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HIGH EFFICIENCY GaAs THIN FILM SOLAR CELLS BY PEELED FILM TECHNOLOGY

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p-GaAs/n-GaAs thin film concentrator solar cells were fabricated by Peeled Film Technology. This is the first paper that reports the concentration characteristics of thin film solar cells. The energy conversion efficiency of thin film solar cells at a concentration ratio of 109 is 9.4% and the output power density is 0.82 W/cm^2. n-$Ga_{1-x}Al_xAs$/p-GaAs heterojunction thin film solar cells were also fabricated. The initial heterojunction thin film solar cell with a Al mole fraction of 0.5 showed an efficiency of up to 13.5% (AM 1.5). It is proposed that Multi-Peeled Film Technology will give numerous GaAs thin films by selective etching of (GaAl)As/GaAs multi-layered structures.

1. Introduction

GaAs has long been recognized as a material with a band gap more favourable than that of Si for maximizing the efficiency of solar cells. An important problem in the development of an efficient GaAs solar cell is that of surface recombination. This problem can be minimized by growing (GaAl)As window layer on top of the GaAs surface. It is well known that heterojunction solar cells consisting of p-$Ga_{0.1}Al_{0.9}As$/p-GaAs/n-GaAs exhibit high conversion efficiencies of over 20% for AM 1 [1,2]. However, the (GaAl)As/GaAs solar cell is too expensive, because the GaAs crystal cost is too high, and cost reduction is needed for terrestrial applications.

There are two important ways in which GaAs solar cells could conceivably have a significant impact on future energy. One is the formation of thin film solar cells. Thin film devices are attractive for terrestrial application, because the amount of expensive and relatively rare semiconductor material used in the cell is minimized. Another way is to increase the output of the cell. A two or three order of magnitude increase in output power can be achieved by solar concentration using lenses. James et al. [3] demonstrated the efficient operation of (GaAl)As/GaAs solar cells with a concentration ratio of 1000. The concentration of sunlight appears to be attractive to improve the cost performance of GaAs solar cells.

In this work, thin film concentrator GaAs solar cells have been fabricated by Peeled Film Technology (PFT) [4,5]. High quality single crystalline GaAs thin films can be formed by PFT, and the energy conversion efficiency of thin film solar cells is expected to to be as high as that of bulk type solar cells. In this paper the electrical characteristics of thin film GaAs homojunction concentrator solar cells are described, but the ultimate purpose of this study is to construct thin film (GaAl)As/GaAs heterojunction solar cells that are low enough in cost to be suitable for use with low-cost moderate-power concentrators.

2. Formation of GaAs thin film solar cells

2.1. Fabrication processes

Fig. 1 shows the basic structure necessary to obtain GaAs thin film solar cells. The $Ga_{1-x}Al_xAs$, with an Al mole fraction of 0.7, and Sn doped n-GaAs are grown on the GaAs substrate by liquid phase epitaxy. Typical $Ga_{0.3}Al_{0.7}As$ and GaAs layer thicknesses are

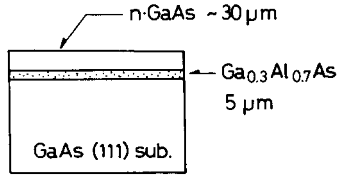

Fig. 1. Basic structure necessary to get a GaAs thin film solar cell.

5 and 30 μm, respectively. Substrate dimensions are from 5 mm × 5 mm to 10 mm × 15 mm. The p–n junction was formed by diffusing Zn into the specimen consisting of n-GaAs/undoped $Ga_{0.3}Al_{0.7}As$/GaAs substrate in a closed tube by utilizing $ZnAs_2$ as a source material of Zn. The junction depth is about 1 μm for a 700°C, 5 min diffusion. Alternatively, Zn doped p-$Ga_{1-x}Al_xAs$ was grown on n-GaAs grown layer. During the LPE growth of Zn doped $Ga_{1-x}Al_xAs$ the p-GaAs region is formed by Zn diffusion. The surface p-$Ga_{1-x}Al_xAs$ is then selectively etched away, and the GaAs p–n homojunction solar cell has been fabricated.

The fabrication processes are illustrated in fig. 2. The grid stripe contact (Ag + Zn) is evaporated onto the p-GaAs by using a lift-off technique (a), and after side etching Au + Ge is evaporated onto n-GaAs (b), followed by the annealing of the contact metals at 400°C. The thick gold is deposited onto the contact metal by electroplating (c). Then, after covering the surface layer by black wax, the wafer is soaked in the selective etchant HF (d). This etchant dissolves the intermediate $Ga_{0.3}Al_{0.7}As$, but not the GaAs. Thus, the thin film solar cells can be peeled off the substrate (e). After fixing the solar cells onto an Al plate the Au wire is bonded on the contact metal, and SiO is evaporated as a 600–800 Å thick anti-reflective coating film.

