View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by NASA Technical Reports Server

NASA Technical Memorandum 103619

Effect of Emitter Parameter Variation on the Performance of Heteroepitaxial Indium Phosphide Solar Cells

Raj K. Jain and Dennis J. Flood
Lewis Research Center
Cleveland, Ohio

(NASA-TM-103619) EFFECT OF EMITTER PARAMETER VARIATION ON THE PERFORMANCE OF HETEROEPITAXIAL INDIUM PHOSPHIDE SOLAR CELLS (NASA) 15 p CSCL 10A
N91-15306
Unclas
G3/20 0325578

Prepared for the
21st Photovoltaics Specialists Conference
sponsored by the Institute of Electrical and Electronics Engineers
Kissimmee, Florida, May 21–25, 1990

EFFECT OF EMITTER PARAMETER VARIATION ON THE PERFORMANCE OF HETEROEPITAXIAL INDIUM PHOSPHIDE SOLAR CELLS

R.K. Jain* and D.J. Flood
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

Metallorganic chemical vapor deposited heteroepitaxial indium phosphide (InP) solar cell experimental results have been simulated by using a PC-1D computer model. The effect of emitter parameter variation on the performance of a $n^+/p/p^+$ heteroepitaxial InP/GaAs solar cell has been presented. The thinner and lighter doped emitters were observed to offer higher cell efficiencies. The influence of emitter thickness and minority carrier diffusion length on the cell efficiency with respect to dislocation density was studied. Heteroepitaxial cells with efficiencies similar to present day homojunction InP cell efficiencies (>16-percent AMO) were shown to be attainable if a dislocation density lower than 10^6 cm^{-2} could be achieved. A realistic optimized design study yielded InP solar cells of over 22-percent AMO efficiency at 25 °C.

INTRODUCTION

Indium phosphide (InP) solar cells have important applications for space power owing to their improved radiation resistance (refs. 1 to 3). They also offer the prospects of high efficiency (refs. 4 to 7). In fact, efficiencies

---

*National Research Council-NASA Research Associate at Lewis Research Center.

as high as 19.1-percent AMO on 2- by 2-cm metallorganic chemical-vapor-deposited (MOCVD) homoepitaxial InP solar cells have been reported recently (ref. 8); however, the present InP wafer cost may limit its large-scale use. This problem is being overcome by growing single-crystal InP films on Si and GaAs wafers (refs. 9 and 10). This approach would provide large-area, lower cost, light-weight, and mechanically strong InP solar cells.

Present day heteroepitaxial cells are not very efficient because of the large number of dislocations (ref. 11) created by lattice and thermal mismatch. Efforts are underway to achieve high efficiencies by improving film quality. Recently, heteroepitaxial InP cells with efficiencies as high as 13.7-percent AMO (25 °C) have been reported (ref. 12). Such efficiencies were achieved by introducing proper MOCVD graded GaInAs buffer layers between InP and GaAs layers, thereby reducing the number of dislocations (ref. 13).

In the present work, MOCVD films of InP on GaAs wafers were considered. The PC-1D computer program (refs. 14 and 15) was used to simulate the heteroepitaxial InP cells, and the simulation results were compared to experimental cell results. The $n^+/p/p^+$ heteroepitaxial Inp cells analyzed in this work were manufactured by Spire Corporation under contract to NASA Lewis Research Center. These 0.5- by 0.5-cm cells had shallow emitter junctions. Minority carrier diffusion lengths have been varied to match the measured results on the InP/GaAs cells (ref. 16). This paper describes the effect of varying the emitter parameters, namely thickness and doping, on the cell performance parameters. Decreasing emitter thickness was observed to have a significant effect on the cell characteristics, and lightly doped emitters gave better results. The effect of emitter thickness and hole diffusion length on the cell efficiency with respect to dislocation density was studied. The results showed that heteroepitaxial cells with efficiencies similar to present day homojunction InP cell efficiencies (>16-percent AMO) are possible, if the dislocation density lower than 10^6 cm^{-2} can be achieved. However, the emitter must be properly tailored to achieve the best possible efficiencies. A realistic optimized design study was carried out, predicting InP cells with over 22-percent AMO efficiency at 25 °C.

