AD-A040 736 AIR FORCE AERO PROPULSION LAB WRIGHT-PATTERSON AFB OHIO F/G 10/2
INVESTIGATION OF GAAS SOLAR CELL POTENTIAL PERFORMANCE AND COST--ETC(U)
FEB 77 C STUERKE
UNCLASSIFIED AFAPL-TR-76-100 NL

1 OF 1
AD
A040736

END
DATE
FILMED
7-77

AFAPL-TR-76-100

INVESTIGATION OF GaAs SOLAR CELL POTENTIAL PERFORMANCE AND COST

ENERGY CONVERSION BRANCH
AEROSPACE POWER DIVISION

FEBRUARY 1977

TECHNICAL REPORT AFAPL-TR-76-100
FINAL REPORT FOR PERIOD JUNE 1975 - DECEMBER 1976

Approved for public release; distribution unlimited

AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been submitted by Lt. Cecil Stuerke. The effort was carried out by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Project 3145 and Work Unit 31451957. The consulting assistance of Dr. A.E. Middleton of Ohio State University was obtained under Contract F33615-74-C-2039.

This report has been reviewed by the Information Office (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Cecil Stuerke

CECIL STUERKE, 2Lt, USAF

FOR THE COMMANDER

JOSEPH F. WISE, Technical Area Manager
Solar Energy Conversion

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: (14) AFAPL-TR-76-100	2. GOVT ACCESSION NO. (9)
	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): (6) Investigation of GaAs Solar Cell Potential Performance and Cost.	5. TYPE OF REPORT & PERIOD COVERED: Final Report, June 1975 — December 1976
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): (10) Lt. Cecil Sturke	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: W.U. #31451957
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, OH 45433	12. REPORT DATE: (11) February 1977
	13. NUMBER OF PAGES: 23
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 23p.	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

(16) 3145

18. SUPPLEMENTARY NOTES

(17) 19

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

GaAs Solar Cells

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the results of a study which investigated GaAs solar cell potential performance and cost. The study which began June 1, 1975 included a literature survey, analyses of cell performance, cost and weapon hardness, and limited cell testing. Dr. A. E. Middleton, of the Ohio State University, a consultant, significantly aided the literature survey, the cost analysis and a determination of possible cell improvements. From the completed study came an Air Force interpretation of the present development of GaAs solar cells and an assessment of their potential performance and cost.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

011540

FOREWORD

This report has been submitted by Lt. Cecil Stuerke. The effort was carried out by the Energy Conversion Branch, Aerospace Power Division, Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Project 3145 and Work Unit 31451957. The consulting assistance of Dr. A. E. Middleton of the Ohio State University was obtained under Contract F33615-75-C-2039. This report covers research for the period June 1975 to December 1976.

TABLE OF CONTENTS

SECTION I
INTRODUCTION

Air Force development of GaAs solar cells for space power was discontinued in the 1960's because of low cell efficiency, low yield, and high cost. But Air Force interest returned with the advent of the high efficiency (GaAl)As/GaAs* heterofaced structure.

A study of new technology GaAs solar cells began 1 June 1975 at the Air Force Aero Propulsion Laboratory, (AFAPL) Wright-Patterson Air Force Base, Ohio. The study, aimed at future Air Force requirements and applications, included a literature survey, an analysis of potential performance, production cost and weapon hardness, limited cell testing, and a determination of possible cell improvement. Dr. A. E. Middleton of Ohio State University, a consultant in this study, significantly aided the literature search, the cost analysis and the improvement determination. Results of the study are presented in this report.

*(GaAl)As is used in this report to denote semiconductor material which is more accurately described as $Ga_{1-x}Al_xAs$. The value of x may vary from 0 to 1. However, high efficiency cells use values of x greater than .9. The term GaAs cell, when used generically, includes the heterofaced structure.

SECTION II

LITERATURE SURVEY

The literature survey included reports of investigation on several different devices. However, the device which has received the greatest theoretical and experimental attention, which has produced the highest efficiencies and which appears to have the greatest near term potential for high efficiency is the (GaAl)As/GaAs heterofaced cell (Reference 1). The heterojunction (References 2, 3) graded bandgap cell (References 2, 4) and the Schottky barrier cell (Reference 5) all require considerably more fabrication technology development.

