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COMPARATIVE PERFORMANCE OF DIFFUSED JUNCTION INDIUM PHOSPHIDE SOLAR CELLS

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A comparison was made between indium phosphide solar cells whose p-n junctions were processed by open tube capped diffusion, and closed tube uncapped diffusion, of sulphur into Czochralski grown p-type substrates. Air mass zero, total area, efficiencies ranged from 10 to 14.2%, the latter value attributed to cells processed by capped diffusion. The radiation resistance of these latter cells was slightly better, under 1 MeV electron irradiation. However, rather than being process dependent, the difference in radiation resistance could be attributed to the effects of increased base dopant concentration. In agreement with previous results, both cells exhibited radiation resistance superior to that of gallium arsenide. The lowest temperature dependency of maximum power was exhibited by the cells prepared by open tube capped diffusion. The average value of dPm/dT, including cells of both types, was found to be $-(5.3 \pm 1.2) \times 10^{-2}$ mW/cm^2 °K at 60°C. Calculated values if dVoc/dT were in reasonable agreement with experimental values. However, contrary to previous results, no correlation was found between open circuit voltage and the temperature dependency of Pmax. It was concluded that additional process optimization was necessary before concluding that one process was superior to the other.

INTRODUCTION

It has been demonstrated that n/p homojunction indium phosphide solar cells have properties which make them excellent candidates for use in the space radiation environment.[1,2,3,4] This follows from their excellent radiation resistance, annealibility at relatively low temperatures and under the influence of light and their potentially high efficiencies.[1,5,6] These desirable properties have served as a stimulus for renewed InP solar cell research both in the USA and abroad.[3,4] However, due to the different ways in which results are reported, and the various standards and light sources used in measuring cell performance it is difficult to meaningfully compare the results emanating from different laboratories.[3] For example, results appear in the literature quoting active area efficiencies and under AM1.5, AM1 and AM0 light intensities. For space use, the latter spectrum with parameters reported in terms of total area has long been the sole accepted mode for reporting cell performance measurements. In the present case we compare the performance of indium phosphide solar cells processed by two different techniques, in two separate laboratories. Performance data are obtained, in the same simulator, under air mass zero conditions with efficiencies and current densities reported in terms of total rather than active area. Our interest lies in comparing cell performance parameters of unirradiated cells and after exposure to 1 MeV electrons and the variations in performance under varying temperature conditions.

EXPERIMENT

The diffused junction InP cells differed principally in the method of p/n junction formation. Referring to Fig. 1, the cells whose junction were formed by closed tube diffusion (labeled J cells) were processed at the Nippon Telephone and Telegraph, Electrical Communication Laboratories in Ibaraki, Japan.[7] On the other hand, the cells processed by open tube capped diffusion (labeled R cells) were processed at the Rensselaer Polytechnic Institute.[8] In both cases, the starting material was p-type, zinc-doped Czochralski grown indium phosphide, sulphur being the n-dopant. Major cell fabrication details are shown in the figure. Additional processing details can be found in references 7 and 8. All performance measurements were carried out at NASA Lewis using an air mass zero X-25 zenon arc solar simulator with a gallium arsenide solar cell used as a standard. The standard cell was calibrated at air mass zero using the Lewis high altitude aircraft technique.[9]

The cells were irradiated by 1 MeV electrons in the Naval Research Laboratories Van De Graaf accelerator. Temperature dependency measurements on unirradiated cells were performed in a nitrogen atmosphere using a variable temperature chamber into which the X-25 simulator beam was introduced through a glass port built into the side of the simulator.

RESULTS

The performance parameters of several R and J cells, determined at 25°C, are shown in Table 1. The efficiencies of 14.2% for R cells and 13.6% for the J cells are the highest AMO, total area efficiencies, measured at 25°C, at NASA Lewis, for these cell types. However, these are not the highest efficiencies obtained for InP cells. For example, we have measured an AMO total area efficiency of 15.9%, at 25°C for a p^+n InP cell whose junction was formed by OMCVD.[10] On the other hand, AMO active area efficiencies of 18%, at 20°C, have been reported for a p^+-I-n cell also fabricated by OMCVD.[11] Since this latter cell had 10% front grid coverage, the total area AMO efficiency at 25°C is calculated to be 16%. To obtain this latter value at 25°C, we used the temperature correction factor $dPm/dT = -5.3 \times 10^{-2}$ mW/cm^2 °K where Pm is cell maximum power output. This numerical value is obtained in a following section of the present work.