EXPERIMENT

Indium phosphide heteroepitaxial cells were manufactured by Spire Corporation under contract to NASA Lewis. They used a metallorganic chemical-vapor-deposition technique to grow InP layers on GaAs wafers. Figure 1 shows the $n^+/p/p^+$ solar cell structure. The emitter, base, and buffer layer were 40 nm, 3 μm, and 1 μm thick and had doping concentrations of 2×10^{18} cm^{-3}, 3×10^{16} cm^{-3}, and 1×10^{18} cm^{-3}, respectively. The front and back contacts were made of Cr/Au/Ag and a Au-Zn alloy respectively. The front grid coverage was 5 percent, and the cells had a double layer ZnS/MgF_2 antireflection coating. The cell area was 0.25 cm^2.

A batch of eight cells was measured at NASA Lewis under a simulated AMO spectrum (137.2 mW/cm^2, 25 °C) by using a NASA Learjet-calibrated InP standard cell. The average values and standard deviations of the measured short circuit current, the open circuit voltage, and the efficiency (total area) of the eight cells are shown in table I.

RESULTS AND DISCUSSION

The PC-1D computer model (refs. 9 and 10) was used to simulate the experimentally measured cell results. Minority carrier diffusion lengths were varied to match the calculated values with the experimentally measured results. A 16-nm hole diffusion length in the emitter and a 0.42-μm electron diffusion length in the base correlated well with the current-voltage (I-V) measurements as shown in table I. Figure 2 shows the calculated and the best matched I-V characteristics of the simulated heteroepitaxial InP/GaAs solar cell. More details about solar cell modeling and the effect of variation of minority carrier diffusion lengths on the heteroepitaxial cell performance are described in reference 16. Figures 3 to 7 describe various calculated results on the effect of varying the emitter parameters and show the realistic optimized design study of the InP space solar cell. During modeling calculations, when one parameter was changed, all other parameters remained constant, except when emitter doping was varied.

In figure 3, from plotting the effect of emitter thickness on the cell performance, we can see that cell short-circuit current and efficiency both improve significantly with decreasing emitter thickness. We also found that the open-circuit voltage remains nearly constant and shows a decreasing trend for emitters thicker than 40 nm (not shown in fig. 3). Thinner emitters offer higher efficiencies, but it would be difficult to correctly predict the cell behavior for very shallow emitters (around 10 nm thick) because of the interaction and effects of surface and space charge fields. Achieving such thin controlled emitters poses a great technological challenge, especially by thermal diffusion techniques. However, with the advancements in MOCVD growth techniques, it should be possible to fabricate approximately 20-nm-thick emitters to achieve the highest possible efficiencies. The improvement in cell current for thinner emitters is due to improved recombination of minority carriers.

Figure 4 depicts the effect of emitter doping on cell performance. The cell efficiency and short-circuit current decrease with increases in emitter doping. The open-circuit voltage values are somewhat scattered in the 10^{18} to 10^{19} cm^{-3} doping range, but they definitly increase for dopings higher than 10^{19} cm^{-3} (not shown in fig. 3). Lightly doped emitters offer better cell performance due to increased minority carrier diffusion lengths, but optimal doping must be determined to learn the effect of an increase in series resistance. A further study to include the effects of a front surface field by high-low junction should be carried out. In calculating the results shown in figure 4, all the parameters were kept constant while doping concentrations were changed; one exception, the variation in hole diffusion length according to internal model calculations, is illustrated in figure 5. In the absence of accurate knowledge of the doping dependence of minority carrier diffusion length, the calculated results of figure 5 are the best approximation in the doping range of interest.

Figure 6 shows a plot of the heteroepitaxial cell AMO efficiency as a function of dislocation density. The dislocation density N_D was calculated from the simple relation (ref. 9) expressed as

$$N_D = \frac{4}{\pi^3} \frac{1}{L_D^2} \tag{1}$$

where L_D is the dislocation limited minority carrier diffusion length and is considered to be the electron diffusion length in the base. The solid line in figure 6 shows the variation of the cell efficiency as a function of dislocation density for a hole diffusion length of 16 nm and emitter thickness of 40 nm. Clearly as the dislocation density decreases, the cell efficiency improves significantly. These results are improved if the hole diffusion length in the emitter is increased to 80 nm, as shown by the dashed curve. The efficiency-dislocation density curve improves further when emitter thickness is reduced to 30 nm and to 20 nm, as shown in figure 6. Here, we can see that heteroepitaxial InP solar cells with efficiencies similar to present day homojunction InP cell efficiencies (>16 percent AMO) are possible if a dislocation density lower than 10^6 cm^{-2} can be achieved. Perhaps such advancements as identifying proper buffer layers, suitable annealing, and improved growth techniques will make possible the manufacture of large-area, highly efficient, radiation-hard, low cost, light weight, and mechanically strong heteroepitaxial InP cells for space power applications. The recently developed method of producing heteroepitaxial InP cells of over 13-percent AMO efficiency by controlling the dislocation density at around 10^7 cm^{-2} (owing to introduction of a proper GaInAs buffer layer) is an important step toward the desired goal. These cells have an emitter thickness of around 25 nm, and their efficiencies are in reasonable agreement with the calculated results in this paper (see fig. 6).

