection on the GaAs CLEFT cell level is possible using the new process describe elsewhere (ref.10). Since both cells can be interconnected on the cell level to form high voltage device, a new two-terminal design with any combination of subcell ratio will be available for any specified mission environment. This new voltage-matched and two-terminal design can replace any single junction solar cell on the existing array to minimize wiring complexity and thus, reduce array fabrication cost.

Structural changes such as the replacement of the window layer of the CIS cell and replacing or eliminating Dow Corning adhesive in the stack will improve the device performance even further or increase the surviving temperature range of this tandem cell. Concepts are being developed to address these intermediate-term tasks.

Demonstration experiments utilizing these tandem cells are currently being prepared to confirm the viability of this approach The PASP Plus (Photovoltaic Array Space Power Plus Diagnostics) flight experiment conducted by Air Force will contain two strings of two-terminal GaAs/CIS tandem cells. We expect to collect significant space flight data on these cells by 1993.

4. Summary

High-efficiency thin-film GaAs/CIS tandem cells have been developed for planar solar array applications. Efficiencies up to 23.1% AM0 have been demonstrated based on four-terminal 4 cm^2 cell design. The tandem cells fabricated using our base line process exhibited a reasonable yield and a satisfactory scatter in deveice perfarmance. A new 8 cm^2 cell design utilizing the configuration of two-terminal and voltage-matching has been developed to minimize wiring complexity at the array level. Further performance improvement is projected when AlGaAs CLEFT top cell is used in the tandem stack. Environmental test results conducted using these tandem cells were favorable, and the tandem cells are ready for space flight experiment.

References

1. N.P.Kim, R.M. Burgess, R.A.Michelsen,B.J. Stanbery, R.W.McClelland, B.D. King, and R.P. Gale, Proceedings of the 10th Space Photovoltaic Research and Technology (SPRAT) Conference, p.88, 1989

2. J.C.C.Fan, and B.J.Palm, Solar Cells, 12, 401, 1984

3. R.M. Burgess, W.S.Chen, W.E. Devaney, D.H. Doyle, N.P. Kim, and B.J. Stanbery, Conference Record 20th IEEE Photovoltaic Specialist Conference, (IEEE, New York 1988), p. 909

4. H. Dursch, W.S. Chen, and D. Russel, Proceedings of the Space Photovoltaic Research and Technology (SPRAT) Conference, NASA Conf, Pub. 2408, p.165

5. R.W. McClelland, C.O.Bozler, J.C.C. Fan, Appl.Phys. Lett., 37, p.560, 1980

6. R.A. Mickelsen, and W.S. Chen, Conference Record 16th IEEE Photovoltaic Specialist Conference, p. 781

7. B.J. Stanbery, J.E. Avery, R.M. Burgess, W.S. Chen, W.E. Devaney, D.H. Doyle, R.A. Mickelsen, R.W. McClelland, B.D. King, R.P. Gale, J.C.C. Fan, Conference Record 19th IEEE Photovoltaic Specialist Conference, p.280, 1987

8. N.P. Kim, R.M. Burgess, B.J. Stanbery, R.A. Mickelsen, J.E. Avery, R.W. McClelland, B.D. King, M.J. Boden, and R.P. Gale, Conference Record 20th IEEE Photovoltaic Specialist Conference, p.457, 1988

9. R.P. Gale, R.W. McClelland, B.D. Dingle, J.V. Gormley, R.M. Burgess, N.P. Kim, R.A. Mickelsen, and B.J. Stanbery, Conference Record, 21th IEEE Photovoltaic Specialist Conference, p.53, 1990

10. R.W. McClelland, B.D. Dingle, R.P. Gale and J.C.C. Fan, Conference Record, 21th IEEE Photovoltaic Specialist Conference, p.168, 1990

11. N.P. Kim, B.J. Stanbery, R.P. Gale, and R.W. McClelland,Proceedings of the 9th Space Photovoltaic Research and Technology (SPRAT) Conference, p.138, 1988