However, the literature survey was more than a device comparison. Cell configuration, associated material properties, and presently reported optimization efforts were studied. Results of various experimental efforts were noted.

Figure 1 illustrates the structure described in the literature as the heterofaced GaAs solar cell. The p-n junction is displaced from the (GaAl)As/GaAs interface toward the GaAs bulk (Reference 7). This serves to locate the junction away from the interface plane which has high crystal structure dislocations. Likewise the (GaAl)As, which serves as a window to most useful photons, serves to locate active bulk away from the cell surface. Both the cell surface and the interface of dissimilar crystal structures are potential minority carrier recombination sites. High cell voltage is dependent on low minority carrier recombination rates.

Contact
GaAlAs Window p-type
GaAs Active Bulk p-type
GaAs Active Bulk n-type
GaAs Substrate n-type
Rear Contact

Figure 1. Structure of Heterofaced (GaAl)As/GaAs Cell

Optimization of the p-n junction depth (below the interface) involves accounting of photon absorption with respect to photon energy. Absorbed photons create electron and hole carrier pairs. The relative ability of the n- and p-type minority carriers to travel from their creation to the junction is also important in the optimization of depth (Reference 6). Light absorption is most productive if it occurs in the GaAs. Only photons of energy great enough (greater than the semiconductor's forbidden bandgap) excite electrons into the conduction band. For GaAs the bandgap is 1.43eV and virtually all sufficiently energetic photons are absorbed within five microns of the surface. However, photons of energy greater than the bandgap of (GaAl)As are partially absorbed in the window. To extend the high energy (short wavelength) cell response, the window layer can be made thin. Increasing the concentration of Al (x) to greater than .9 is also effective. Since it increases the window's bandgap to above 2.1eV, it also increases the cell's response to higher energy photons.

The structure's window layer can also be manipulated to reduce the sheet resistance of the top layer and thus cell series resistance. Doping with Be on the order of $10^{18}/cm^3$ creates a window which is a better conductor in parallel with the thick surface layer of p-type GaAs. The need for closely spaced, light obscuring, contacts can thus be reduced. As the window layer material approaches pure AlAs the dopant saturation level decreases. Difficulty of electrical contacting has caused many experimental efforts to rely on gold alloy contacts (Reference 9). Optimization calls for a window absorption-series resistance trade off for the window thickness and aluminum concentration.

Reports of fabrication results indicate that material grown by the liquid phase epitaxy process (LPE) presently yields the longest minority carrier diffusion length (Reference 7). This in turn yields the greatest solar cell electrical current. In fact, starting substrate crystal inhomogeneity and minority carrier diffusion lengths can be improved with an epitaxial "clean up" layer (References 6, 8).

The bandgap of GaAs is closer than Si's to the theoretical optimum based on solar spectrum match (Reference 17). In addition the percentage of power degradation vs. temperature is reduced because of high GaAs cell voltage. GaAs cells are thus more applicable (than Si) to high temperature environments.

All of these facts were brought out by the literature survey. They are all important in the development of GaAs solar cells for Air Force applications.

SECTION III

CELL MODEL

A theoretical model which incorporates these facts was the next effort in the study. Figure 1 depicts the solar cell model and Table 1 lists material property estimates which were developed in this study. The model includes an n-type GaAs crystal layer grown epitaxially (LPE) on an n-type substrate. The layer covers crystalline defects of the substrate and is thick enough to become the entire active bulk. A p-type layer is either epitaxially grown or created by diffusion of dopant out of a (GaAl)As window layer which is also formed by LPE growth. Minimizing the space charge volume at the p-n junction interface and hopefully minority carrier recombination in that volume increases cell voltage and is an objective in fabricating the p layer. The highly doped transparent window covers the p layer. Carrier recombination at the interface is two orders of magnitude lower than that of the original surface. Figure 1 shows the p-n junction below the (GaAl)As window and thus the structure is deservedly called a heterofaced cell.

