NASA Technical Memorandum 106255

Lattice-Mismatched $In_{0.40}Al_{0.60}As$ Window Layers for Indium Phosphide Solar Cells

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Prepared for the
23rd Photovolaic Specialists Conference
sponsored by the Institute of Electrical and Electronics Engineers
Louisville, Kentucky, May 10–14, 1993

NASA

LATTICE-MISMATCHED $In_{0.40}Al_{0.60}As$ WINDOW LAYERS FOR INDIUM PHOSPHIDE SOLAR CELLS

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SUMMARY

The efficiency of indium phosphide (InP) solar cells is limited by its high surface recombination velocity ($\sim 10^7$ cm/s). This might be reduced by a wide-bandgap window layer. In this work we calculated the performance of InP solar cells with wide-bandgap (1.8 eV) lattice-mismatched $In_{0.40}Al_{0.60}As$ as a window layer. Because the required window layer thickness is less than the critical layer thickness, growth of strained (pseudomorphic) layers without interfacial misfit dislocations should be possible. Calculations using the PC–1D numerical code have shown that the efficiencies of baseline and optimized p^+n (p-on-n) cells are increased to more than 22 and 24 percent, (air mass zero (AM0), 25 °C), respectively for a lattice-mismatched $In_{0.40}Al_{0.60}As$ window layer of 10-nm thickness. Currently, most cell development work has been focused on n^+p (n-on-p) structures although comparatively little improvement has been found for n^+p cells.

INTRODUCTION

The improved resistance of indium phosphide (InP) solar cells to electron (ref. 1) and proton (ref. 2) irradiations and the prospects for high efficiency (ref. 3) make the InP cells very promising for space applications. The efficiencies achieved to date are limited by high values of surface recombination velocity (SRV $\sim 10^7$ cm/s), which could be reduced by window layers and proper passivation. The use of suitable wide-bandgap window layers on gallium arsenide (ref. 4) and silicon (ref. 5) solar cells has resulted in significant improvements in device performance. Other factors that could improve cell efficiency are increased minority carrier diffusion length and reduced cell series resistance. This report presents the predicted results on the effective reduction of SRV with lattice-mismatched wide-bandgap $In_{0.40}Al_{0.60}As$ used as a window layer.

Figure 1 shows the calculated effect of the front SRV on the efficiency of optimized InP solar cells (refs. 6 and 7). These results indicate that the SRV has a major effect on the cell performance. Because

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n^+p (n-on-p) cells have relatively thin emitters ($\sim$0.02 μm), they are less affected by the SRV than p^+n (p-on-n) cells. Thicker emitters are required in p^+n cells to keep the series resistance low.

A recent systematic modeling study (ref. 8) has shown that p^+n structures could become more efficient than n^+p structures if surface recombination is reduced. This study generated renewed interest in the study of p^+n structures, engaging several research groups in theoretical and experimental work. The p^+n structure could also offer an additional advantage by avoiding the problem of n-type impurity doping into the base from the substrate (Si, Ge) in n^+p structures grown by heteroepitaxy.

APPROACH

Selection of Window Layer Material

The energy bandgap and lattice constant for III–V semiconducting compounds are shown in figure 2 (ref. 9). Unlike the case of GaAs, where $Al_xGa_{1-x}As$ forms a naturally lattice-matched ternary system for all values of x, wide-bandgap window layers for InP are more constrained. As seen in figure 2, the possibilities for lattice-matched heteroepitaxial systems for InP are relatively limited. Little experimental data exist about growth of the ternary compound AlAsSb; however, the ternary compound $In_xAl_{1-x}As$ seems to be quite suitable as a window layer for InP solar cells. At the lattice-matched composition of $x = 0.52$, the bandgap is only slightly higher than that of InP. The steep slope of the curve showing changes in the bandgap with a change in the lattice parameter for InAlAs suggests that a significant increase in window layer transparency could be achieved by only a small deviation in the lattice parameter from the lattice-matched value of 5.86 Å.

The use of $In_xAl_{1-x}As$ has been widespread in electronic and optical devices. Most of the work has been focused on $In_{0.52}Al_{0.48}As$, which is lattice matched to InP. This resulted in a state-of-the-art performance for several types of optoelectronic devices (refs. 10 and 11); however, no experimental data for solar cells are available, with the exception of our predicted performance of InP solar cells with lattice-matched InAlAs (ref. 12). Our work shows that absorption in the InAlAs layer is a significant factor, because of the small difference in E_g for lattice-matched material. If the constraint of lattice matching can be removed by the use of strained (pseudomorphic) material, a further increase in performance could be realized.