12. R. Burgess, C.Flora, and M. Schneider, Conference Record 21st IEEE Photovoltaic Specialist Conference, (IEEE, New York 1990), p. 1340

13. R.Y. Loo and G.S. Kamath, Conference Record 20th IEEE Photovoltaic Specialist Conference, (IEEE, New York 1988), p. 635

14. B.E. Anspaugh, JPL Publication 82-69, Addendum 1: 1982-1988, Solar Cell Radiation Handbook

Table 1. Projected Two-terminal Performance

Temp	Voc (V)	Jsc (mA/cm²)	Fill Factor (%)	Efficiency(%)
28°C	1.012	.298	.83	22.80
40°C	0.990	.298	.83	22.30
55°C	0.965	.301	.82	21.30
70°C	.935	.302	.81	20.70

Table 2. Summary of environmental tests performed on GaAs/CIS tandem solar cells

Environmental Test	Test Range	Results
Electron Irradiation	1.0 and 2.0 MeV Fluences to 5.0 x 10^{15} cm^{-2}	CIS; nodegradation GaAs; same as bulk GaAs
Proton irradiation	0.2, 0.4, 0.8, 1.0, and 2.0 MeV; Fluences to 10^{13} cm^{-2}	CIS; Factor of ten more radiation resistant GaAs; Some energies show more radiation resistant than bulk GaAs
Thermal Cycling	+80°C to -100°C; 850 cylcles	Negligible degradation
UV Exposure	3 month AM0 equivalent	No UV degradation
Photo Illumination	164 hrs continuous illumination	No degradation
Off-Angle Performance	Normal to 50°C off-angle	Follows cosine law
Vacuum Stability	10^{-7} torr vacuum pressure 25°C to 110°C	No measurable difference to ambient pressure measurements

