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Two-terminal Monolithic InP-based Tandem Solar Cells with Tunneling Intercell Ohmic Connections

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SUMMARY

We have successfully fabricated a monolithic two-terminal InP/InGaAsP tandem solar cell. This tandem solar cell consists of a p/n InP homojunction top subcell and a 0.95 eV p/n InGaAsP homojunction bottom subcell. A patterned 0.95 eV n^+/p^+ InGaAsP tunnel diode was employed as intercell ohmic connection. The solar cell structure was prepared by two-step liquid phase epitaxial growth. Under one sun, AM1.5 global illumination, our best tandem cell delivered a conversion efficiency of 14.8%.

INTRODUCTION

Although multijunction solar cells have exhibited higher conversion efficiency than single junction solar cells in recent years, its full potential is far from being realized. Most of the R & D work on III-V tandem solar cells is based on GaAs and its related ternary compound semiconductors. The highest conversion efficiency reported for a monolithic two-terminal tandem solar cell under one-sun, AM1.5 global illumination is about 27% [1][2]. InP-based multijunction tandem solar cells have not received much attention until recently. InP and its related ternary and quaternary compound semiconductors such as InGaAs and InGaAsP offer desirable combinations of energy bandgap values and show great promises for multijunction tandem solar cell applications; especially for tandem solar cells which consist of three subcells.

One of the key components for a two-terminal monolithic mulitijunction tandem solar cell is a low-loss, highly conductive intercell ohmic contacts (IOCs) for the series connection of individual subcells. Two types of IOCs are considered to be feasible for monolithic tandem solar cells. They are tunnel junctions and metal interconnects (MICs). Both tunnel junctions and metal interconnects have been used as IOCs for GaAs-based multijunction tandem cells [1] [2] [3]. For InP-based mutijunction solar cells, only MICs have been used recently as IOCs for the InP/InGaAs tandem solar cells developed by M. Wanlass and coworkers at SERI [4]. In this work, we have developed a 0.95 eV n^+/p^+ InGaAsP tunnel diode and successfully employed it as IOCs for a monolithic two-terminal InP/InGaAsP tandem solar cell. Details of the device structure, device fabrication procedures and device performance are discussed in following sections.

DEVICE STRUCTURE, EPITAXIAL GROWTH AND DEVICE FABRICATION

A schematic cross section of a two-terminal monolithic InP/InGaAsP tandem solar cell is shown in Fig. 1. The entire tandem cell structure was grown on a (100) oriented n-type InP substrate by using two-step liquid-phase epitaxial (LPE) growth. The two subcells are connected with a patterned 0.95 eV n^+/p^+ InGaAsP tunnel junction. The patterned n^+/p^+ InGaAsP tunnel junction covers about 12.5% of the total surface area. The patterning of the tunnel junction was accomplished by using photolithography and selective wet chemical etching. A p-InP layer was grown on top of the InGaAsP lower cell and used as an etch-stop layer to facilitate the patterning processes. A patterned p^+-InGaAs layer was employed as the contacting layer for the front grid contacts. The front contacts cover about 12.5% of the surface area. The complete solar cells are of mesa type, with a total surface area of 4 mm^2. Single layer of Sb_2O_3 was used as antireflection coating.

In the early stage of this work, n^+/p^+ $In_{0.53}Ga_{0.47}As$ tunnel junctions were considered for IOCs for the series connection of the InP subcell and the InGaAsP subcell. $In_{0.53}Ga_{0.47}As$ has a direct energy bandgap of 0.75 eV and is lattice matched to InP, which makes it an attractive material for tunnel junctions. In our previous work [5], we have investigated the electrical properties of p^+/n^+ $In_{0.53}Ga_{0.47}As$ tunnel junctions prepared by LPE. Since then, we have made better p^+/n^+ $In_{0.53}Ga_{0.47}As$ tunnel junctions with higher conductivities and larger peak current densities. We have also developed 0.95 eV p^+/n^+ InGaAsP tunnel junctions by LPE. Their electrical properties are listed in Table 1, along with several different type of tunnel junctions which have been used as IOCs for GaAs-based tandem solar cells. Although $In_{0.53}Ga_{0.47}As$ tunnel junctions offer the highest peak current densities as well as the largest conductivities, we found that it was difficult to incorporate them into our tandem solar cell structures by LPE, since melt-back problem during LPE growth forbids the direct growth of InP on $In_{0.53}Ga_{0.47}As$. As a result, we switched to InGaAsP tunnel junctions and were successful in using them as IOCs.