Recently, some work has been reported on the growth and use of lattice-mismatched InAlAs in fabricating heterostructure field effect transistors (HFET's) (refs. 13 and 14). The approach of growing strained layers offers freedom to vary the material optical and electronic properties. The growth of thick lattice-mismatched layers may result in the generation of misfit dislocations attributed to the relaxation of the strain energy. The misfit dislocations at the interface and their propagation will deteriorate device performance; however, lattice-mismatched layers grown less than the critical layer thickness will be strained and are free from misfit dislocations. For a fixed lattice mismatch, the thickness at which misfit dislocations begin to form is known as the critical layer thickness. The critical layer thickness decreases with the increase in lattice mismatch. Several theories on critical layer thickness calculations and experimental data on the different heteroepitaxial structures are available in the literature.

For InP (bandgap energy 1.35 eV) solar cells, the optimum choice is an InAlAs layer with the widest bandgap possible to reduce the light absorption losses. We selected $In_{0.40}Al_{0.60}As$ for our calculations. In this composition, the lattice mismatch with InP is -0.77 percent and the bandgap energy is around 1.8 eV. This wide bandgap makes the $In_{0.40}Al_{0.60}As$ layer nearly transparent to the incoming light that is useful for the InP solar cell.

For a lattice mismatch of −0.77 percent, calculations using the Matthews and Blakeslee (M–B) (ref. 15) theory give an estimation of about 13 nm for the critical layer thickness, although a more recent work by Bennett and del Alamo (ref. 13) shows that it was considerably larger. HFET's with 30 nm of a strained $In_{0.40}Al_{0.60}As$ layer showed no degradation due to mismatch (fig. 10(b) of ref. 13). Using high-resolution x-ray diffraction, it is found that for a lattice mismatch of $\leq \pm 1$ percent, the crystalline quality of the InAlAs epitaxial layer remains high to thicknesses from three to nine times the M–B critical layer thickness (ref. 13).

In the calculations reported in this paper, we have considered a 10-nm-thick $In_{0.40}Al_{0.60}As$ lattice-mismatched layer as a window, which is less than the critical layer thickness calculated by the most conservative (M–B) approximation.

Estimation of $In_{0.40}Al_{0.60}As$ Parameters

Since limited information is available concerning (optical, electrical, physical, and other) properties of ternary InAlAs material, we attempted to estimate the critical parameters based on InP and lattice-matched $In_{0.52}Al_{0.48}As$ available literature. The bandgap energy of the strained $In_{0.40}Al_{0.60}As$ is 1.8 eV (fig. 2) and the strained layer lattice constant is 5.815 Å, compared with 5.86 Å for InP. A value of 0.294 eV for the conduction-band energy discontinuity has been considered, which is the same as the lattice-matched InAlAs. The intrinsic carrier concentration, n_i for the strained $In_{0.40}Al_{0.60}As$ was scaled from the value for InP (8×10^6 cm^{-3} (ref. 16)) using the relation,

$$n_i\,(In_{0.40}Al_{0.60}As) = n_i\,(InP)\,\exp\{-\,\Delta E_g/(2kT)\}$$

where ΔE_g is the bandgap difference, k is the Boltzmann constant, and T is the temperature in kelvin. The optical absorption coefficient of the lattice-mismatched InAlAs was assumed to be the same as that of InP but shifted in wavelength by the bandgap ratio (1.35/1.8). In the calculations, other parameters were assumed to be the same as those of InP.

RESULTS AND DISCUSSION

We have considered both the baseline and the optimized designs of the InP cells. The baseline cell design uses material parameters that are representative of the current state-of-the-art InP solar cells. The optimized cell design assumes improvements in material parameters, which we believe are achievable by suitable processing improvements. More details about InP cell modeling are available in references 4 to 6. The design parameters of p^+n InP cells used in our calculations are described in table I. The PC–1D numerical code (ref. 17) was used to calculate the cell current-voltage characteristics and the external quantum efficiency response with and without the InAlAs window. A strained $In_{0.40}Al_{0.60}As$ window layer with a surface recombination velocity of 10^7 cm/s was assumed. The window layer doping and diffusion length were assumed equal to the cell emitter values (table I). To avoid heavy doping effects, moderate dopings (10^{18} cm^{-3}) of the window and emitter regions were considered. An optimum base doping of 10^{17} cm^{-3} was assumed (refs. 5 and 6). Figure 3 shows the InP cell structure with a window layer.

