MONOLITHIC, TWO-TERMINAL $\text{InP}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ TANDEM SOLAR CELLS

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Introduction

Monolithic $\text{InP}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ tandem solar cells have been studied extensively in our laboratory over the last 4 years (1-7). The key features and advantages of the tandem cell, for both space and concentrator terrestrial applications, have been described previously (1-7). Initial research on the device was devoted to the development of three-terminal tandem cells for the purpose of studying the top (InP) and bottom ($\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$) subcells independently, and to circumvent the problem of electrically interconnecting the subcells within the the monolithic structure. Using the three-terminal approach, the tandem cell performance progressed rapidly (2-6), and improvements in the epitaxial growth and device processing procedures eventually led to a terrestrial concentrator tandem cell efficiency of 31.8% (4, 6), which is the highest value yet attained for a monolithic solar cell.

Recently, our research has been directed towards the development of two-terminal (i.e., series-connected) monolithic $\text{InP}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ tandem cells. Two-terminal tandem cells are desirable because they can be substituted directly for single-junction solar cells in photovoltaic module circuits that are being manufactured presently. Furthermore, in principle, two-terminal tandems should take less time to grow and process than three-terminal tandems, which would lead to reduced cell manufacturing costs. The data obtained from our previous study of three-terminal $\text{InP}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ tandem cells have shown that the potential performance of two-terminal $\text{InP}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ cells is quite high. However, two fundamental problems must be addressed to realize high-performance, two-terminal cells. First, an ohmic electrical interconnect between the top and bottom subcells must be integrated into the monolithic structure to connect the subcells in series. The optical and joule losses in the interconnect should be negligible

compared to the tandem cell output. Second, because the subcells are connected in series, techniques for matching the subcell photocurrents and maximizing the tandem cell photocurrent, under relevant solar spectra, are necessary to achieve the highest tandem cell efficiency. In this paper, we describe preliminary progress towards solving these problems and outline directions for future work.

Tandem Cell Structure

A schematic diagram of the two-terminal $\text{InP}/\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ tandem cell structure under study is shown in figure 1. Details of the layer thicknesses and respective doping levels are not given because they are proprietary at this time. The lattice-matched device structure is grown epitaxially on a $\text{p}^+\text{-InP}$ substrate. A thin $\text{p}^+/\text{n}^+ \text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ tunnel junction is used to interconnect the top and bottom subcells, each of which contain an n^+/p junction. A shallow-homojunction configuration is used for the InP subcell because a convenient, high-band-gap, lattice-matched material is not presently available to provide minority-carrier confinement for InP . The $\text{n}^+\text{-InP}$ emitter layer is grown very thin to allow the bulk of the high-energy photons to pass into the p-InP base layer, where they are absorbed and collected efficiently. In contrast, the $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ subcell is a double-heterostructure design, which utilizes InP cladding layers for minority-carrier confinement on either side of the active-junction layers. The $\text{n}^+\text{-InP}$ window layer above the $\text{n}^+\text{-Ga}_{0.47}\text{In}_{0.53}\text{As}$ emitter layer is also very thin to minimize absorption of photons with energies greater than the band gap of InP , which may pass through the top subcell and into the $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ subcell. The importance of this design aspect is discussed in more detail later in the paper.

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Figure 1. Schematic diagram of the two-terminal, monolithic InP/GaInAs tandem solar cell.

Experimental Procedures

Atmospheric-pressure metalorganic vapor phase epitaxy (APMOVPE) was used to grow the monolithic tandem cell structures. High-purity trimethylindium, trimethylgallium, arsine, and phosphine were the primary reactants, and diethylzinc and 1500-ppm hydrogen sulfide in hydrogen were used for p- and n-type doping, respectively. Growth took place at 620°C in a patented (8) vertical reactor vessel using palladium-purified hydrogen as the carrier gas. p⁺-InP wafers used for substrates were supplied by Sumitomo Electric, Inc., doped with zinc to a concentration of $\sim 4 \times 10^{18} \text{ cm}^{-3}$, and were oriented (100), two degrees toward the nearest (110) plane. The wafers were prepared by the vendor to be ready immediately for epitaxial growth, and were loaded directly into the reactor without any de-greasing or etching treatments in our laboratory. Typical growth rates were $0.075 \mu\text{m}\cdot\text{min}^{-1}$ for InP, and $0.14 \mu\text{m}\cdot\text{min}^{-1}$ for $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$. Growth of the individual layers in the tandem structure proceeded in a continuous sequence without stop-growth periods at heterointerfaces or p-n junctions. The epitaxial process is automated using a Macintosh computer control system.