The thickness and doping concentration of individual epitaxial layer for the first and second LPE growth are listed in Table 2. The LPE growth procedures for the p/n InP upper cell and the p/n InGaAsP lower cell were similar to what we reported previously [6] [7]. Typical growth temperatures for the first and second growth are 630^0C-625^0C and 580^0C-550^0C, respectively. In order to simplify the InP growth processes for the InP/InGaAsP tandem structure, the p-InP region and the p-InGaAsP region were not grown epitaxially as we did for the single-junction InP and InGaAsP solar cells but were created by in-diffusion of p-type impurities (Zn) during the growth period. Consequently, both subcells are essentially of diffused junction type rather than grown junction type. The depth of both p/n diffused junctions is about one micron, no attemps were made to optimize the junction depth for maximum conversion efficiencies. The processing sequence for the fabrication of the InP/InGaAsP tandem solar cell is illustrated in Fig. 2.

Several InP/InGaAsP tandem solar cells were evaluated at SERI under 1 sun, global AM1.5 illuminations. Shown in Figure 3(a) and 3(b) are the light I-V characteristics for the two most efficient InP/InGaAsP tandem solar cells we have tested so far. The open-circuit voltage (V_{OC}), short-circuit current (J_{SC}) and Fill factor exhibited by the best device were 1.363 V, 13.85 mA/cm^2 and 0.786, respectively. The total-area power conversion efficiency was 14.8%. The second best tandem solar cell which was processed from the same wafer exhibited a conversion efficiency of 14.6%. The V_{OC}, J_{SC}, and Fill factor exhibited by this second best device were 1.383 V, 12.94 mA/cm^2 and 0.816, respectively. The relative quantum efficiency of the InP upper cell and the 0.95 eV InGaAsP lower cell is shown in Fig. 4.

DISCUSSION

Because of the current matching requirements imposed on a series-connected two-terminal tandem solar cell, its output current is limited by the subcell which generates the least current. For the two-terminal InP/InGaAsP tandem solar cell reported here, the output current is limited by the InGaAsP lower subcell. The short-circuit current density of 13.85 mA/cm^2 exhibted by the 14.8% efficient InP/InGaAsP tandem solar cell is comparable in value to what has been reported on the most efficient monolithic $Ga_{0.5}In_{0.5}P$/GaAs tandem solar cell and the most efficient $Al_{0.37}Ga_{0.63}As$/GaAs tandem solar cell [1] [2]. Our results thus confirm that the 0.95 eV InGaAsP solar cell performs quite well underneath an InP solar cell when they are connected in series. With the incorporation of another 1.93 eV wide bandgap solar cell such as AlGaInP solar cell as the top subcell, with the InP subcell in the middle and the InGaAsP subcell at the bottom, the total conversion efficiency can be expected to increase to 30% or more, assuming the output voltage can be enhanced without sacrificing the output current.

REFERENCES:

1. J. M. Olson, S. R. Kurtz, A. E. Kibbler and P. Faine,"A 27.3% efficient $Ga_{0.5}In_{0.5}P$/GaAs tandem solar cell," Appl. Phys. Lett. **56**, 623, (1990).

2. B.- C. Chung, G. F. Virshup, S. Hikido, and N. R. Kaminar, "27.6% efficiency (1 sun, air mass 1.5) monolithic $Al_{0.37}Ga_{0.63}As$/GaAs two-junction cascade solar cell with prismatic cover glass," Appl. Phys. Lett. **55**, 1741, (1989).

3. C. Amano, H. Sugiura, M. YamGuchi, and K. Hane, "Fabrication and numerical analysis of AlGaAs/GaAs tandem solar cells with tunnel interconnections," IEEE Trans. on Electron Device, **ED-36**, 1026, (1989).

4. M.W. Wanless, J.S. Ward, T.A. Gessert. K.A. Emery, G.S. Horner and T.J. Coutts, "Development of High-Performance GaInAsP Solar Cells for Tandem Solar Cell Applications," Proceeding of 21st IEEE Photovoltaic Specialist Conference, (IEEE, New York 1990). p. 172.

5. C.C. Shen, P.T. Chang, and K.Y. Choi, "An $In_{0.53}Ga_{0.47}As$ tunnel diode for monolithic multijunction solar cell applications," Proceeding of 20th IEEE Photovoltaic Specialist Conference, (IEEE, New York 1988) p 771.

6. K.Y. Choi and C.C. Shen "p/n InP homojunction solar cells with modified contacting scheme by liquid phase epitaxy," J. Appl. Phys. **63**, 1198, (1988).