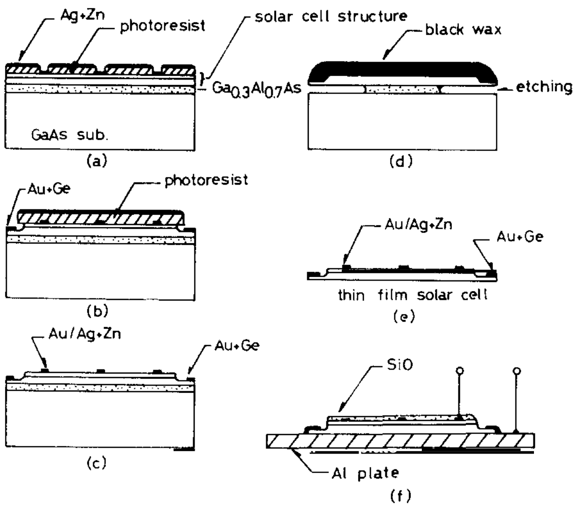

Fig. 2. Fabrication processes of thin film solar cells.

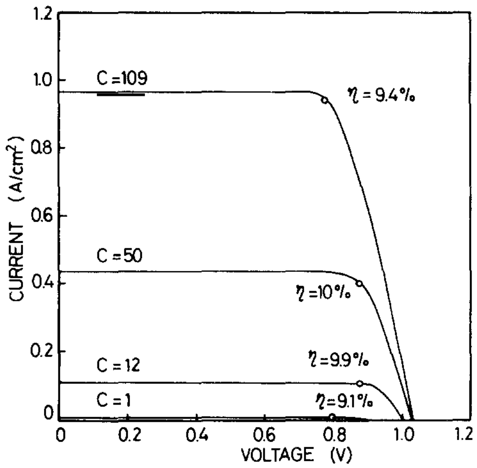

Fig. 3. Current-voltage characteristics of thin film solar cells under the concentration of sunlight. C = concentration ratio, η = efficiency. Input power is 80 mW/cm^2 for C = 1 (1 sun).

2.2. Characteristics

The cell was first tested as a normal cell in direct sunlight (concentration ratio $C = 1$) outside the concentrator assembly. The measured 1 sun ($C = 1$) efficiency ranges from 9 to 11% including the contact area. The input power, which was measured by an Epley Thermopile, was 80–90 mW/cm^2 on a clear day in Tokyo (AM 1.5). The cell was then placed in the concentrator assembly and operated with various values of solar concentration. Fig. 3 shows the typical current–voltage (I–V) characteristics under concentrated sunlight. The symbol C in fig. 3 means the concentration ratio. The efficiency increases from 9.1% ($C = 1$) to 10% ($C = 50$) by the concentration of sunlight. At $C = 109$, the efficiency is 9.4%, a value which is a little higher than 1 sun efficiency, and the output power density is 0.82 W/cm^2. The cell operating temperature at $C = 109$ is about 75°C. The maximum output power density obtained from the cell is 1.0 W/cm^2 for $C = 157$. We believe that this is the highest output power density that has been obtained from thin film solar cells.

3. (GaAl)As/GaAs heterojunction solar cells

We have also fabricated thin film solar cells with the growth of a third epitaxial layer to provide a

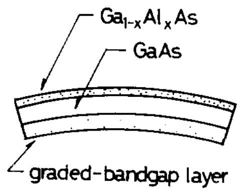

Fig. 4. Structure of a heterojunction thin film.

heteroface or heterojunction window on the thin GaAs structure. As is well known, the lattice match and thermal expansion coefficient match between $Ga_{1-x}Al_xAs$ and GaAs are good, but there exists about a 0.13% lattice mismatch ($x = 1$) between the two at room temperature [6]. Therefore the heterojunction (GaAl)As/GaAs thin film is curved by the strain. Many cracks are induced into the peeled film if the radius of curvature is less than 10 cm. In this work the radius of curvature has been theoretically analyzed assuming that the elastic constant of both materials is equal [7]. Fig. 4 shows the structure of a heterojunction thin film. The existence of the graded band gap layer, which is inevitable in the continuous growth technique used in our experiment (see ref. [4]), has been confirmed by the Electron Probe X-ray Micro Analyzer (EPMA). A typical graded band gap layer thickness and Al mole fraction at the back surface are 20 μm and 0.1, respectively. By using these parameters, the radius of curvature R has been calculated by putting $x = 0.7$ (fig. 5). The radius of curvature increases with thickness of the $Ga_{0.3}Al_{0.7}As$ layer (t_3) in the range $t_3 < 1$ μm, and R becomes infinite at $t_3 = 1.0$ μm. R again decreases with t_3 for $t_3 > 1$ μm. This fact means that the bending force from the $Ga_{0.3}Al_{0.7}As$ is just compensated by the bending force from the graded band gap layer. The optimum $Ga_{0.3}Al_{0.7}As$ thickness is in the range 0.8–1.2 μm, which corresponds to a value of $R > 40$ cm.