Current-Voltage Characteristics

Figure 4 shows the calculated I–V characteristics (AM0, 25 °C) of the baseline and optimized cell using the parameters of table I. This figure also includes the calculated I–V results of the cell with the lattice-mismatched $In_{0.40}Al_{0.60}As$ window layer of 10-nm thickness. The use of a window layer on the baseline cell improves the cell's efficiency from 14.7 percent AM0 to more than 22 percent, while the optimized cell efficiency increases from 15.4 percent AM0 to more than 24 percent. This greater improvement of the optimized cell is caused by its reduced bulk recombination.

For comparison we calculated the I–V curve of a p^+n InP cell with decreased front SRV. A reduction in the front SRV from 10^7 to 10^4 cm/s is necessary to achieve the efficiencies obtained with the 10-nm window layer. This reduction demonstrates that the window layer is effectively improving the SRV.

Calculations were also performed to study the effect of a lattice-mismatched window layer on the efficiency of n^+p InP solar cells. Comparatively little improvement (~1 percent) in efficiency was obtained for these cells. These results can be explained by the large conduction-band energy discontinuity at the window/cell emitter (InAlAs/InP) interface. This discontinuity acted as an effective potential barrier for the minority carriers (electrons) of the p^+n cell, thereby stopping them from recombining at the surface. The holes in the n^+p cell emitter were not influenced much by the conduction-band energy discontinuity, which resulted in a less significant reduction in surface recombination.

As discussed earlier, $In_{0.40}Al_{0.60}As$ layers up to 30-nm thick were grown with high crystalline quality and HFET's (majority carrier devices) were fabricated without any degradation resulting from mismatch. We also calculated the p^+n cell efficiency for a 30-nm-thick $In_{0.40}Al_{0.60}As$ window layer. The short circuit current was slightly reduced, but the efficiency remained high, as shown in figure 5. This slight reduction suggested that the wide-bandgap (1.8 eV) lattice-mismatched window layer was quite transparent to the incoming light and absorption losses were negligible. However, it was desired to keep the window layer thickness lower than 30 nm, since this thickness was approximately the maximum allowable thickness before strained layers gradually changed to unstrained layers by generation of misfit dislocations. Any dislocations generated in the interface region may greatly affect the solar cell (minority carrier device) performance. InAlAs layers of 10 nm or thinner can be grown by the molecular beam epitaxy (MBE) or the metal organic vapor phase epitaxy (MOVPE) techniques.

External Quantum Efficiency

The calculated cell external quantum efficiency response for the baseline and the optimized p^+n InP solar cells in the 300- to 950-nm wavelength range is shown in figure 6. The cell response was calculated with and without a 10-nm $In_{0.40}Al_{0.60}As$ window layer. Since the cell external quantum efficiency curve with a 10-nm window is almost flat in the 375- to 800-nm wavelength range, these results indicate that the efficiency improves significantly with the lattice-mismatched window layer, especially in the blue response.

CONCLUSIONS

The calculated results demonstrated that a wide-bandgap strained InAlAs layer is a potential window-layer material. Pseudomorphic InAlAs material that is less than the critical layer thickness is required. The light absorption loss in the strained InAlAs considered was almost negligible.

A 10-nm lattice-mismatched $In_{0.40}Al_{0.60}As$ window layer resulted in significant improvement in the cell and external quantum efficiencies of p^+n InP cells. Comparatively little improvement was predicted for the n^+p cells.

The calculations using the PC–1D numerical code were based on extrapolated values of the optical and electrical parameters of InAlAs using the best available data. In particular, the results were sensitive to the absorption coefficient and to the conduction-band discontinuity, neither of which was measured for strained InAlAs. It must be cautioned that better measurements of the basic parameters were necessary to confirm these calculations. The measurements may have also caused the predicted efficiencies to be different than what was expected.

ACKNOWLEDGMENT

The authors thank Prof. Jesus A. del Alamo at the Massachusetts Institute of Technology and Dr. Timothy J. Coutts at the National Renewable Energy Laboratory for helpful discussions on the issues related with the InAlAs critical layer thickness and the use of strained layers as window in InP solar cells respectively.

