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HETEROSTRUCTURE SOLAR CELLS*

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This paper presents the performance of GaAs solar cells grown on the Ge substrates, in some cases the substrate was thinned to reduce overall cell weight with good ruggedness. The conversion efficiency of 2x2cm cells under AMO reached 17.1% with the cell thickness of 6 mils. The experience gained in this structure will be used to increase GaAs cell efficiency. Also the work described forms the basis for future cascade cell structures, where similar interconnecting problems between the top cell and the bottom cell must be solved. The details include discussion of substrate properties, growth conditions of GaAs cells, and cell construction including possible substrate thinning. A discussion will follow regarding applications of the GaAs/Ge solar cell in space and expected payoffs over present solar cell technologies.

INTRODUCTION

It has been known that GaAs solar cells have higher conversion efficiency and higher radiation resistance than Si solar cells. However, GaAs solar cells are more than twice as heavy as Si cells. For space applications it is desirable that the solar cell is lightweight, have high efficiency, and high radiation resistance. In order to meet all these requirements GaAs solar cells have to be fabricated on a substrate which is not only lighter or thinner than GaAs, but also more rugged than GaAs. Both silicon and germanium were considered as the starting substrates on which the GaAs solar cell may be fabricated. Because of the huge lattice mismatch between Si and GaAs the silicon substrate was ruled out. Germanium was selected because Ge and GaAs have very close lattice constants and thermal expansion coefficients. Also, Ge is a very rugged material so that it can be thinned to reduce the overall cell weight without introducing any mechanical problem. In this paper, we present the results of p on n GaAs solar cells on n-type Ge substrates.

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CELL FABRICATION

The structure of the p on n GaAs/Ge solar cell is shown in Figure 1. The n-type Ge substrate is doped with Sb and the electron concentration is in the middle of 10^{17} cm^{-3}. The starting Ge wafer is approximately 7 mil thick and the crystal orientation is 4 degrees off the (100) direction. The heteroface GaAs/AlGaAs solar cell structure was deposited by the low pressure organometallic vapor phase epitaxy (OMVPE) technique. First an n-type GaAs buffer layer doped with Se was grown on top of the n-type Ge wafer. Then a p-type GaAs emitter and a thin p-type window layer were deposited and the p-type dopant was Zn. During the OMVPE growth the chamber pressure was 130 torr and the growth temperatures were 720 and 680^{o}C. The 720^{o}C was used to take advantage of the Ge auto-doping effect so that the electron concentration in the initial buffer layer was so high that it eases the electric properties at the hetero-interface between the Ge substrate and the GaAs buffer layer. This auto-doping effect was ceased by lowering the growth temperature to 680^{o}C. The actual GaAs homojunction was grown at this temperature to obtain higher short-circuit current. The typical thickness for the buffer layer, the emitter, and the window layer is 9, 0.5, and 0.1um, respectively.

After layer growth the front p-contact made of Au/Zn and Ag were deposited onto the revealed p-emitter and the grid pattern was defined by the liftoff process. The multiple layer AR coatings made of TiO and AlO were next deposited on the window layer. At this point the GaAs/Ge structure was further thinned to 3 mils by removing Ge from the backside. Then the back n-contact made of Au/Ge, Ni, and Ag was deposited and sintered. Finally, the cell was cut into size. The entire cell fabrication sequence is shown in Figure 2.

RESULTS

Doping Profiles

The doping profile of the typical GaAs/Ge solar cell was measured using a Polaron C-V profiler. Figure 3 shows the doping profile of both the hole concentration in the emitter and the electron concentration in the buffer layer. The hole concentration was about 1.3 x 10^{18} cm^{-3}. The electron concentration was 2 x 10^{17} cm for the first 3um near the junction and it increased to 1 x 10^{18} cm^{-3} for the remaining 6um. This higher electron concentration was due to the auto-doping (out-diffusion) by Ge which is an n-type dopant in GaAs for the OMVPE growth. The difference in the electron concentration in the buffer layer was due to the growth temperatures. The growth temperature, Tg, was 720^{o}C for the initial 6um and it was 685^{o}C for the remaining 3um and the p-layer.