Results of the 1 MeV electron irradiations are shown in Figs. 2, 3, and 4 for the InP cells listed in Table II. Also shown are results for state of the art GaAs cells, obtained from Varian.[12] Preirradiation cell parameters for the GaAs cells are shown in Table III. Since these latter cells had efficiencies close to 20%, they produce more output power over the present fluence range than do the InP cells. However, when plotted on a normalized basis, in terms of preirradiation output power, the InP cells exhibit greater radiation resistance. This latter result is in agreement with previous results.[1,2]

DISCUSSION

From Fig. 2, the cells processed by open tube capped diffusion have slightly higher radiation resistance, at the lower fluences, than the cells processed by closed tube diffusion. However, one cannot state from these results that one specific process inherently results in superior radiation resistance. This follows from the observation that, in the present concentration range, radiation resistance increases with base dopant concentration.[13]

Considering the remaining cell performance parameters it is seen that, for irradiated InP,the greatest drop occurs in Isc while for GaAs, the greatest drop occurs in Voc as a result of the irradiation. This would tend to indicate that a decrease in diffusion length with irradiation is a major factor in decreased output for the InP cells while for GaAs, the change in dark current with irradiation appears to be the major factor in decreased cell output.

Decreased cell output power with increasing temperature is an additional significant loss factor. An example of the variation in cell output power with temperature shown in Fig. 5, while Fig. 6 graphically summarizes the variation in cell maximum power, Pmax, with temperature determined for a number of R and J cells at 60°C. This temperature was chosen as representative of that experienced by solar cells in low earth and geosynchronous orbit. Cell performance parameters for these cells are listed in Table IV. From the table, the average value of dPm/dT for these cells is $-(5.3 \pm 1.2) \times 10^{-2}$ mW/cm^2 °K.

To consider temperature effects in greater detail it is convenient to express the temperature dependencies of the cell performance parameters as relative variations, using the expression[14]

$$\frac{1}{Pm}\frac{dPm}{dT} = \frac{1}{Isc}\frac{dIsc}{dT} + \frac{1}{Voc}\frac{dVoc}{dT} + \frac{1}{FF}\frac{dFF}{dT} \qquad (1)$$

The temperature variation terms in the right hand side of Equation 1 are listed in Table V. In the past, the term in dVoc/dT was found to be a major factor in the variation of Pmax with temperature.[14,15] Hence, we examine this term in some detail using the expression[14]

$$\frac{dVoc}{dT} = \frac{Voc-Eg(T)}{T} - \frac{3k}{q} - \frac{\alpha T\,(T+2\beta)}{(T+\beta)^2} + \frac{kT}{I_{sc}q}\frac{dIsc}{dT} \qquad (2)$$

where k is Boltzmann's constant and q is the electronic charge with,

Eg(T) = the band gap at temperature T in electron volts

$$Eg(T) = Eg(0) - \frac{\alpha T^2}{(T+\beta\ )} \qquad (3)$$

Eg(0) = 1.421 electron volts

$\alpha = 6.63 \times 10^{-4}$ V/°K

$\beta = 552$ °K

It is noted here that, in reference 16, the value of β is given as 162°K. However, this latter quantity yields the value 1.292 eV for Eg at 300°K rather than the more correct value 1.351 eV.[16] The present value of β used in Eq. 3 yields the more correct bandgap value at 300°K.

Using the preceding set of equations, calculated values of dVoc/dT are found to be in reasonable agreement with experiment (Table VI). The success of equation 2 in predicting experimental values has led to the prediction of an inverse relation between Voc and the absolute magnitude of (1/Voc)(dVoc/dT).[14] From Fig. 7, it is seen that the present data is in rough agreement with the preceding statement. Also, if the term in dVoc/dT were dominant in Eq. 1, then there should be an inverse relation between Voc and the magnitude of (1/Pm) (dPm/dT).[14] However, as seen from Fig. 8, this is not the case for the present data. In fact, from the data of Table V, one cannot generalize and state that for InP, the temperature variation of any specific quantity is dominant in determing the temperature variation of Pmax. Noting however that the temperature dependencies in Table V are both positive and negative, it is desirable that dIsc/dT be as large as possible while the absolute magnitude of the negative terms in Voc and FF be as small as possible.