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TABLE I.—BASELINE AND OPTIMIZED p^+n InP SOLAR CELL PARAMETERS USED IN THE CALCULATIONS

Solar cell parameter	Baseline	Optimized
Grid shadowing, percent	5	5
Series resistance, Ω-cm^2	0.3	0.3
Two-layer antireflection coating (ZnS/MgF_2), nm	[a]50/[b]100	[a]50/[b]100
Emitter		
Thickness, μm	0.15	0.15
Doping, cm^{-3}	10^{18}	10^{18}
Front surface recombination velocity, cm/s	10^7	10^7
Minority carrier diffusion length, μm	0.5	2
Base		
Thickness, μm	5	5
Doping, cm^{-3}	10^{17}	10^{17}
Back surface recombination velocity, cm/s	10^7	10^7
Minority carrier diffusion length, μm	2	5

[a]Value for ZnS.
[b]Value for MgF_2.

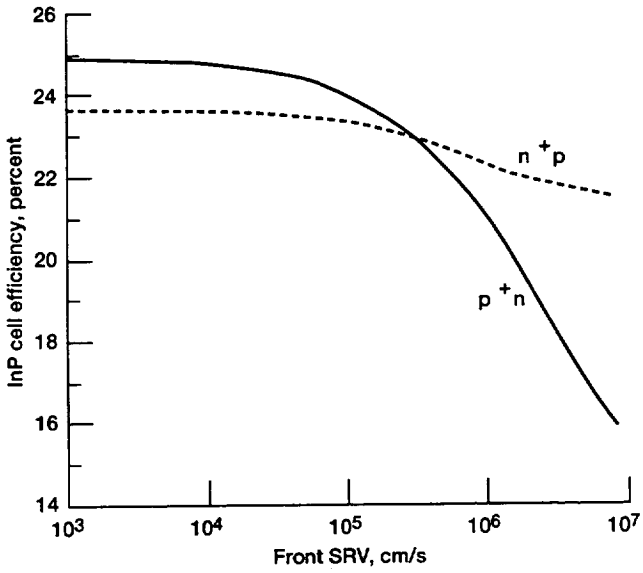

Figure 1.—Calculated effect of the front surface recombination velocity on the efficiency of optimized indium phosphide solar cells, (AM0, 25 °C).

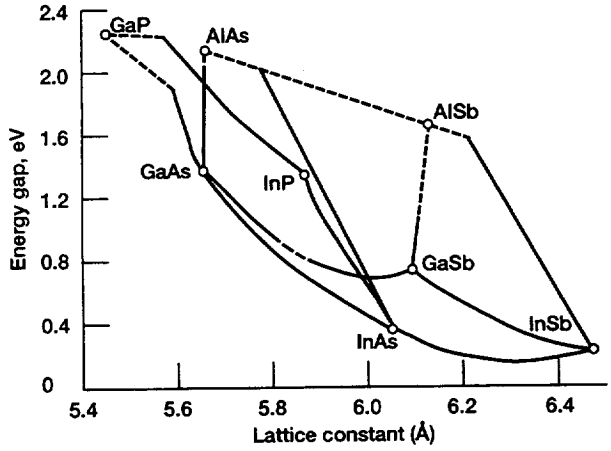

Figure 2.—Energy bandgap and lattice constant for III-V compound semiconductors. Solid and dashed lines show direct and indirect bandgaps for alloys.

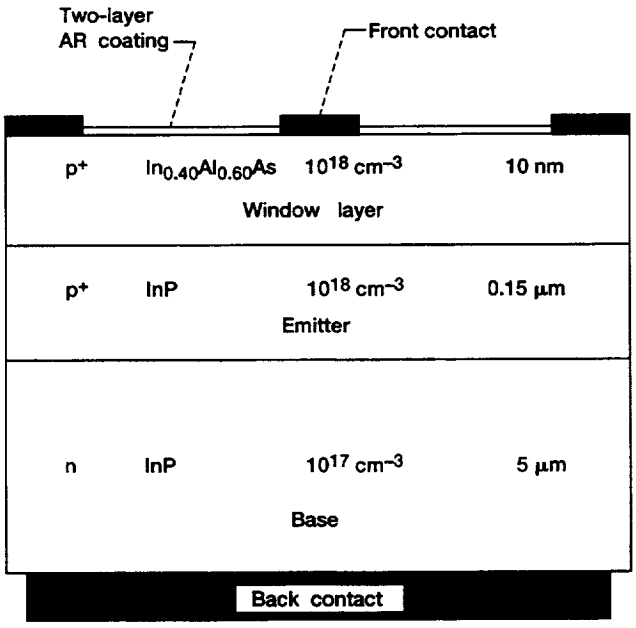

Figure 3.—Indium phosphide solar cell structure with strained $In_{0.40}Al_{0.60}As$ window layer.