7. C.C. Shen, P.T. Chang and K.Y. Choi,"Photovoltaic properties of 0.95 eV p/n InGaAsP homojunction solar cells prepared by liquid-phase epitaxy," IEEE Trans. on Electron Device, **ED-37**, 464, (1990).

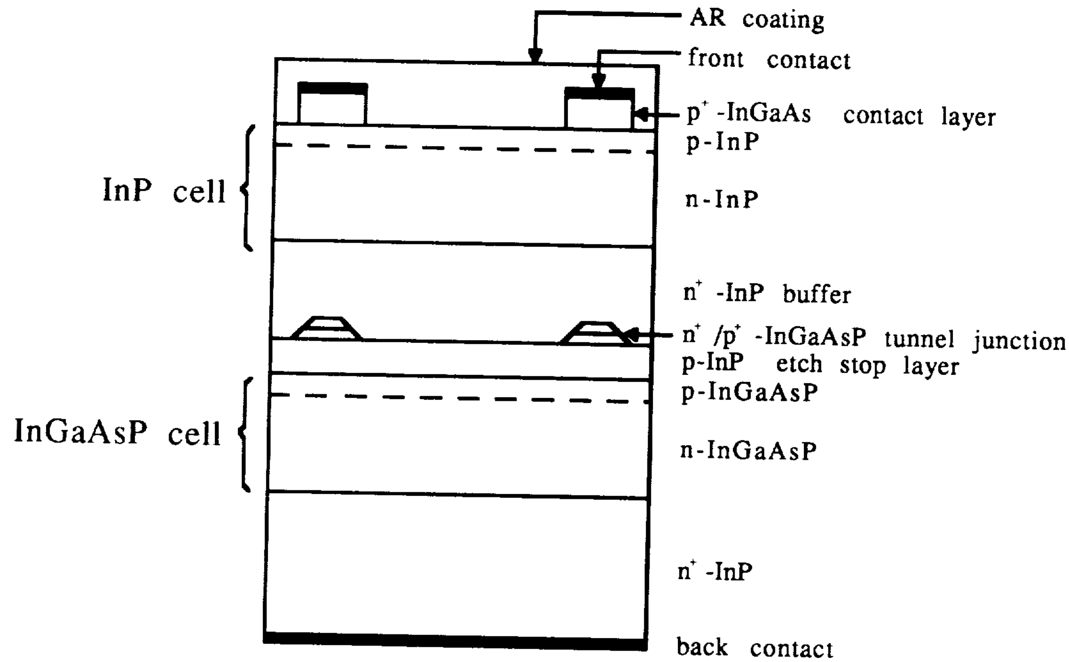


Fig. 1. Schematic cross section of a two-terminal, monolithic InP/InGaAsP tandem cell.

Table 1. Electrical properties of various types of tunnel Junctions

Material System	Peak current density J_P (A/cm^2)	Resistivity R (10^{-3}, Ω-cm^2)	Ref.
p^+-GaAs/n^+-GaAs	34	3.0	a
p^+-GaAs/n^+-GaAs	15	4.7	b
p^+-GaAs/n^+-GaAs	23	1.7	c
p^+-GaAs/n^+-GaAs	45	2.0	d
p^+-Ge/n^+-Ge	3	10	e
p^+/n^+-$In_{0.53}Ga_{0.47}As$	793	0.4	This Work
p^+/n^+-InGaAsP	28	2.0	This Work

a. D. L. Miller, S. W. Zehr, and J. S. Harris, Jr., *J. Appl. Phys.*, Vol. 53, pp. 744-748, 1982.
b S. K. Ghandhi, R. T. Huang, and J. M. Borrego, *Appl. Phys. Lett.*, Vol. 48, 415-416, 1986.
c. R. E. Hayes *et al.*, *Solar Cells*, Vol. 15, pp. 231-238, 1985.
d. P. Basmaji *et al.*, *J. Appl. Phys.*, Vol. 62, pp. 2103-2106, 1987.
e. P. K. Chiang, M. L. Timmons, G. G. Fountain, and J. A. Hutchby, *Proc. 18th IEEE Photovoltaic Specialist Conf.*, pp. 562-567, 1985.

Table 2. Thicknesses and doping concentrations of epitaxial layers in the InP/InGaAsP tandem cell.