Modeling

The reason that the GaAs/Ge cell had high open circuit voltage and lower fill-factor is due to electric properties of the interface between the n-type Ge substrate and the n-type GaAs buffer layer. An experiment was performed to analyze the interface properties. An as-grown cell structure was etched in a 3:1:1 solution to remove the window layer and the p-emitter. N-type ohmic contacts were deposited and sintered on the GaAs buffer layer and the backside of the Ge substrate. The sample was cut into 5x5mm after sintering the n-contacts. A typical dark I-V characteristics of the isotype heterojunction interface is shown in Figure 4. The I-V characteristics are non-linear and the resistance of the 5x5mm sample was approximately 2 ohms near the origin. Therefore the series resistance of the isotype heterojunction between GaAs and Ge was high enough to result in low fill-factor.

Also a third terminal was made to the (n)GaAs buffer layer of a GaAs/Ge cell to evaluate the photovoltaic effect at the (n)GaAs/(n)Ge isotype heterojunction. It was found that Voc was 0.035V and that the polarity of this photovoltage agreed with that of the p/n GaAs cell. The polarity of this photovoltage suggests that the junction between the (n+)GaAs and (n)Ge be an n-type Schottky barrier. Figure 5 shows the band structure of the GaAs p/n junction and the (n+)GaAs/(n)Ge Schottky barrier. The degenerated (n+)GaAs acts as a metal on the (n)Ge semiconductor. The magnitude of the barrier height affects the collection photocurrent; i.e. Cff. The Schottky barrier height can be reduced by lowering the resistivity of the Ge substrate. It has been verified that better CFF for GaAs/Ge cells has been obtained by using low resistivity Ge wafers.

Light I-V Characteristics

The 2x2cm GaAs/Ge solar cells made on the 0.015 ohm-cm Ge substrates were tested under an AMO simulator at 28^{o}C. Figure 6 shows the light I-V characteristics of a 2x2cm GaAs/Ge cell. The conversion efficiency of the cell was 17.1%; the open-circuit voltage 1.075V; the short-circuit current 115.9mA; and the fill-factor 0.742. The thickness of this cell was approximately 7 mils.

Table I lists the performance of the GaAs/Ge cells fabricated in the same lot. All cells have efficiency higher than 16% under AMO at 28^{o}C. At 50% cummulative yield the cell efficiency was 16.8%; the open-circuit voltage 1.088V; the short-circuit current 115.7mA; and CFF 0.722. The thickness of these cells was about 7 mils.

Contact Integrity

The contact integrity is defined by low contact resistance, good adhesion, solderability, and weldability. The Ag-plated tabs were soldered onto the p-contact ohmic pads of a GaAs/Ge solar cell with 16% efficiency. The light I-V curves of the cell before and after soldering the tabs are shownin Figure 7. No degradation in electrical output of the cell was introduced by soldering process. The soldered tabs were pulled at 45 degrees with respect to the cell surface. The pull strength was 925 and 475 grams. The separation between the tabs and the cell was caused by divots in GaAs. Figure 8 shows the microphotograph of the large divots in GaAs after pulling off the tab on the p-contact ohmic pad. This kind of failure mode is acceptable because the pull strength was higher than 250 grams, which was the criteria for GaAs solar cells, and because the separation was due to large divots in GaAs.

Applications

It has been recognized that development of a lightweight GaAs solar cell is critical for achieving arrays with specific power approaching 300 W/kg (Ref. 1). The work presented here is a major step in approaching this type of performance. With the thin GaAs/Ge solar cell, a 50% improvement over silicon in EOL output can be realized with about the same cell weight. Table 2 outlines the relative performance of three cell technologies; silicon, gallium arsenide, and gallium arsenide on germanium. All values represent solar cells with 150 micron (6 mil) coverglasses in a 5 year, mid altitude orbit.