In general, the temperature dependence of Isc arises from the fact that diffusion length increases with temperature while band gap decreases with increasing temperature, the net result being an increase in current. With respect to the temperature dependence of Voc, from Eq. 2, it is seen that at fixed temperature, higher values of Voc lead to the desired lower values in the absolute magnitude of dVoc/dT. In this respect it is noted that, in Eq. 2, the term in dIsc/dT yields a relatively small contribution to dVoc/dT the principal contribution arising from the first term. The fill factor term in Eq. 1 is perhaps the most process dependent. Here one would expect shunt (Rsh) and series resistance (Rs) to play significant roles. However, a theoretical expression for dFF/dT is needed which includes the effects of Rs and Rsh.[14] Aside from this, the factors operative in determining the temperature dependencies of Voc and Isc are apparent from the preceding discussion and warrant further consideration in attempts to reduce the temperature dependency of Pmax.

CONCLUSION

In comparing the performance of these diffused junction cells one cannot conclude that either process is preferable in terms of increased radiation resistance. Although the cells prepared by open tube capped diffusion have slightly higher efficiencies, as measured at Lewis, it is possible that neither process was optimized at the time the present cells were processed. Hence a choice, based on efficiency, would be premature. The greatest difference appears in the temperature dependency, which favors the R cells. However the data is inconsistent in the sense that the present results do not show the dependency of dPm/dT on open circuit voltage which was observed in previous work.[14,15] In addition, the exact dependencies of the temperature variation of fill factor on Rs and Rsh is unclear at present. Thus, in summation, it can be stated that further efforts in both theory and experiment are required before concluding that one process is preferable to the other.

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TABLE I

AMO PERFORMANCE PARAMETERS OF InP CELLS

T=25°C

CELL	CARRIER CONC (cm^{-3})	EFFICIENCY (%)	Voc (mV)	Jsc (ma/cm^2)	FF (%)
R-1	$4.5X10^{16}$	14.2	814	30.5	78.5
R-2	$9.0X10^{16}$	13.7	825	28.8	79.1
R-3	$4.5X10^{16}$	12.9	815	26.3	82.6
J-1	$5.0X10^{15}$	13.6	826	27.6	81.8
J-2	$5.0X10^{15}$	13.3	823	28.0	79.0
J-3	$1.0X10^{17}$	10.05	812	22.6	75.1

TABLE II

PRE-IRRADIATION InP SOLAR CELL PARAMETERS

T=25°C

CELL	CARRIER CONC (cm^{-3})	EFFICIENCY (%)	Voc (mV)	Jsc (ma/cm^2)	FF (%)
R-3	$4.5X10^{16}$	12.9	815	26.3	82.6
R-4	$4.5X10^{16}$	12.7	814	26.0	82.6
J-2	$5.0X10^{15}$	13.3	823	28.0	79.0
J-4	$5.0X10^{15}$	12.1	813	27.8	73.5

TABLE III

PRE-IRRADIATION AMO PARAMETERS OF GaAs CELLS

T=25°C

EFFICIENCY (%)	Voc (mv)	Jsc (ma/cm^2)	FF (%)
19.6	1041	31.8	81.2
19.8	1044	32.1	81.1

TABLE IV

PERFORMANCE PARAMETERS OF InP CELLS

T=60°C

CELL	CARRIER CONC (cm^{-3})	Pm (mw/cm^2)	Voc (mv)	Jsc (ma/cm^2)	FF (%)	dPm/dT (mw/cm^2 $^{\circ}$K)
R-5	4.5X10^{16}	14.95	741	25.62	78.8	-3.13X10^{-2}
R-6	4.5X10^{16}	15.53	749	27	76.8	-4.86X10^{-2}
J-5	5.0X10^{15}	16.01	751	29.6	71.1	-6.23X10^{-2}
J-6	5.0X10^{15}	15.64	767	25.9	78.9	-6.25X10^{-2}
J-7	1.0X10^{16}	12.45	725	24.73	69.5	-5X10^{-2}
J-8	1.0X10^{16}	13.44	731	25.6	71.2	-6.3X10^{-2}