Layer	Thickness (μm)	Doping Concentration (cm^{-3})
First Crystal Growth		
undoped InGaAsP	3.0	3.0×10^{17}
p-InP	1.0	2.5×10^{18}
p^+-InGaAsP	0.5	2.0×10^{19}
n^+-InGaAsP	0.5	2.0×10^{19}
Second Crystal Growth		
n^+-InP	2.5	7.0×10^{18}
undoped InP	2.5	1.0×10^{17}
p^+-InGaAs	1.3	6.0×10^{18}

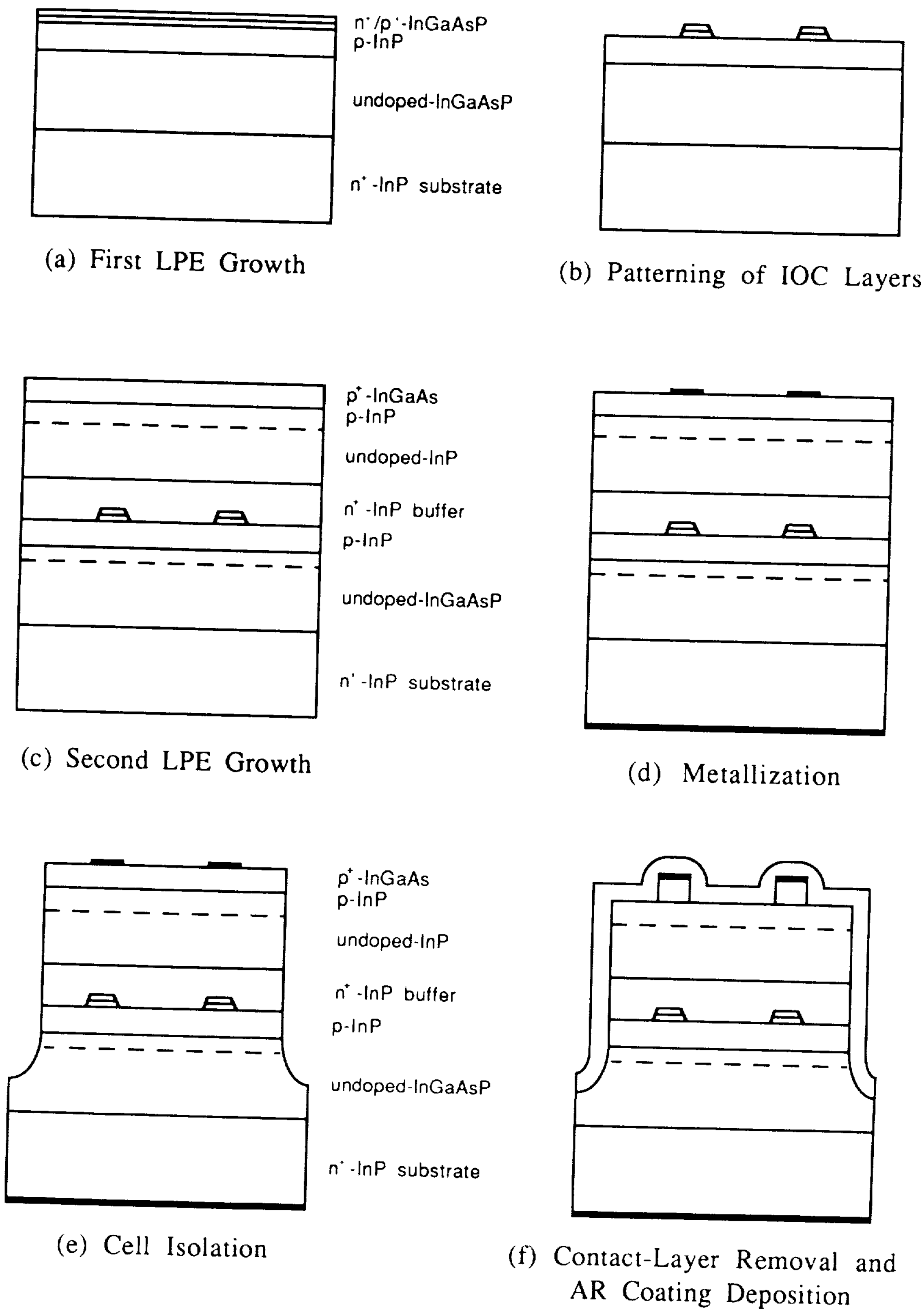
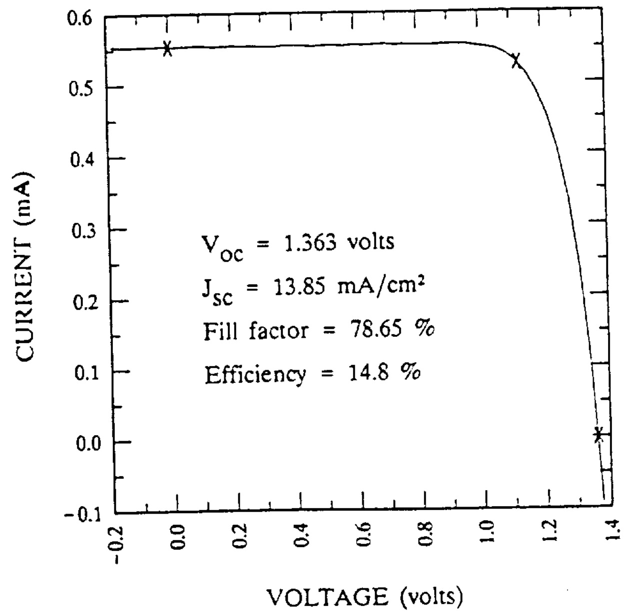
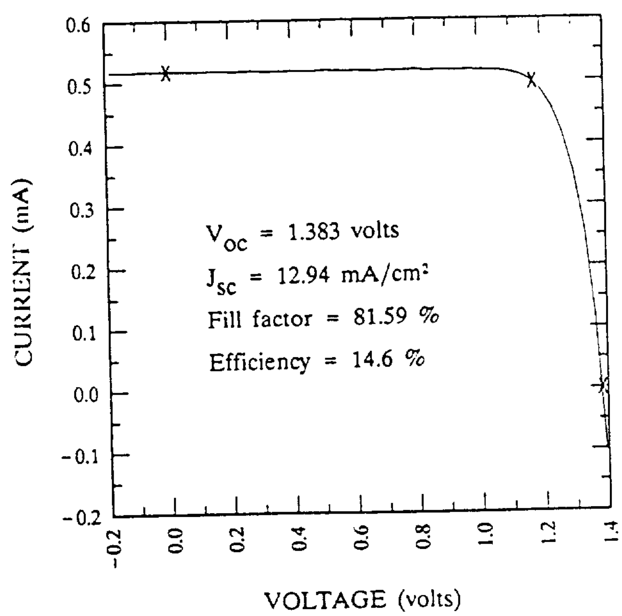