In figure 7 we have plotted the calculted I-V results of a 4-cm^2 area n^+p InP solar cell based on our realistic optimized design study. This study yielded a cell efficiency of over 22-percent AMO at 25 °C; fabrication of such cells should be possible in the near future because of cell material growth and processing improvements according to design. The details of the optimal design study of high efficiency InP solar cells will be discussed in a future paper. Table II describes the optimum design parameters for achieving high efficiency InP cells.

CONCLUSIONS

From the work reported herein, the following conclusions can be drawn:

(1) Short minority carrier diffusion lengths in the emitter and base are associated for the heteroepitaxial InP solar cells considered in this work.

(2) Thin emitters offer higher cell performance because of reduced recombination. To achieve high efficiencies, target thicknesses should be around 20 nm.

(3) Cells with lightly doped emitters achieve better cell performance due to improved minority carrier diffusion length. Doping densities of about 10^{18} cm^{-3} should be targeted to achieve high efficiencies.

(4) Fabrication of heteroepitaxial InP cells with efficiencies equivalent to homojunction cell efficiencies (>16-percent AMO) should be possible, provided a dislocation density below 10^{6} cm^{-2} is achieved. This would require the advancements in the development of suitable buffer layer and growth techniques to improve the lattice and thermal mismatch.

(5) An optimal design yields InP solar cells with over 22-percent AMO efficiencies at 25 °C. Based on the design parameters, fabrication of high

efficiency cells should be possible in the near future because of cell material and processing improvements.

ACKNOWLEDGMENTS

Valuable discussions with Dr. P.A. Basore of Sandia National Laboratories, Dr. I. Weinberg and Mr. D. Wilt of NASA Lewis Research Center, and Dr. G. Landis of Sverdrup Technology, Inc., NASA Lewis Research Center Group, are gratefully acknowledged.

REFERENCES

1. Yamaguchi, M.; and Ando K.: Mechanism for Radiation Resistance of InP Solar Cells. J. Appl. Phys., vol. 63, June 1, 1988, pp. 5555-5562.

2. Weinberg,I., et al.: Radiation and Temperature Effects in Gallium Arsenide, Indium Phosphide, and Silicon Solar Cells. IEEE Photovoltaic Specialists Conference, 19th, New Orleans, LA, May 4-8, 1987; Proceedings, IEEE, 1987, pp. 548-557.

3. Takamoto, T., et al.: Radiation Effects on n^+-p Homojunction Indium Phosphide Solar Cells. To be published in the proceedings on the Second International Conference on InP and Related Materials, Denver, April 23-25, 1990.

4. Yamamoto, A.; Yamaguchi, M.; and Uemura, C.: High Efficiency Homojunction InP Solar Cells. Appl. Phys. Lett., vol. 47, Nov. 1, 1985, pp. 975-977.

5. Keavney, C.J.; and Spitzer, M.B.: Indium Phosphide Solar Cells by Ion Implantation. Appl. Phys. Lett., vol. 52, Apr. 25, 1988, pp. 1439-1440.

6. Okazaki, H., et al.: Production of Indium Phosphide Solar Cells for Space Power Generation. IEEE Photovoltaic Specialists Conference, 20th, Las Vegas, NV, Sept, 26-30, 1988, IEEE, 1988, vol. 2, pp. 886-892.

7. Gessert, T.A., et al.: Progress in the ITO/InP Solar Cell. To be published in the Proceedings of the Second International Conference on InP and Related Materials, Denver, April 23-25, 1990.

8. Keavney, C.J.; Haven; V.E., and Vernon, S.M.: Surface Recombination and High Efficiency in InP Solar Cells. Proceedings to be published in the Second International Conference on InP and Related Materials, Denver, April 23-25, 1990.