A substitute for gold alloys, which makes good mechanical and electrical contact to GaAs, may eventually be found (Reference 10). However, for reliable contacts, the present model shows a NiAu eutectic as the rear contact material and a ZnAu eutectic on the front. The rear contact covers the entire surface but the front contact is limited to 4.5%. With photolithographic contacting technology this minimized obscuration of active cell area can be accomplished despite a high contact grid finger density (Reference 11) (20 fingers/cm) which greatly reduces cell series resistance.

In space applications the model in Figure 1 would include an antireflection coating, an adhesive, an ultraviolet rejection filter, and a solar cell coverglass. In the very earliest satellite programs it was discovered that electronic devices such as solar cells must be protected from damage caused by low energy protons of the Van Allen belts. The adhesive for this protective shield also has requirements unique to the space application. Adhesives have been developed to withstand temperature cycling and humid pre-launch environments but an ultraviolet rejection filter is still required to avoid solarization (darkening due to ultraviolet light). This stack of optical materials, each with a different index of refraction, causes a transmission loss at each interface and at the front surface. The antireflection coatings are an attempt to match the refraction indices and to maximize the transmission of useful light into the GaAs material.

TABLE 1

CALCULATION MODEL PARAMETERS

	Material	Thickness	Properties & Considerations
Front Contact	Zn-Au alloy	10μm	Cell coverage vs. series resistance optimized.
Window	$(Ga_{.05}Al_{.95})As$ High acceptor conc.	5μm	L^*=1μm $\tau^{**}=10^{-9}$ sec, $S^{***}=10^6$cm/sec., minimized absorptance. Doping level and thickness optimized for low series resistance.
p-type bulk	GaAs $10^{17}/cm^3$ acceptors	1μm	L^*=6μm, $\tau^{**}=10^{-8}$ sec., $S^{***}=10^4$cm/sec.
p-n interface (space charge region)	Compensated GaAs	.05μm at V_{oc}	Minimized width, $\tau^{**}=5\times10^{-9}$ sec.
n-type bulk	GaAs $10^{17}/cm^3$ donors	5μm	L^*=5μm, $\tau^{**}=10^{-8}$ sec.
Substrate	GaAs $10^{18}/cm^3$ donors	300μm	Crystal support, low resistivity.
Back Contact	Ni-Au alloy	20μm	Minimum series resistance, mechanical strength.

* L means minority carrier diffusion length
** τ means minority carrier lifetime
***S means surface recombination velocity

SECTION IV

PERFORMANCE ANALYSIS

The minority carrier continuity equation (Equation 1) was solved (similar to the solution of Hovel and Woodall (Reference 12)) using the parameters of Table 1, the absorption coefficients (Reference 12), and the energy distribution of the solar spectrum (Reference 13).

If each photon with energy greater than the bandgap of GaAs created a carrier pair, then 38 ma/cm^2 would be created in single sun intensity space sunlight. Equation 1 was solved for m using appropriate boundary conditions. Collection current density is given by Equation 2. If all sunlight of wavelength greater than .35 um (ultraviolet rejection) were absorbed within active bulk, 32 ma/cm^2 would be collected (84% collection efficiency).

But not all light is absorbed in the active device. Four and one half percent is lost to contact obscuration. Absorption in a fused silica coverglass is about 2% (Reference 14). Additional losses due to absorption and reflection are estimated at 4%. The model thus leads to a light generated current density (J_g) of 28 ma/cm^2.

The bulk recombination current density (J_d) contributed by both sides of the junction is given by Equation 3. Space charge region recombination current density (J_r at open circuit) is given by Equation 4. The relationship of these reverse currents and cell series resistance to operating voltage (V) and current (I) for a 1 cm^2 cell is given by Equation 5. Using parameters of the structural model an open circuit voltage of 1.06 volts is predicted. Analysis of contact design and material parameters indicates .5 ohm series resistance is possible (Reference 15). From the model parameters and Equation 5 maximum power voltage is .897 volts. Maximum power current is 26.8 ma. Projection of output according to the model is 24.0 mw (17.7% efficiency in the 135 mw/cm^2 air mass zero spectrum).