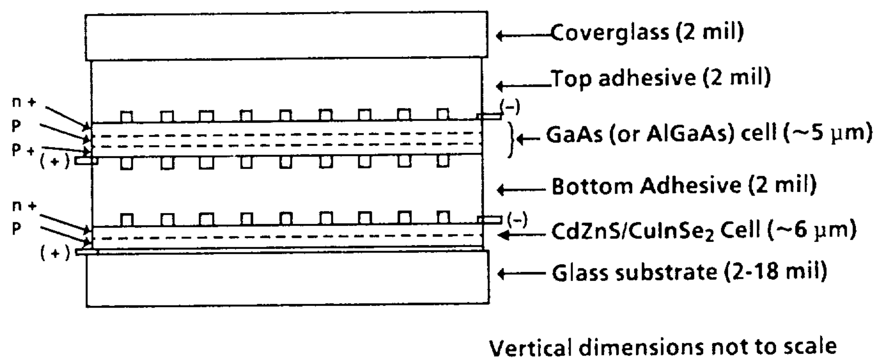


Figure 1. Schematic of Tandem Cell Structure

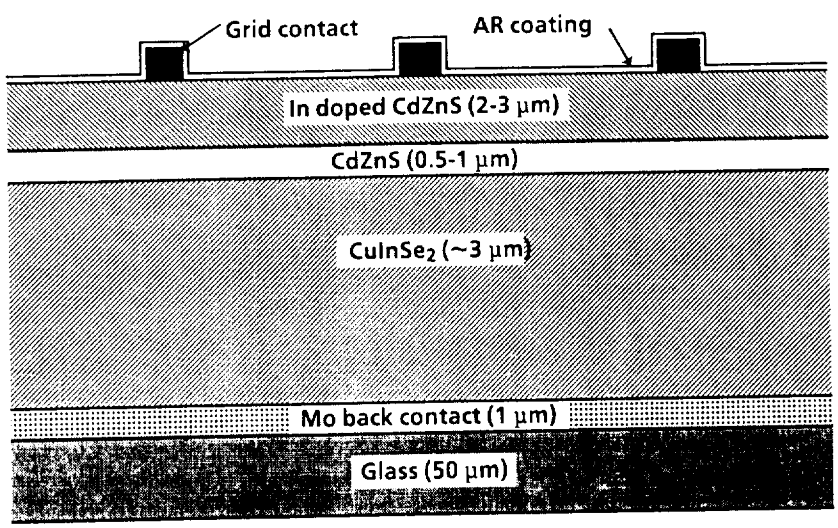


Figure 2. Cross Sectional View of $CuInSe_2$ Cell

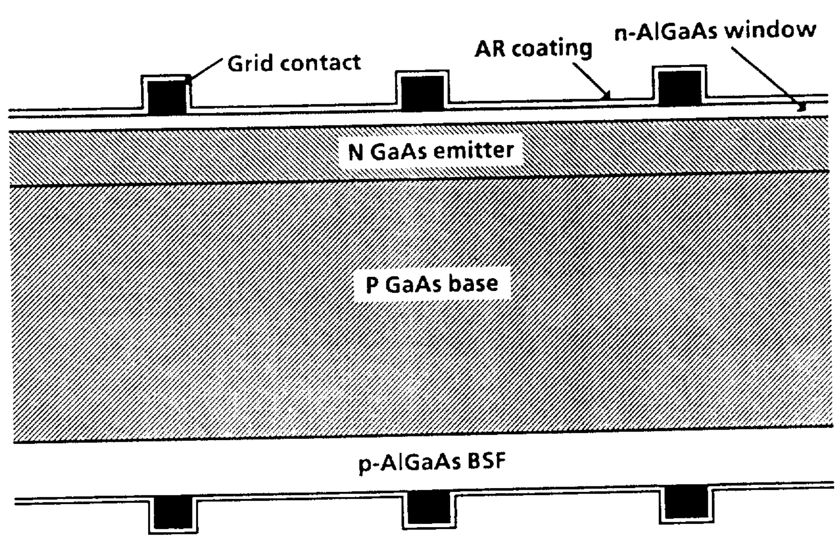


Figure 3. Cross Sectional View of GaAs Thin-film Cell

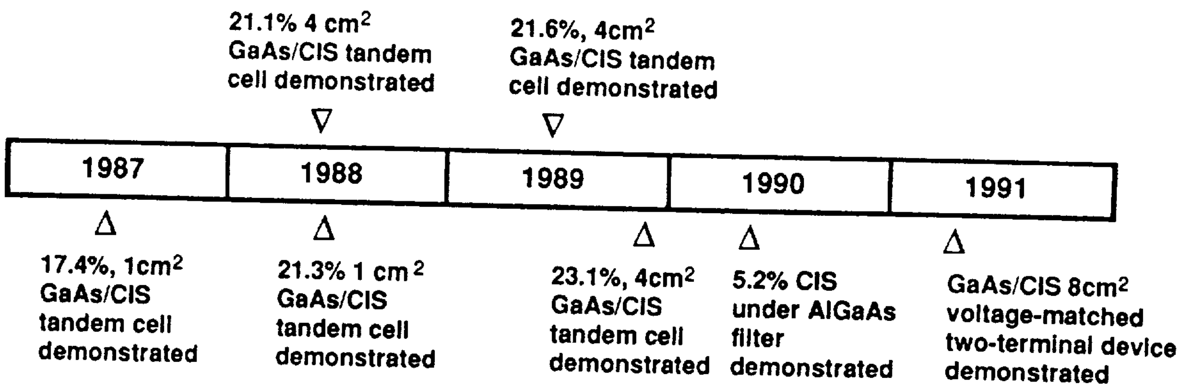