9. Yamaguchi, M., et al.: A New Approach for Thin Film InP Solar Cells. Solar Cells, vol. 19, Nov. 1986, pp. 85-96.

10. Keavney, C.J., et al.: Fabrication of n^+/p InP Solar Cells on Silicon Substrates. Appl. Phys. Lett., vol. 54, 1989, pp. 1139-1141.

11. Pearton, S.J.; Short. K.T; Macrander, A.T.; Abernathy, C.R.; Mazzi, V.P.; Haegel, N.M.; Al-Jassim, M.M.; Vernon, S.M.; and Haven, V.E.: Characterization of InP/GaAs/Si Structures Grown by Atmosperic Pressure Metalorganic Chemical Vapor-Deposition, J. Appl. Phys., vol. 65, Mar. 1989, pp. 1083-1088.

12. Wanlass, M.W., et al.: Recent Advances in Epitaxial InP Based Solar Cells at SERI. To be published in the Proceedings of the Second International Conference on InP and Related Materials, Denver, April 23-25, 1990.

13. Al-Jassim, M.M., et al.: The Characterization of InP Layers Grown on Si Substrates by MOCVD. To be published in the Proceeding of the Second International Conference on INP and Related Materials, Denver, April 23-25, 1990.

14. Basore, P.A.; Rover, D.T.; and Smith, A.W.: PC-1D Version 2: Enhanced Numerical Solar Cell Modeling. IEEE Photovoltaic Specialists Conference, 20th, Las Vegas, NV, Sept. 26-30, 1988, IEEE, 1988, vol. 1, pp. 389-404.

15. Basore, P.A.: PC-1D Installation Manual and User's Guide Version 2.1. Iowa State University Research Foundation, Ames, IA, 1989.

16. Jain, R.K.; and Flood, D.J.: Estimation of Minority Carrier Diffusion Lengths in InP/GaAs Solar Cells. To be published in the Proceedings of the Second International Conference on InP and Related Materials, Denver, April 23-25, 1990.

TABLE I. - COMPARISON OF MEASURED AND CALCULATED HETEROEPITAXIAL InP CELL PARAMETERS

	Short-circuit current, I_{sc}, mA	Open-circuit voltage, Voc, mV	Efficiency, Eff, percent
Measured average (standard deviation)	6.654 (.180)	666.6 (.037)	8.92 (.138)
Calculated	6.657	665.2	9.05

TABLE II. - DESIGN PARAMETERS OF AN OPTIMALLY DESIGNED InP SOLAR CELL

Emitter thickness, nm	20
Emitter doping, cm^{-3}	10^{18}
Hole diffusion length, µm	0.1
Front surface recombination velocity, cm/sec	10^4
Front grid coverage, percent	5
Intrinsic carrier concentrate, cm^{-3}	8×10^6
Base thickness, µm	5
Base doping, cm^{-3}	5×10^{16}
Electron diffusion length, µm	20
Back surface recombination velocity, cm/sec	10^5
Cell series resistance, Ω cm^2	1
Energy bandgap, eV	1.35

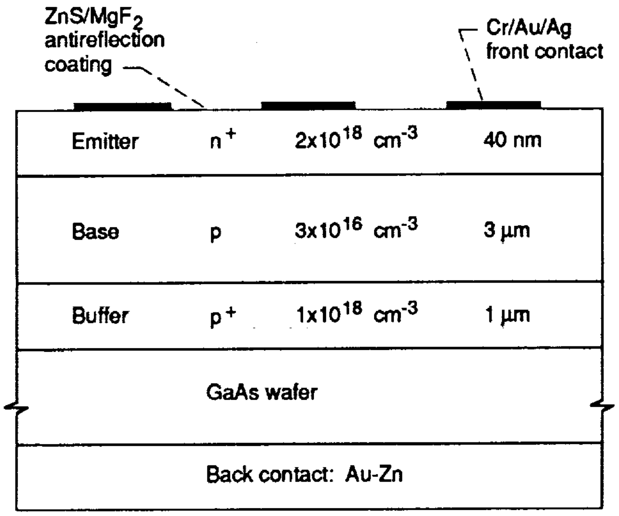

Figure 1.—Structure of a MOCVD InP/GaAs solar cell.