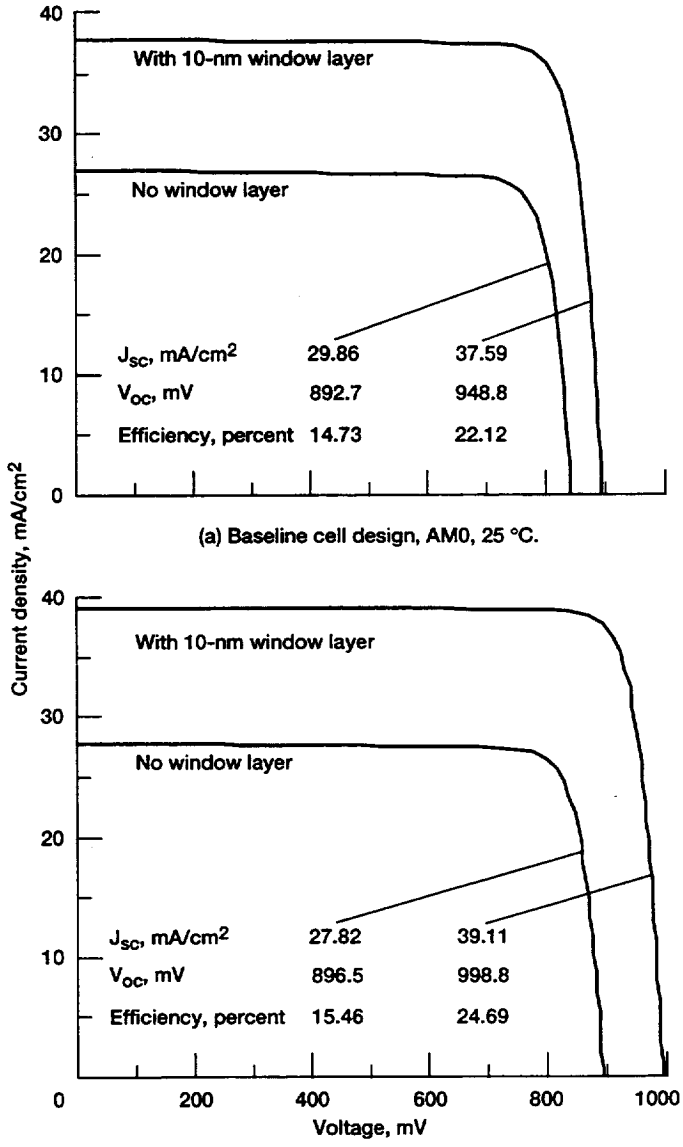

Figure 4.—Calculated current-voltage characteristics (AM0, 25 °C) of the p+n InP cell with and without 10-nm $In_{0.40}Al_{0.60}As$ window layer.

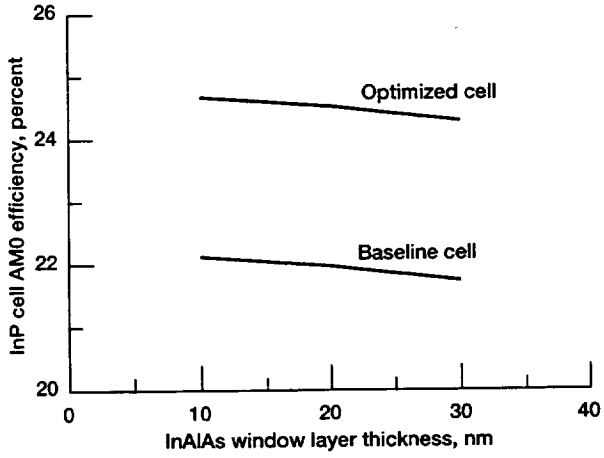

Figure 5.—Calculated p+n InP AM0 cell efficiency as a function of lattice-mismatched $In_{0.40}Al_{0.60}As$ window layer thickness.