TABLE V

TEMPERATURE VARIATION TERMS

T=60^{o}C

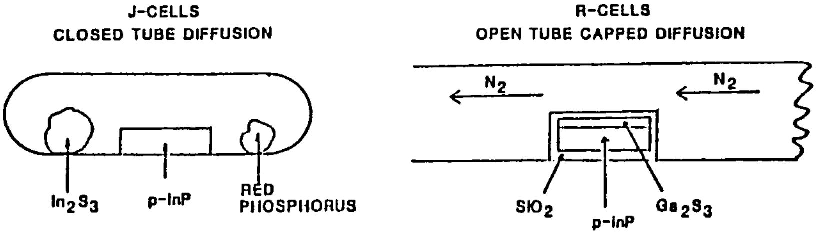
CELL	$\frac{1}{Isc}\frac{dIsc}{dT}$ ($^{o}K^{-1}$)	$\frac{1}{Voc}\frac{dVoc}{dT}$ ($^{o}K^{-1}$)	$\frac{1}{FF}\frac{dFF}{dT}$ ($^{o}K^{-1}$)
R-5	12.6X10^{-4}	-3.12X10^{-3}	-3.71X10^{-4}
R-6	6.25X10^{-4}	-3.11X10^{-3}	-1.12X10^{-3}
J-5	7.67X1o^{-4}	-3.09X10^{-3}	-1.63X10^{-3}
J-6	5.56X10^{-4}	-2.88X10^{-3}	-1.24X10^{-3}
J-7	9.66X10^{-4}	-3.28X10^{-3}	-1.35X10^{-3}
J-8	6.33X10^{-4}	-3.37X10^{-3}	-2.39X10^{-3}

TABLE VI

CALCULATED AND MEASURED TEMPERATURE VARIATIONS OF Voc

T=60^{o}C

	$\frac{dVoc}{dT}$ (mv/^{o}K)	
CELL	MEASURED	CALCULATED
R-5	-2.31	-2.38
R-6	-2.33	-2.39
J-5	-2.32	-2.32
J-6	-2.21	-2.34
J-7	-2.38	-2.46
J-8	-2.46	-2.45



	J-CELLS	R-CELLS
DIFFUSION TEMP. (°K)	625	700
DIFFUSION TIMÉ (min)	100	25
AR COATING	SIO	SIO
FRONT CONTACT	Au	Au
BACK CONTACT	Au/Zn	Au/Zn
CELL AREA (cm^2)	0.273	0.313

FIGURE 1.- JUNCTION FORMATION PROCESSES WITH ADDITIONAL InP CELL DETAILS.

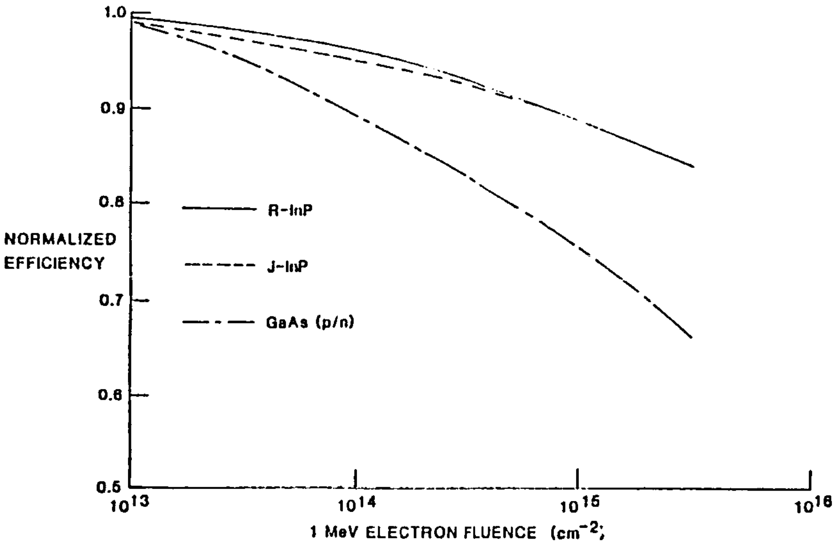


FIGURE 2.- NORMALIZED EFFICIENCY VS 1 MeV ELECTRON FLUENCE.