$$D \frac{d^2m}{dx^2} + \alpha N_{ph} e^{\alpha x} - \frac{m}{\tau} = 0 \qquad (1)$$

$$Jg = qD \frac{dm}{dx} = 32 \text{ ma/cm}^2 \qquad (2)$$

$$Jd = \frac{qn_i^2 L}{N\tau} \times \frac{\frac{S\tau}{L} + \tanh\left(\frac{X}{L}\right)}{1 + \frac{S\tau}{L}\tanh\left(\frac{X}{L}\right)} = 4.4\text{x}10^{-19} \text{ amperes/cm}^2 \text{ (total)} \qquad (3)$$

$$J_r = \frac{qn_i W}{\tau} \frac{\pi/2}{V_g - V} \frac{KT}{q} = 4.5\text{x}10^{-11} \text{ amperes/cm}^2 \qquad (4)$$

$$I = Ig - (I_{d(p)} + I_{d(n)}) \left(e^{\frac{q(V+IR)}{KT}} - 1\right) - I_r \left(e^{\frac{q(V+IR)}{2KT}} - 1\right) \qquad (5)$$

D = minority carrier diffusion constant (cm^2/sec)

m = excess minority carrier concentration (carriers/cm^3)

α = absorption coefficient (cm^{-1})

N_{ph} = incident photon flux (photons/cm^2 sec)

τ = minority carrier lifetime (seconds) *

X = distance into cell (cm) *

V_g = semiconductor bandgap (volts)

L = minority carrier diffusion length (cm) *

n_i = intrinsic carrier concentration ($2\text{x}10^6$ carriers/cm^3)

N = ionized dopant level (carriers/cm^3) *

S = surface recombination velocity (cm/sec)

V = cell operational voltage (volts)

q = $1.6\text{x}10^{-19}$ (coulombs/charge carrier)

W = thickness of space charge region (cm)

R = cell series resistance (ohms)

K = Boltzman's constant ($1.38\text{x}10^{-23}$ joules/°K)

T = Temperature (300°K)

*These parameters apply to the appropriate p- or n-type material.

SECTION V

COST PROJECTION

Dr. Middleton completed an analysis of projected GaAs solar cell cost. The relation of materials, labor, and equipment costs to cell cost is reviewed in Table 2. This analysis is based upon 10,000 cells (1 cm^2) per day production for a period of five years. In private communication, Dr. Tarrants of Air Force Materials Laboratory indicated that the 3-inch diameter GaAs crystal growth technology required by this analysis is at least ten years away. The level of process integration (not typical in silicon cell production) should also be noted. The cost projection was \$3.00 to \$5.80 /cm^2.

TABLE 2

GaAs SOLAR CELL COST ANALYSIS

	Labor [1] ($/cm²)	Material ($/cm²)	Equipment [2] ($ x Space Cell Fraction)
Crystal growth[2,3] to polished blanks	.024	.280	40,000
Epitaxy and[4] junction formation	.100	.053	137,500
Cell completion[2] Coating, contacts, tests	.087	.0575	23,300
	.211	.3905	200,800
Labor Cost	.211		
Material Cost	.3905		
Equipment Amortization[5]	.2133		
	.8148		
30% Yield	1.9012		
	2.716		
G&A & Profit 18%	.489		
	3.205		

[1] $10/hour labor with 200% overhead.

[2] 1,000 cm²/day, space cells processed with 9,000 1 cm² terrestrial cells/day.

[3] 33 1/3% of GaAs material removed in cutting, surface finishing and shaping operations reclaimed without cost.

[4] Processed in 10,000 cm²/day lot for epitaxial clean up layer, and in a 1,000 cm² day junction formation lot. Melt volume only depleted by grown material.

[5] Amortized over five years at interest 10%/year. 20 working days/mo.

SECTION VI

WEAPON EFFECTS ANALYSIS

A solar cell model similar to Figure 1 was sent to Aerospace Corporation, Inc. via SAMSO for an analysis of laser and nuclear weapon survivability. The nuclear weapon effects analysis involved calculating the energy deposition and temperature profile resulting from weapon simulating black body radiation. It was found that melting of the gold contacts is the damage mode with the lowest threshold.