Photolithographic and wet-chemical etching steps were used to define, and electrically isolate, individual mesa-type tandem cells. Various mesa areas and front-grid-contact metallization designs have been used, depending upon the application (e.g., diagnostic, 1-sun, and concentrator devices have been fabricated). Computer modeling was used to optimize the grid designs. A gold-zinc alloy annealed at 375°C was used to form an ohmic contact to the back surface of the p⁺-InP substrate. Gold was electroplated through photolithographically defined patterns to create ohmic front grid contacts on the cell mesas. Selective chemical etching was accomplished using concentrated HCl at room temperature to etch InP, and 2 NH_4OH : 1 H_2O_2 : 2 H_2O at room temperature to etch $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$. MgF_2/ZnS two-layer antireflection coatings were deposited in a resistively heated vacuum evaporator.

Results and Discussion

We have investigated p⁺⁺/n⁺⁺ $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ tunnel homojunctions as a solution to the subcell electrical interconnect problem. Such tunnel junctions have been fabricated previously by liquid phase epitaxy (9), with electrical characteristics suitable for tandem cells operated under high concentration. The maximum doping concentrations attainable in our APMOVPE system at present are $\sim 1 \times 10^{19} \text{ cm}^{-3}$ for n⁺⁺- $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ layers and $\sim 1 \times 10^{20} \text{ cm}^{-3}$ for p⁺⁺- $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ layers, as determined by Hall measurements. These doping levels were used to fabricate p⁺⁺/n⁺⁺ $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ tunnel junctions with individual layers $\sim 0.4 \mu\text{m}$ in thickness. Current-voltage data for a typical tunnel diode are shown in figure 2. Values for the peak current density (J_p), peak-to-valley current ratio (I_p/I_v), and specific resistance at low bias all indicate that the junctions have tunneling properties that are consistent with low-loss operation in the tandem cell, even under high concentration.

Thin $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ tunnel junctions were successfully integrated into tandem cell structures with nearly optically thick InP top cells. The selective etchants mentioned previously were used to process the component subcells in the structure in order to study the subcell characteristics individually. Relative

Figure 2. Current-voltage data for a GaInAs tunnel junction.

quantum efficiency data and current-voltage data for the subcells are given in figures 3 and 4, respectively. The quantum efficiency data show that both subcells have a high, uniform response, indicative of high minority-carrier diffusion lengths and close lattice matching. Current-voltage data for the same pair of subcells clearly demonstrate that the subcells are

Figure 3. Relative quantum efficiency data for each of the tandem subcells. The GaInAs cell was measured with the InP top cell removed.

Figure 4. Current-voltage data for each of the tandem subcells measured under simulated one-sun AM0 spectral conditions at 25°C.

operating efficiently in the tandem structure, and that the junctions are of high quality.

Complete two-terminal InP/Ga_{0.47}In_{0.53}As tandem cells were tested under 1-sun, AM0 illumination using a multi-source solar simulator to obtain the correct subcell photocurrents. Current-voltage data for the best tandem cell measured in this manner are displayed in figure 5. The data exhibit a kink in the current-voltage characteristic at ~0.3 V, which is due to a low-reverse-voltage breakdown of the Ga_{0.47}In_{0.53}As bottom subcell. The breakdown phenomenon allows the larger photocurrent generated by the InP top cell to flow through the tandem device. This effect has been observed previously for GaAs/Ge series-connected tandem cells (10), and it is interesting, and useful, because it clearly shows the photocurrent mismatch between the subcells in the tandem. In this case, the mismatch is about 8%. The InP/Ga_{0.47}In_{0.53}As tandem cell has a 1-sun, AM0 efficiency of 19.5% at 25°C, which is the highest value reported to date for a two-terminal InP-based solar cell. Areas for further improvement are discussed briefly below.

Figure 5. Current-voltage data for a two-terminal InP/GaInAs tandem solar cell.

Future Directions

The band-gap differential afforded by the InP/Ga_{0.47}In_{0.53}As tandem pair (0.6 eV) is insufficient to yield subcell current matching, under either the standard AM0 spectrum or direct terrestrial spectrum, when the InP top cell is optically thick. This results in a reduced efficiency because the tandem photocurrent is limited by the photocurrent of the bottom subcell. However, it is possible to match the subcell currents, and improve the tandem cell efficiency, by allowing a fraction of the photons that are normally absorbed in the top subcell to pass into the bottom subcell. One method of achieving the current match is to reduce the thickness of the top cell. In this way, the tandem photocurrent is improved and reaches a maximum value that is the average of the subcell photocurrents, when the top subcell is optically thick. From the data shown in figure 5, it is obvious that the efficiency could be improved using this approach. We have used a computer model to calculate the value of the tandem photocurrent for current-matched subcells using the characteristics of the present subcells and an optimized two-layer antireflection coating. Based on the modeling results, we predict that the tandem is capable of the following efficiencies, without any further

improvement in the quality of the subcells: ~23% under the 1-sun, AM0 spectrum at 25°C, and ~31% at 500 suns concentration under the standard direct spectrum at 25°C. Efforts are underway to attain these values.