Further weight reduction and thermal survivability could be achieved by the use of deposited integral coverglasses. The relatively low tensile strength of standard GaAs cells inhibits use of integral covers due to cell bowing (Ref. 2). Use of a germanium substrate, with its higher strength, should allow for integral covers to be deposited on the thin GaAs cells, eliminating the need for adhesives. Further work is required in this area to ensure that the cover deposition temperature does not cause germanium diffusion into the GaAs buffer layer.

Other areas which warrant further research include fabrication and processing of the germanium substrate, larger area ($\gtrsim 4cm^2$) device fabrication, and a cell interconnect process. Optimization of these processes would result in a planar solar array specific power of about 290 W/kg using present array blanket technology. This value compares to about 185 W/kg for a silicon array of the same basic design.

Use of the thin GaAs/Ge solar cells would not have to be limited to planar arrays or single junction applications. These cells could be used in concentrator arrays as well, although their advantages over conventional GaAs cells diminishes in this configuration. One remaining advantage, which could become significant, would be a reductiion in cost due to the substrate. The present cost of germanium is about half that of gallium-arsenide. Finally, the design of the thin GaAs cells lends itself well to multi junction cell applications. The materials technology developed for this cell could be applied to an AlGaAs/Ge monolithic multi-juncton cell design promising even higher efficiencies. In addition, the thin cell technology would yield a lightweight multi-junction solar cell.

CONCLUSION

In conclusion, the conversion efficiency of 2x2cm GaAs/Ge solar cells under AMO at 28°C reached 17.1% and a lot average of 16.8% has been demonstrated. It was found that the fill factor of the cell could be improved by reducing the barrier height at the isotype heterojunction between the Ge substrate and the (n) GaAs buffer layer.

This solar cell design presents many significant options for application to future space power systems. The most obvious use would be in ultra lightweight arrays, where the thin cell's high efficiency and radiation resistance would greatly improve power densitites. The GaAs/Ge solar cell could also be used in concentrators, where the biggest contribution would probably be in cell cost reduction. Additionally, the technology developed for this work represents an important step in the development of high efficiency monolithic multi-junction solar cells.

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TABLE 1

PERFORMANCE OF 2x2cm GaAs/Ge CELLS UNDER AMO AND 28°C

INDIVIDUAL CELL PERFORMANCE						CUMMULATIVE CELL PERFORMANCE					
CELL #	Voc (mV)	Isc (mA)	CFF (%)	Vm (mV)	EFF (%)	Yield (%)	Voc (mV)	Isc (mA)	CFF (%)	Vm (mV)	EFF (%)
12	1075	115.9	74.2	856	17.1	8.3	1075	115.9	74.2	856	17.1
5	1101	115.1	72.0	856	16.9	16.7	1088	115.5	73.1	856	17.0
2	1091	116.6	71.7	860	16.8	25.0	1089	115.9	72.6	857	16.9
6	1092	115.2	72.5	864	16.8	33.3	1090	115.7	72.6	859	16.9
7	1083	116.1	71.8	856	16.7	41.7	1088	115.8	72.4	858	16.9
4	1094	115.5	71.2	824	16.6	50.0	1089	115.7	72.2	853	16.8
1	1092	115.5	71.1	868	16.6	58.3	1090	115.7	72.1	855	16.8
9	1098	116.4	70.0	856	16.5	66.7	1091	115.8	71.8	855	16.8
11	1061	116.3	72.0	828	16.4	75.0	1087	115.8	71.8	852	16.7
10	1096	113.3	70.9	864	16.3	83.3	1088	115.6	71.7	853	16.7
3	1080	116.[illegible]	693	828	16.2	91.7	1088	115.7	71.5	851	16.6
8	1088	115.1	69.1	824	16.0	100.0	1088	115.6	71.3	849	16.6