Figure 4. Key Milesones of GaAs(AlGaAs)/CIS Tandem Cell Project

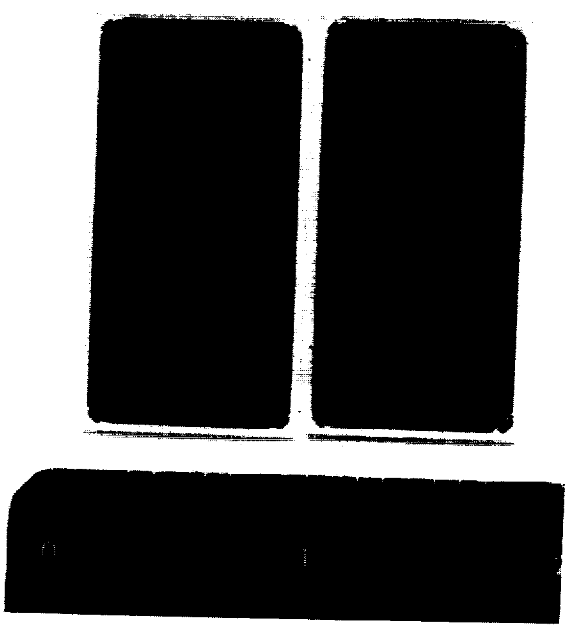


Figure 5. The GaAs CLEFT Cells (8 cm^2 each)

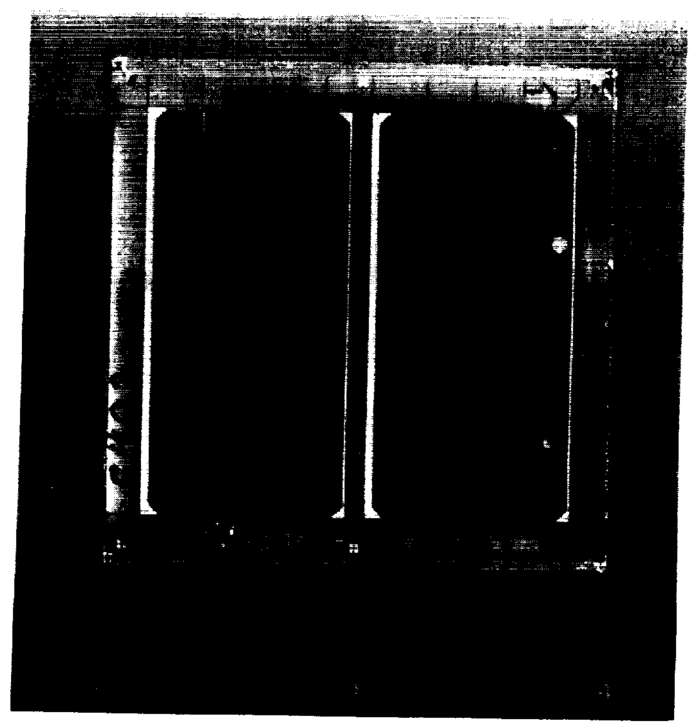


Figure 6. Two CIS Cells Containing Four Monolithicaly Interconneted Subcells (8 cm^2 each)