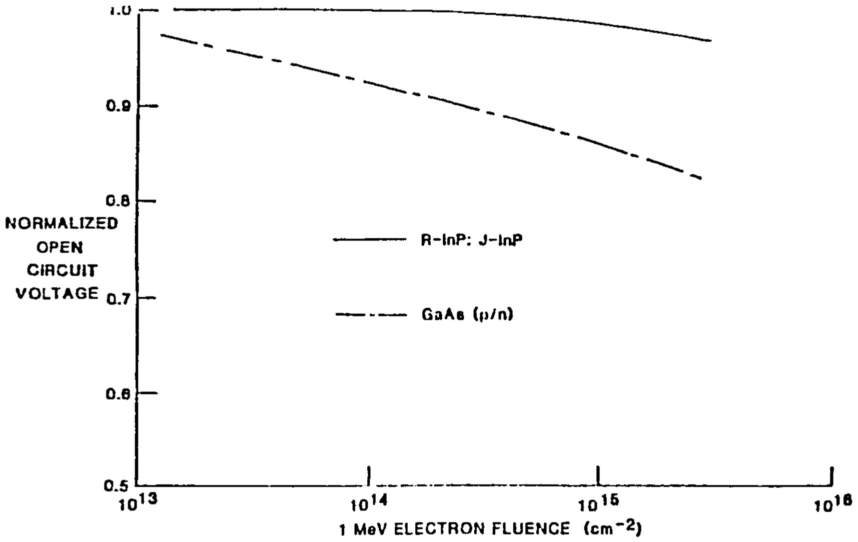


FIGURE 3.- NORMALIZED OPEN CIRCUIT VOLTAGE VS 1 MeV ELECTRON FLUENCE.

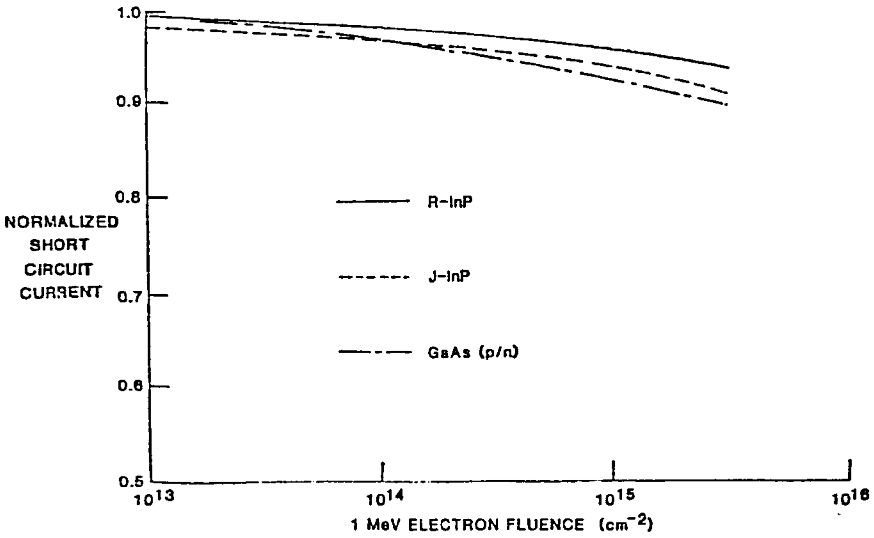


FIGURE 4.- NORMALIZED SHORT CIRCUIT CURRENT VS 1 MeV ELECTRON FLUENCE.

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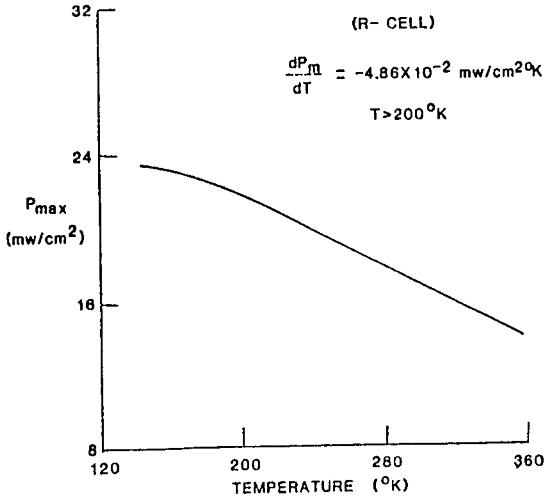

FIGURE 5. - VARIATION OF CELL MAXIMUM POWER WITH TEMPERATURE FOR A CELL PROCESSED BY OPEN TUBE DIFFUSION.