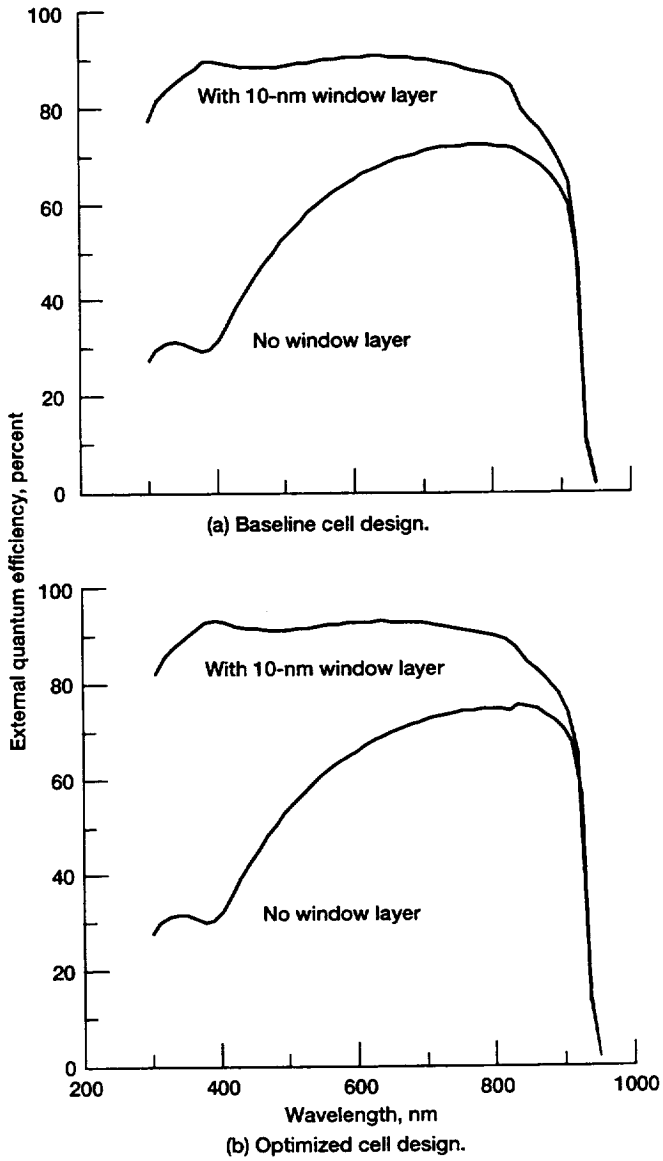

Figure 6.—Calculated external quantum efficiency response of the p+n InP cell with and without 10-nm $In_{0.40}Al_{0.60}As$ window layer.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1993	Technical Memorandum

4. TITLE AND SUBTITLE

Lattice-Mismatched $In_{0.40}Al_{0.60}As$ Window Layers for Indium Phosphide Solar Cells

5. FUNDING NUMBERS

WU-506-41-11

6. AUTHOR(S)

R.K. Jain, G.A. Landis, D.M. Wilt, and D.J. Flood

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
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Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E-7879

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-106255

11. SUPPLEMENTARY NOTES

Prepared for the 23rd Photovoltaic Specialists Conference sponsored by the Institute of Electrical and Electronics Engineers, Louisville, Kentucky, May 10-14, 1993. R.K. Jain, National Research Council, NASA Research Associate at Lewis Research Center; G.A. Landis, Sverdrup Technology, Inc., Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142 (work funded by NASA contract NAS3-25266); and D.M. Wilt and D.J. Flood, NASA Lewis Research Center. Responsible person, R.K. Jain, (216) 433-2227.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 33

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The efficiency of indium phosphide (InP) solar cells is limited by its high surface recombination velocity (~ 10^7 cm/s). This might be reduced by a wide-bandgap window layer. In this work we calculated the performance of InP solar cells with wide-bandgap (1.8 eV) lattice-mismatched $In_{0.40}Al_{0.60}As$ as a widow layer. Because the required window layer thickness is less than the critical layer thickness, growth of strained (pseudomorphic) layers without interfacial misfit dislocations should be possible. Calculations using the PC-1D numerical code have shown that the efficiencies of baseline and optimized p^+n (p-on-n) cells are increased to more than 22 and 24 percent, (air mass zero (AMO), 25 °C), respectively for a lattice-mismatched $In_{0.40}Al_{0.60}As$ window layer of 10-nm thickness. Currently, most cell development work has been focused on n^+p (n-on-p) structures although comparatively little improvement has been found for n^+p cells.

14. SUBJECT TERMS

Space power; Lattice-mismatched InAlAs; Indium Phosphide; Solar cells; Window layer

15. NUMBER OF PAGES

10

16. PRICE CODE

A02

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	