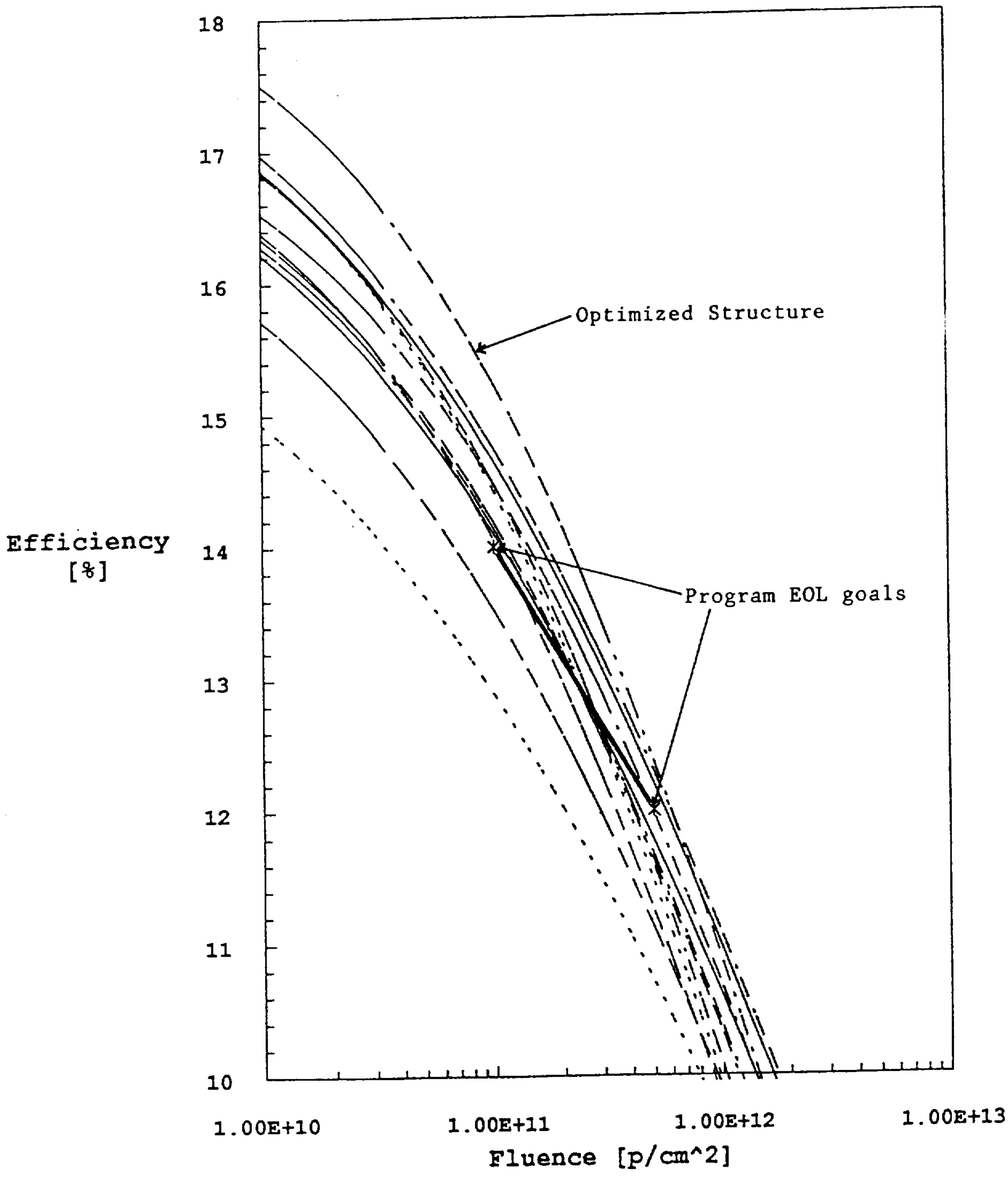
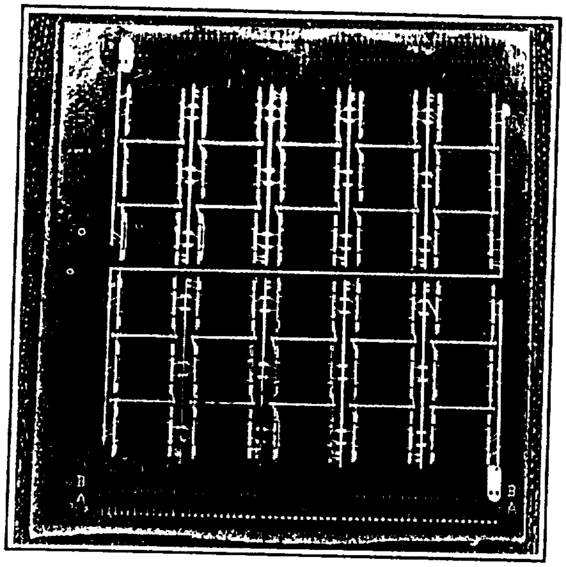


Figure 7. Efficiency Degradation Curves of GaAs CLEFT Cells with Various Device Parameters vs. 1 MeV Proton Fluence