TABLE 2

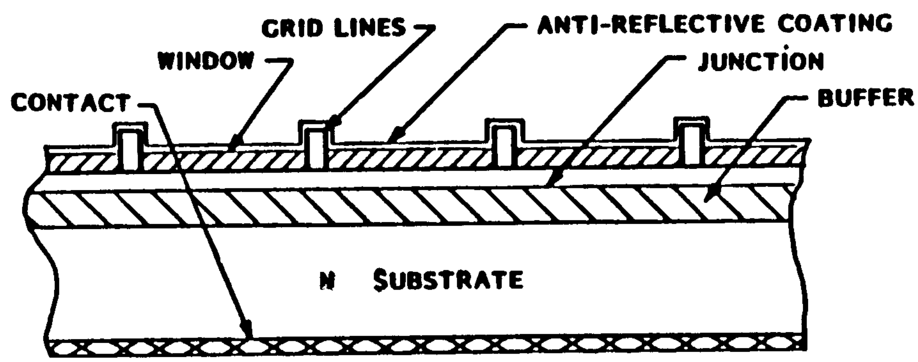
COMPARISON OF SOLAR CELL TECHNOLOGY PERFORMANCE

CELL TYPE	CELL THICKNESS (MICRONS)	TOTAL WEIGHT (GRAMS)	η %	
			BOL	EOL[3]
Si	100	0.35[1]	15	5.4
GaAs	305	0.82[2]	17	9.5
GaAs/Ge	78	0.35	18.5	10.4

[1] From Ref. 2

[2] From Ref. 3

[3] EOL values based on data in Ref.4; values for GaAs/Ge cells are calculated assuming agreement with data for GaAs performance.



ELEMENT	THICKNESS (μm)	COMPOSITION	DOPANT CONCENTRATION ($\times 10^{18}$ cm^{-3})
GRID (p-CONTACT)	4.4	Ag – Au Zn Au	–
AR COATING	0.1	TiO_x/Al_2O_3	–
WINDOW (p^+)	0.1	$Al_xGa_{1-x}As$ (Zn)	2 TO 4
JUNCTION (p)	0.45	GaAs (Zn)	2
BUFFER (n)	9	GaAs (Se)	0.2 TO 0.5
SUBSTRATE (n^+)	75	Ge (Sb)	–
n – CONTACT	3.38	Ag – Au Ge Ni Au	–

FIGURE 1

GaAs/Ge SOLAR CELL STRUCTURE

1. Thin Ge Substrates to 7-8 Mils.
2. Prepare the surface of Ge wafers.
3. Grow GaAs and AlGaAs by MOCVD technique.
4. Etch window layer.
5. Deposit front p-contacts.
6. Deposit AR coating.
7. Thin GaAs/Ge cells to 3 mils.
8. Deposit back n-contacts.
9. Cut cells to size.
10. Test