Further improvements in the tandem-cell performance are still possible, and an improved understanding of aspects of the device design and processing-related issues are required. For example, the InP top cell could be improved significantly through the development of a transparent, passivating window layer, or by incorporating a graded-emitter doping profile to improve the short-wavelength response. Similarly, the open-circuit voltage of the n⁺/p Ga_{0.47}In_{0.53}As bottom cell could be improved by roughly 50 mV under typical 1-sun light intensities, according to previous results with p⁺/n Ga_{0.47}In_{0.53}As cells (3). Issues concerning contact adhesion and stability, tunnel junction stability and performance, and concentrator cell fabrication all need to be addressed. Finally, radiation damage effects in the Ga_{0.47}In_{0.53}As bottom cell should be studied carefully to assess the viability of the tandem cell for eventual space-power applications.

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References

- 1 M.W. Wanlass, "Monolithic Tandem Solar Cell," U.S. Patent No. 5,019,177, 5/28/91.
- 2 M.W. Wanlass, T.A. Gessert, G.S. Horner, K.A. Emery, and T.J. Coutts, "InP/Ga_{0.47}In_{0.53}As Monolithic, Two-Junction, Three-Terminal Tandem Solar Cells," Proc. 10th Space Photovoltaic Research and Technology Conf. (SPRAT X), 11/89, NASA Lewis Research Center, Cleveland, OH, USA, p. 102.

3. M.W. Wanlass, J.S. Ward, T.A. Gessert, K.A. Emery, G.S. Horner, T.J. Coutts, G.F. Virshup, and M.L. Ristow, "Development of High-Performance GaInAsP Solar Cells for Tandem Solar Cell Applications," Proc. 21st IEEE Photovoltaic Specialists Conf., 5/90, Orlando, FL, USA, p. 172., IEEE Catalog #90CH2838-1, Library of Congress #84-640812.
4. M.W. Wanlass, J.S. Ward, K.A. Emery, T.A. Gessert, C.R. Osterwald, and T.J. Coutts, "High-Performance Concentrator Tandem Solar Cells Based on IR-Sensitive Bottom Cells," Solar Cells, 30, 363 (1991).
5. M.W. Wanlass, J.S. Ward, T.J. Coutts, K.A. Emery, T.A. Gessert, and C.R. Osterwald, "Monolithic InP/Ga_{0.47}In_{0.53}As Tandem Solar Cells for Space," Proc. 11th Space Photovoltaic Research and Technology Conf. (SPRAT XI), NASA Lewis Research Center, Cleveland, OH, USA, p. 16-1.
6. M.W. Wanlass, T.J. Coutts, J.S. Ward, K.A. Emery, T.A. Gessert, and C.R. Osterwald, "Advanced High-Efficiency Concentrator Tandem Solar Cells," Proc. 22nd IEEE Photovoltaic Specialists Conf., 10/91, Las Vegas, NV, USA, p. 38, IEEE Catalog #91CH2953-8.
7. C.R. Osterwald, M.W. Wanlass, J.S. Ward, B.M. Keyes, K.A. Emery, and T.J. Coutts, "Modeled Performance of Monolithic, 3-Terminal InP/Ga_{0.47}In_{0.53}As Concentrator Solar Cells as a Function of Temperature and Concentration Ratio," Proc. 22nd IEEE Photovoltaic Specialists Conf., 10/91, Las Vegas, NV, USA, p. 216, IEEE Catalog #91CH2953-8.
8. M.W. Wanlass, "Reactor Design for Uniform Chemical-Vapor-Deposition-Grown Films Without Substrate Rotation," U.S. Patent No. 4,649,859, 3/17/87.
9. 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 Application," Proc. 20th IEEE Photovoltaic Specialists Conf., 9/88, Las Vegas, NV, USA, p. 771, IEEE Catalog #88CH2527-0.
10. L.D. Partain, G.F. Virshup, and N.R. Kaminar, "Quantum Yield Spectra and I-V Properties of a GaAs Solar Cell Grown on a Ge Substrate," Proc. 20th IEEE Photovoltaic Specialists Conf., 9/88, Las Vegas, NV, USA, p. 759, IEEE Catalog #88CH2527-0.

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