Efforts to model the laser and thermal shock vulnerability were not completed due to the lack of necessary optical and mechanical properties of cell materials especially (GaAl)As.

SECTION VII

APPLICATIONS OF THE GaAs CELL

The advantages of the new GaAs solar cell structure over the conventional silicon cell lie in its greater area power density (mw/cm^2) and in the smaller detrimental effect of high temperature operation.

Five 4 cm^2 (GaAl)As/GaAs cells produced by Hughes Research Laboratory were interconnected as a flight experimental string for the NTS-2 satellite. Efficiency measured at AFAPL for this string was 14%. AFAPL also measured 16% efficiency on a 1.44 cm^2 cell produced by Varian Associates. More recently Hughes Research Laboratories have reported 16.3% efficiency (Reference 18).

Dr. W. Patrick Rahilly of the Air Force Aero Propulsion Laboratory in conjunction with Donald Locker of the Air Force Avionics Laboratory made radiation damage studies of GaAs cells. Radiation damage due to 1 Mev electron is shown in Figure 2. The data for the tested cell indicates sensitivity to radiation damage greater than that which is common for silicon cells (Reference 16).

Although 1 Mev electron equivalence to space may not directly transfer from silicon to GaAs solar cells, this is an indication that effort may be required to ensure high end of life efficiency of GaAs cells in a natural radiation environment.

The higher power of GaAs solar cells (approximately 25% higher at 25°C) may be particularly useful in cases where spacecraft power requirements are larger than that which can be supplied by silicon solar cells in the given available solar cell area. Gallium arsenide cells designed for direct replacement can solve the problem without the necessity of solar array or spacecraft redesign that would otherwise be required to increase the array area of new designs by approximately 20%. (Assuming 18% efficient GaAs cells and 14.5% efficient Si cells.)