FIGURE 2

PROCESS STEPS FOR THIN GaAs/Ge SOLAR CELLS

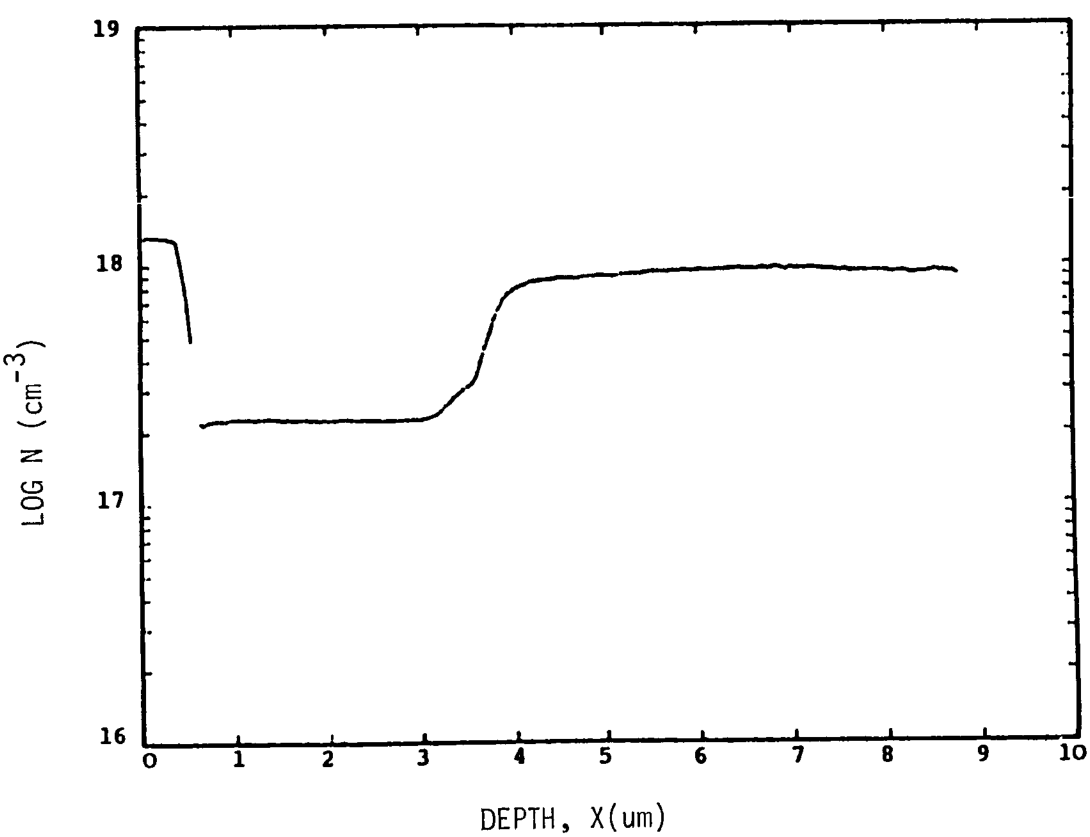


FIGURE 3

DOPING PROFILE OF A GaAs P/N JUNCTION GROWN ON A Ge SUBSTRATE

FIGURE 4

DARK I-V CHARACTERISTICS OF A (n)GaAs/(n)Ge ISOTYPE HETEROJUNCTION. THE SIZE OF THE DEVICE IS 5mm SQUARE