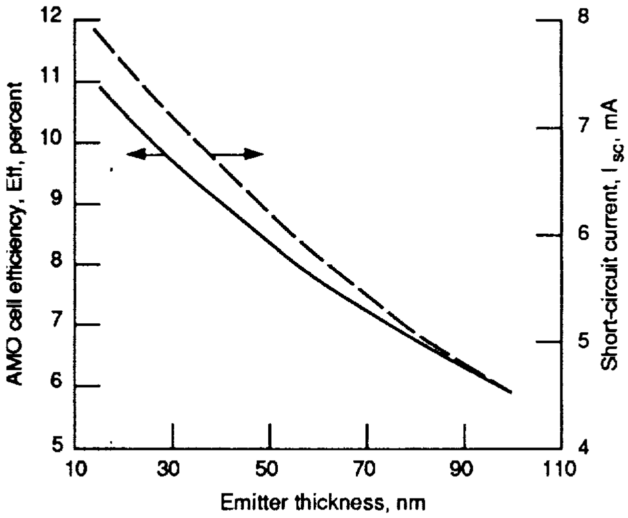

Figure 3.—Calculated InP/GaAs cell efficiency and short-circuit current as a function of emitter thickness.

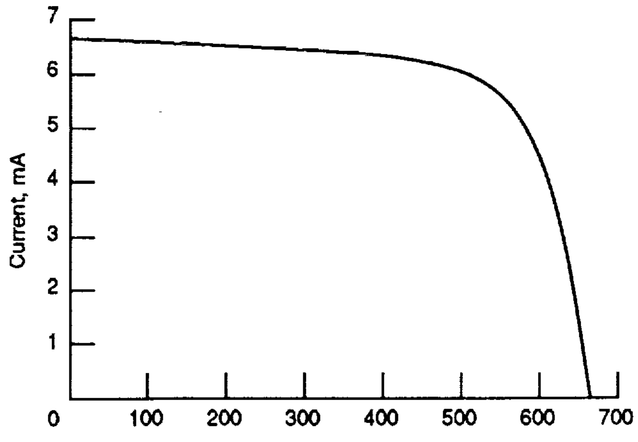

Figure 2.—Calculated current-voltage plot of the heteroepitaxial InP/GaAs solar cell (I_{sc} = 6.657 mA; V_{oc} = 665.2 mV, Eff = 9.05-percent AMO (137.2 mW/cm^2, 25 °C); cell area = 0.25 cm^2) giving best matching with average experimental results.

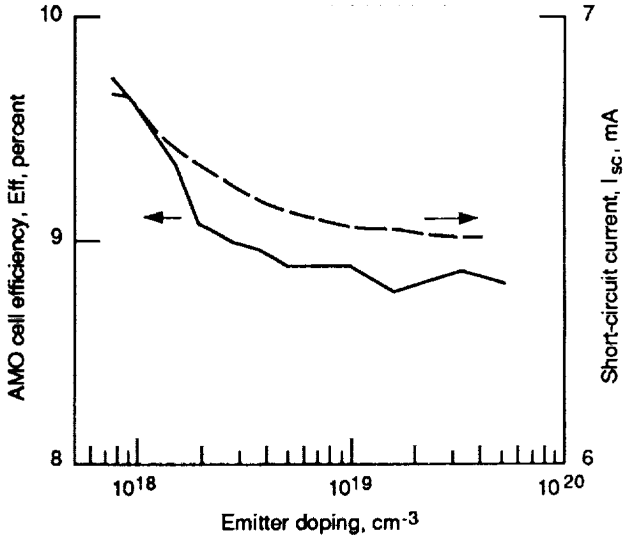

Figure 4.—Calculated InP/GaAs cell efficiency and short-circuit current as a function of emitter doping.

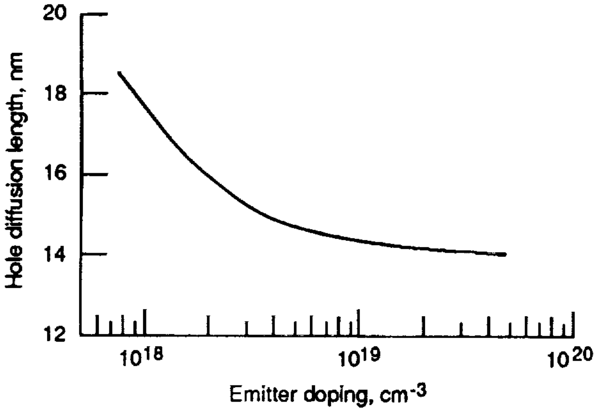

Figure 5.—Variation of hole diffusion length as a function of emitter doping.