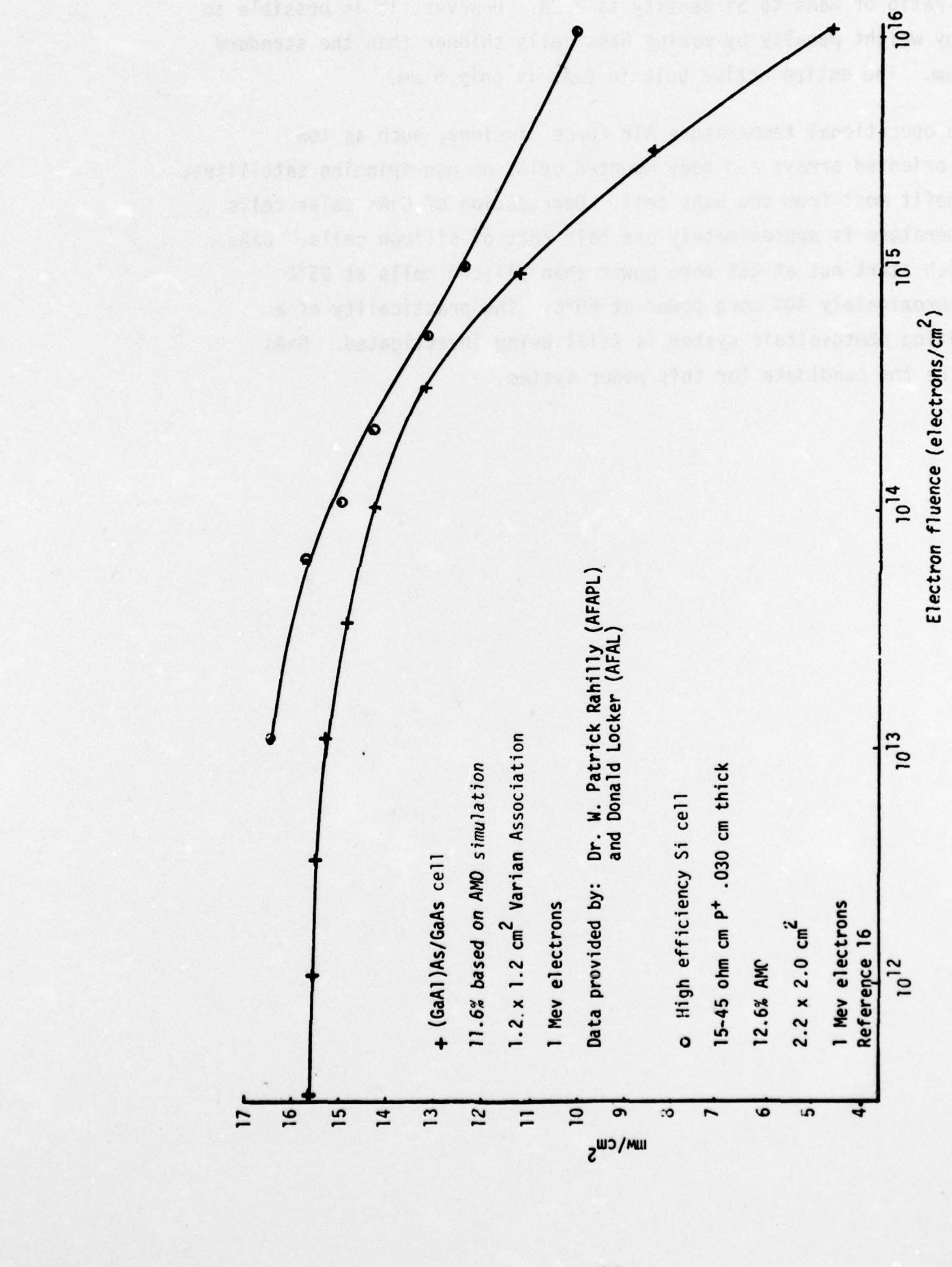

Figure 2. Comparison of 1 Mev Electron Damage in Si and (GaAl)As/GaAs Solar Cells

The ratio of GaAs to Si density is 2.28. However, it is possible to negate any weight penalty by making GaAs cells thinner than the standard 200-300 μm. The entire active bulk in GaAs is only 5 μm.

High operational temperature Air Force missions, such as low altitude oriented arrays and body mounted cells on non-spinning satellites, could benefit most from the GaAs cell. Degradation of GaAs solar cells with temperature is approximately one half that of silicon cells. GaAs cells which start out at 25% more power than silicon cells at 25°C supply approximately 40% more power at 60°C. The practicality of a concentrating photovoltaic system is still being investigated. GaAs may also be the candidate for this power system.

SECTION VIII

POSSIBLE IMPROVEMENT

A number of areas for improvement in GaAs solar cells were discovered in the course of this study. First, higher efficiency can be realized with increased "blue" response. A technology for deposition of thinner less absorbing window layers which still reduce recombination at the GaAs surface is needed. In addition, improved dopants for higher conductivity and increased minority carrier diffusion lengths are needed throughout the structure. Characterization of natural, nuclear, and laser radiation is needed along with appropriate hardening efforts. Fabrication technology improvements are necessary for the increased yield of large devices and reduced processing cost.

Since space power systems require an array of individual GaAs solar cell devices an appropriate assembly technology is also necessary. The fragile nature of GaAs crystals requires handling techniques. Interconnections are required which are environmentally stable, weapon hard and of low electrical resistance. Coverglassing and bonding to array substrates may also need to be investigated. This incorporation into the system is necessary in addition to development of the individual cell.

SECTION IX

CONCLUSIONS

The best GaAs cell for near term space power use is the (GaAl)As/GaAs heterofaced cell. Fourteen percent efficiency has already been measured and this study predicts 18% for a 4 cm^2 cell. Radiation resistance and weapon survivability are yet to be determined.

Long-range projection of cost is \$3.00 to \$5.80 per 1 cm^2 cell. High operational temperature environments are seen as a particularly promising application. AFAPL is now pursuing (GaAl)As/GaAs heterofaced cell development through Contract F33615-76-C-2121 with Hughes Aircraft.

The present program is expected to result in 18% efficient (single sun intensity) cells with preliminary natural and weapon radiation hardness design modifications. Concentrating power systems are also being studied. If development of the GaAs solar cell progresses properly, development of array procedures will follow.

REFERENCES

1. United States Patent No. 3,675,026, Jerry M. Woodall (IBM), "Converter of Electromagnetic Radiation to Electrical Power", (June 30, 1969).