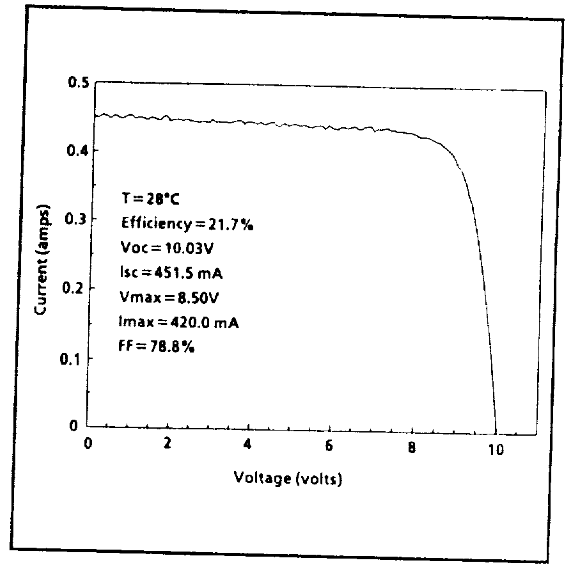


Figure 8. Voltage-matched 30 GaAs/CIS tandem Cell Demonstration Panel and I-V Curves

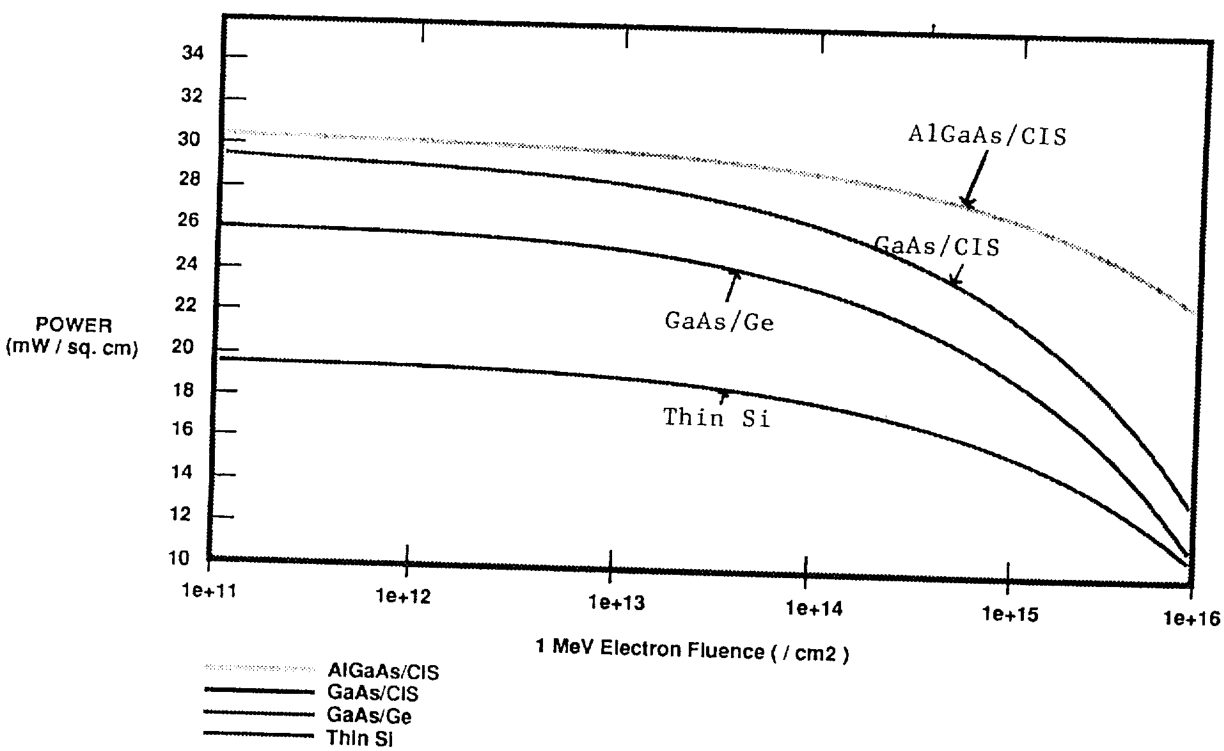


Figure 9. Calculated Cell Power Output as a Function of 1 MeV Electron Fluence