Fig. 2. The Processing sequence for the fabrication of the InP/InGaAsP tandem solar cell.



(a)



(b)

Fig. 3. Light I-V characteristics under 1 sun, AM1.5 global illuminations for two InP/InGaAsP tandem solar cells. The total surface area is 0.04 cm^2.

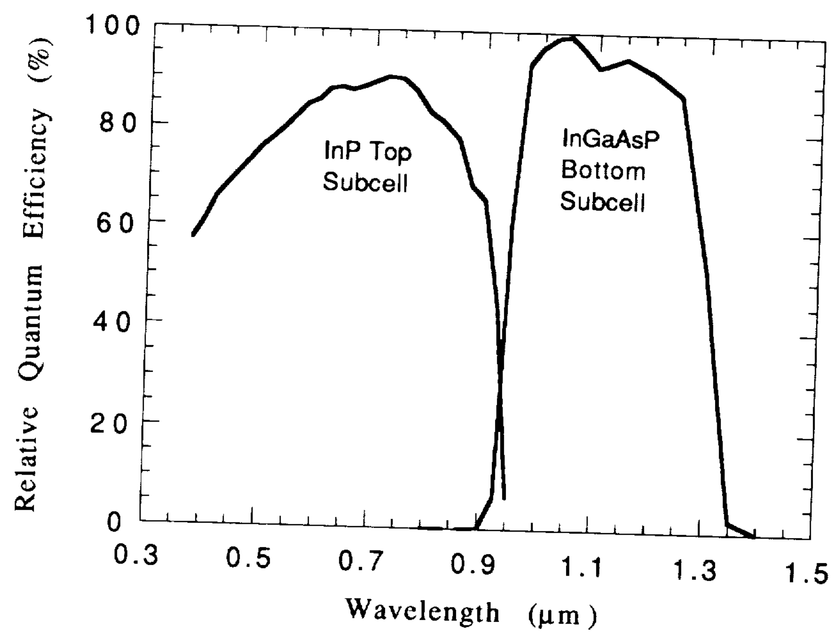


Fig. 4 Spectral response of the InP upper subcell and the 0.95 eV InGaAsP lower subcell.