2. V. M. Andreev, M. B. Kagan, T. L. Lyubashevskaya, T. A. Nuller, and D. N. Tret'yakov, "Comparison of Different Models of p Al_xGa_{1x} As-n GaAs Heterojunction Solar Cells from the Point of View of Maximum Efficiency" Soviet Physics Semiconductors 8 Vol. 7, 860 (January 1975).

3. M. B. Kagan, N. S. Karoleva, and T. P. Nuller, "Solar Elements Based on Epitaxial GaAs Films". Geliotekhnika, 2, 28-31 (1970).

4. J. A. Hutchby, "High Efficiency Graded-Band-Gap $Al_x\ Ga_{1-x}$ As - GaAs p on n Solar Cell:, Conf. Record Eleventh IEEE Photovoltaic Specialists Conference, p. 414, (May 1975).

5. Y. C. M. Yeh and Richard J. Stirn, "Improved Schottky Barrier Solar Cells", Conf. Record Eleventh IEEE Photovoltaic Specialists Conference, p. 391, (May 1975).

6. H. J. Hovel and J. M. Woodall, "Diffusion Length Improvements in GaAs Associated with Zn Diffusion During $Ga_{1-x}\ Al_x$ as Growth", Conf. Record Eleventh IEEE *Photovoltaic Specialists* Conference, p. 433, (May 1975).

7. L. W. James and R. L. Moon, "GaAs Concentrator Solar Cells", Conf. Record Eleventh IEEE Photovoltaic Specialists Conference, p. 402, (May 1975).

8. J. Ewan, G. S. Kamath, and R. C. Knechtli, "Large Area GaAlAs/GaAs Solar Cell Development", Conf. Record Eleventh IEEE Photovoltaic Specialists Conf., P. 409, (May 1975).

9. H. J. Hovel and J. M. Woodall, J. Electrochem, Soc. 120 1246 (1973).

10. A.G. Milnes and D. L. Feucht, "Studies of Heteroface Solar Cell Performance - Report for April 16, 1974 - October 15, 1974", NASA Grant NGR 39-087-021.

11. Private Communications with Alan Kirkpatrick of Simulation Physics, Inc.

12. H. J. Hovel and J. M. Woodall, "Theoretical and Experimental Evaluations of $Ga_{1-x}\ Al_x$ As - GaAs Solar Cells", Conf. Record Tenth IEEE Photovoltaic Specialists Conf., p. 25, (Novenber 1973).

13. M. P. Thekaekara, The Solar Constant and the Solar Spectrum Measured from a Research Aircraft, NASA-TR-R-351, NASNA, Nat. Aeronautics and Space Administration, (October 1970).

REFERENCES (CONTINUED)

14. H. W. Rauch Sr., D. R. Ulrich, and J. M. Green, "Glasses Designed for Use as Integral Solar Cell Covers", Conf. Record Tenth IEEE Photovoltaic Specialists Conference, p. 182, (November 1973).

15. A. G. Milnes and D. L. Feucht, "Studies of Heteroface Solar Cell Performance - Report for October 16, 1971 - April 14, 1972", NASA Grant NGR 39-087-021.

16. Leland J. Goldhammer, "Particle Irradiations of an Advanced Silicon Solar Cell", Conf. Record Eleventh IEEE Photovoltaic Specialists Conference, p. 172, (May 1975).

17. Joseph J. Loferski, "Principles of Photovoltaic Solar Energy Conversion", Conf. Record Tenth IEEE Photovoltaic Specialists Conference, p. 25, (November 1973).

18. S. Kamath, J. Ewan, and R. C. Knechtli, "Large Area High Efficiency (AlGa)As/GaAs Solar Cells", IEEE Transactions on Electron Devices (December 1976).

19. Private communications with E.H. Tarrants, Advanced Electronic Devices Branch, Electronic Technology Division, Air Force Avionics Laboratory, Wright-Patterson AFB, OH.

20. A.E. Middleton "GaAlAs-GaAs Space Type Solar Cells - Technical Report No. 3", Air Force Contract F33615-75-C-2039.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1977 — 757-001/315