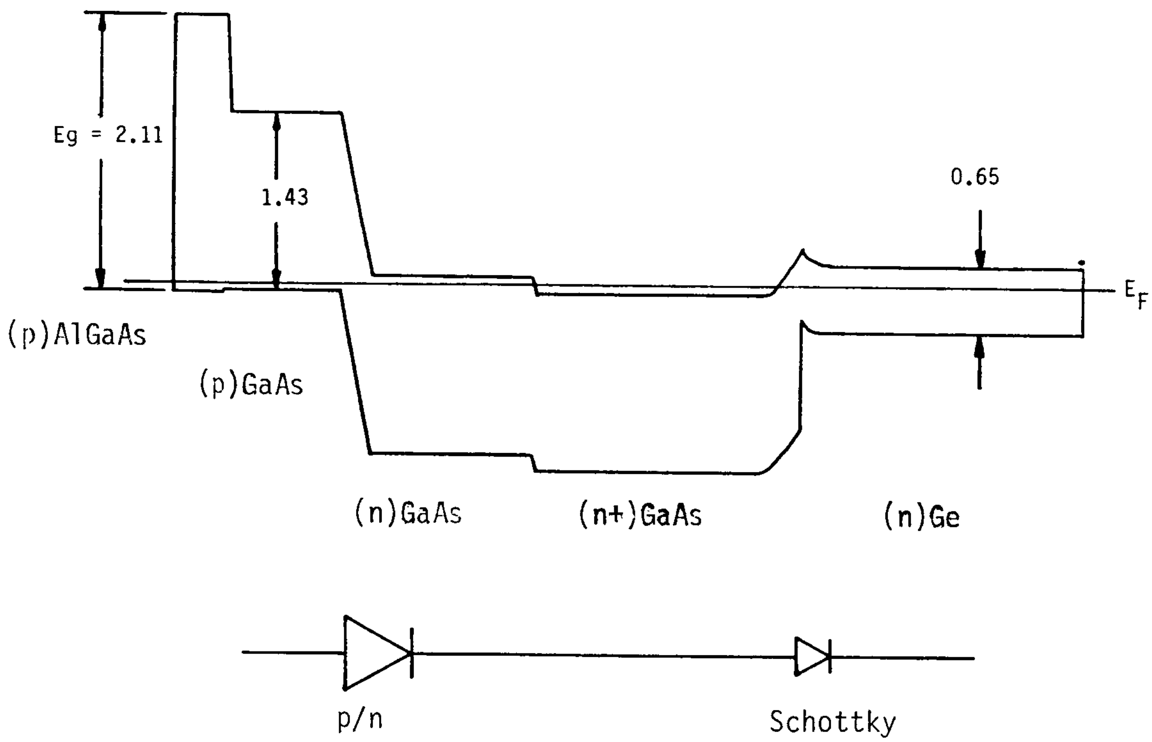


FIGURE 5

BAND STRUCTURE OF THE GaAs/Ge SOLAR CELL

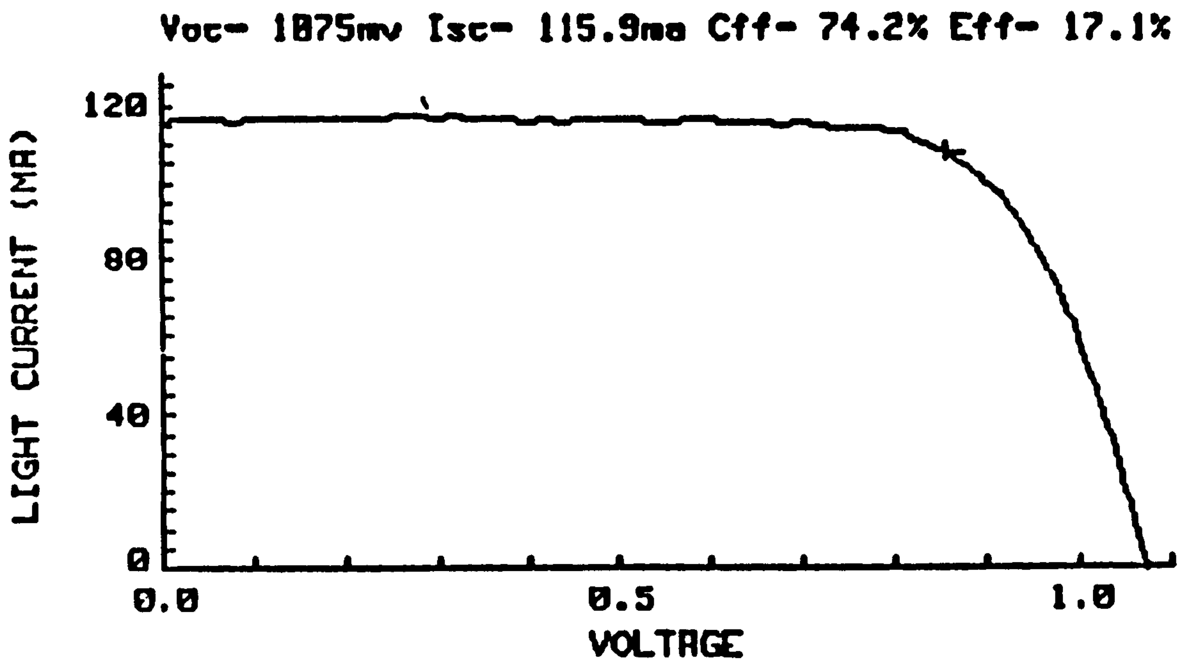


FIGURE 6

LIGHT I-V CURVES OF A 2x2cm P ON N GaAs/Ge SOLAR CELL (#12) TESTED UNDER AMO AND 28°C. THIS CELL IS 6 MIL THICK.