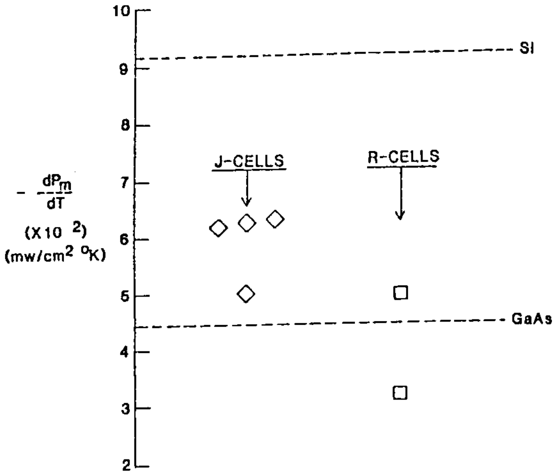

FIGURE 6.- TEMPERATURE DEPENDENCY OF CELL MAXIMUM POWER. GaAs AND Si DATA SHOWN FOR COMPARISION.

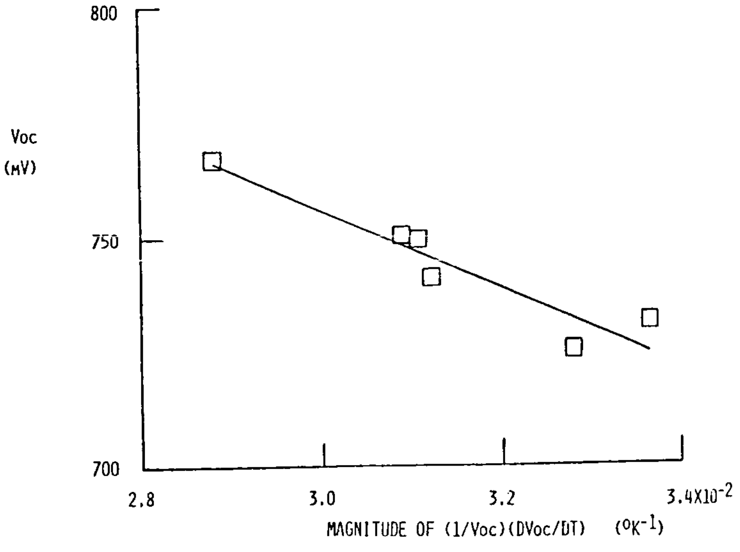

FIGURE 7.- Voc VS MAGNITUDE OF (1/Voc)(DVoc/DT).

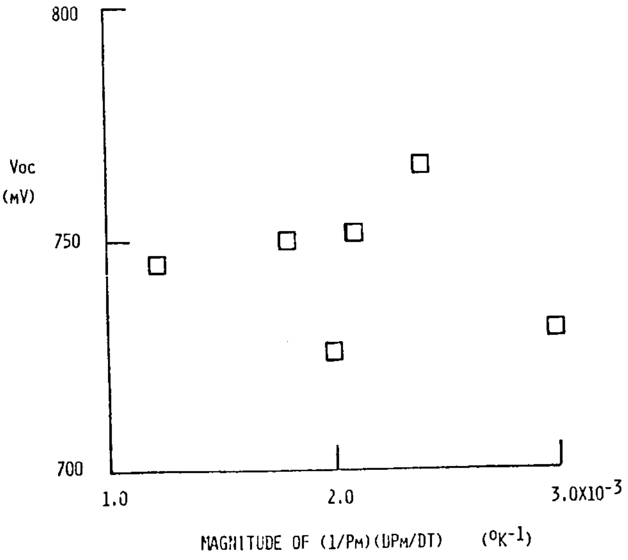

FIGURE 8.- Voc VS MAGNITUDE OF (1/PM)(DPM/DT)