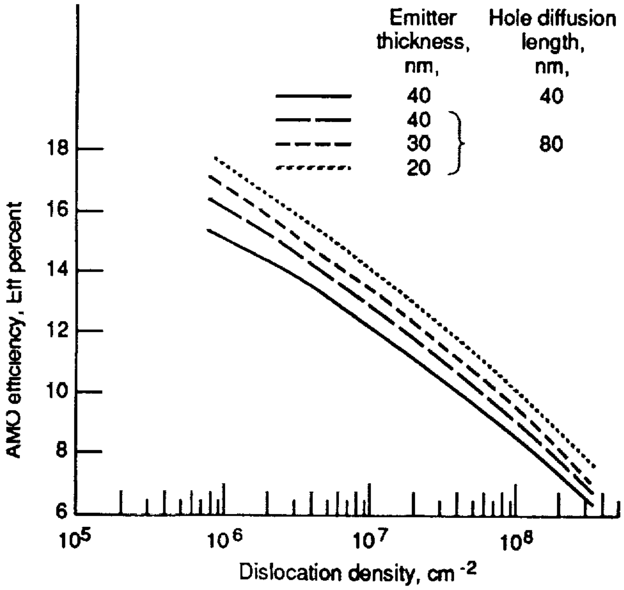

Figure 6.—Effect of dislocation density on InP cell AMO efficiency.

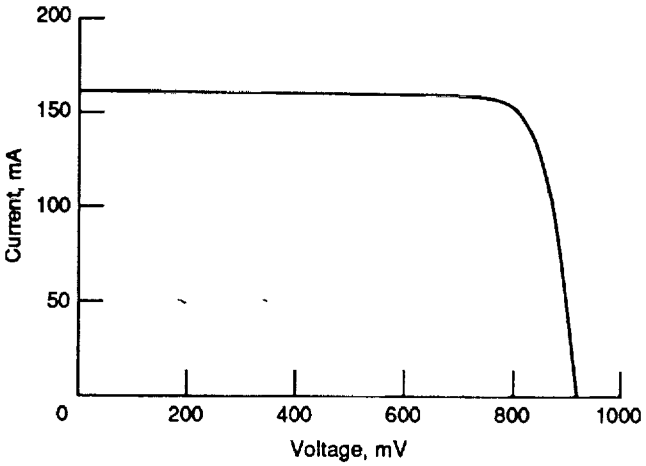

Figure 7.—Predicted current-voltage characteristics of the optimally designed n^+p InP/GaAs solar cell. Cell area = 4 cm^2; I_{sc} = 161.40 mA; V_{oc} = 920.9 mV; FF = 83.2 percent; and Eff = 22.54-percent AMO at 25 °C.

National Aeronautics and Space Administration

Report Documentation Page

1. Report No.
NASA TM-103619

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Effect of Emitter Parameter Variation on the Performance of Heteroepitaxial Indium Phosphide Solar Cells

5. Report Date
December 1989

6. Performing Organization Code

7. Author(s)
Raj K. Jain and Dennis J. Flood

8. Performing Organization Report No.
E-5776

10. Work Unit No.
506-41-11

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 21st Photovoltaics Specialists Conference sponsored by the Institute of Electrical and Electronics Engineers, Kissimmee, Florida, May 21-25, 1990. Raj K. Jain, National Research Council—NASA Research Associate at Lewis Research Center. Dennis J. Flood, Lewis Research Center.

16. Abstract

Metallorganic chemical-vapor-deposited heteroepitaxial indium phosphide (InP) solar cell experimental results have been simulated by using a PC-1D computer model. The effect of emitter parameter variation on the performance of $n^+/p/p^+$ heteroepitaxial InP/GaAs solar cell has been presented. The thinner and lighter doped emitters were observed to offer higher cell efficiencies. The influence of emitter thickness and minority carrier diffusion length on the cell efficiency with respect to dislocation density was studied. Heteroepitaxial cells with efficiencies similar to present day homojunction InP efficiencies (> 16-percent AMO) were shown to be attainable if a dislocation density lower than 10^6 cm^{-2} could be achieved. A realistic optimized design study yielded InP solar cells of over 22-percent AMO efficiency at 25 °C.

17. Key Words (Suggested by Author(s))
Indium phosphide
Solar cells
Emitter parameters
Solar power

18. Distribution Statement
Unclassified – Unlimited
Subject Category 20

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of pages
14

22. Price*
A03

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161