(a) (b)

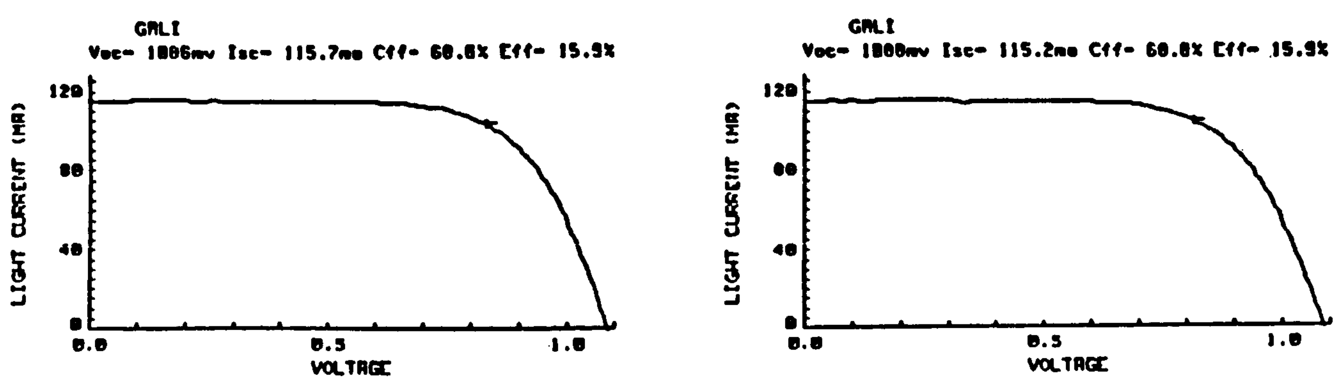


FIGURE 7

LIGHT I-V CHARACTERISTICS OF A GaAs/Ge SOLAR CELL #8 (a) BEFORE AND (b) AFTER SOLDERING TABS TO THE FRONT P-OHMIC CONTACTS.

(a) (b)

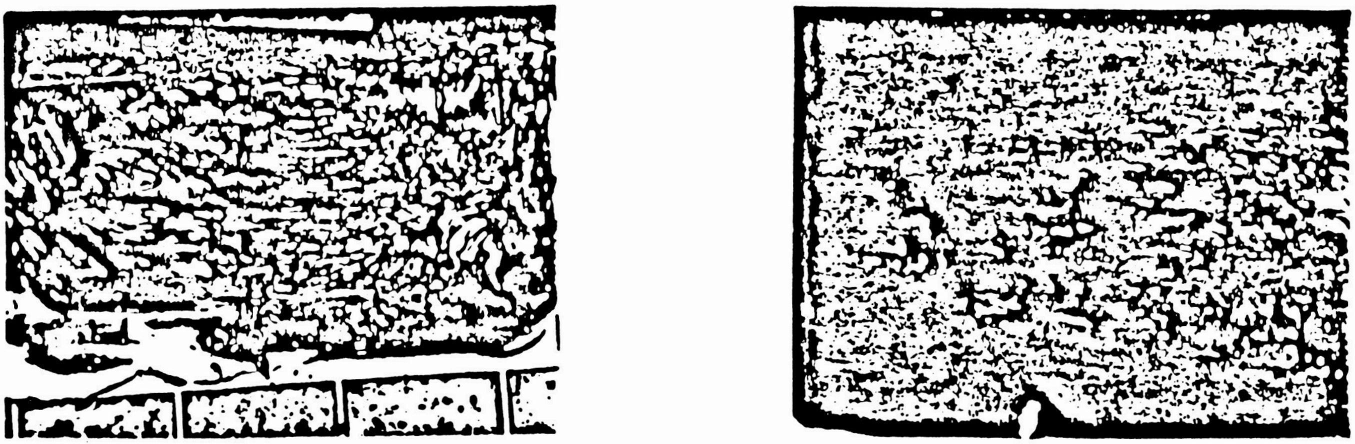


FIGURE 8

MICROPHOTOGRAPHS (50X) OF (a) THE PAD AND (b) THE TAB AFTER PULL TEST FOR CELL #8.