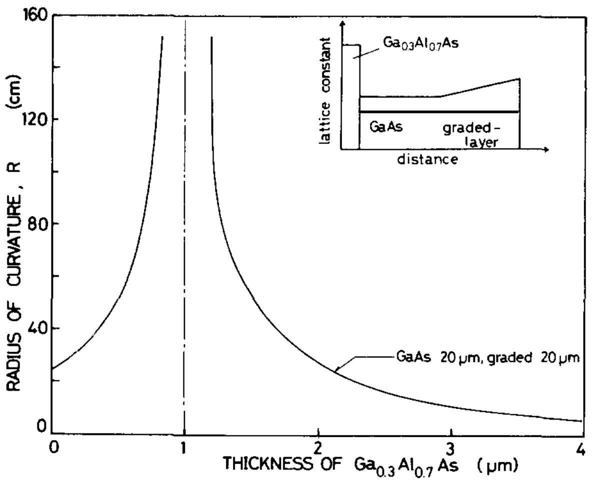

Fig. 5. Variation of the radius of curvature of a heterojunction thin film solar cell with the thickness of a $Ga_{0.3}Al_{0.7}As$ window layer. Both the thickness of GaAs and graded band gap layers are 20 μm.

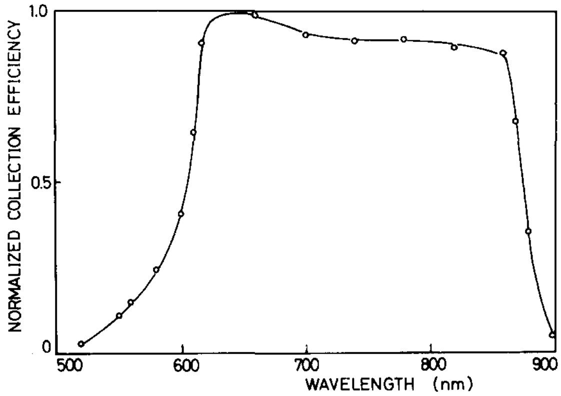

Fig. 6. Spectral response of a $n\text{-}Ga_{0.5}Al_{0.5}As/p\text{-}GaAs$ heterojunction thin film solar cell.

$n\text{-}Ga_{1-x}Al_xAs/p\text{-}GaAs$ heterojunction thin films have also been obtained by PFT. The fabricated thin film geometry is as follows; thin film whole area = 4×5 mm^2, junction area = 2×3.3 mm^2 (the side of the junction is etched), $n\text{-}Ga_{1-x}Al_xAs$ thickness = 1 μm, Al mole fraction $x = 0.5$–0.7, and p-GaAs thickness = 40–50 μm.

The initial cells showed efficiencies of up to 13.5% and higher efficiencies should be obtained with a higher Al mole fraction. Fig. 6 shows the measured spectral response of the $n\text{-}Ga_{0.5}Al_{0.5}As/pGaAs$ thin film solar cell.

4. Approaches to Multi-PFT

In this paper, a new technique, designated as Multi-PFT (Multi-Peeled Film Technology), has been proposed to give numerous GaAs thin films from a (GaAl)As/GaAs multi-layered structure. The (GaAl)As and GaAs layers are grown alternatively on the GaAs substrate and the intermediate (GaAl)As

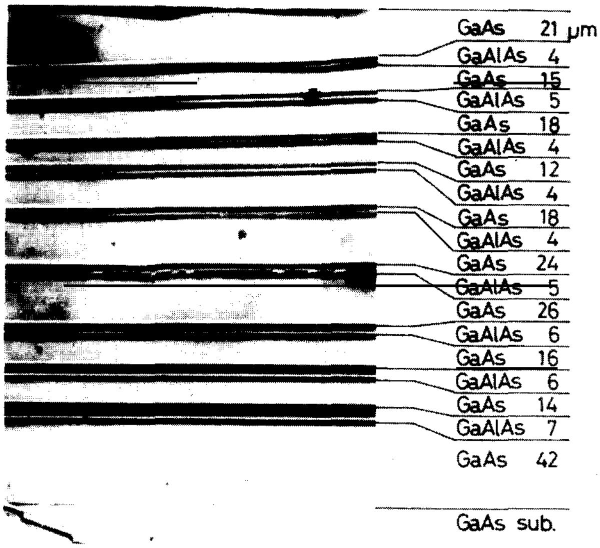

Fig. 7. Stain etched cleaved cross section of (GaAl)As(9 layers)/GaAs(10 layers) multi-layered structure grown by temperature gradient LPE.

layers are selectively dissolved by HF. Numerous GaAs thin films can be detached from the substrate. Hence, the substrate can be used again.

In this paper, temperature gradient liquid phase epitaxy has been attempted in order to grow thick (GaAl)As/GaAs layers. The most important factor necessary to obtain a flat grown layer is the temperature programme. The Ga melt is cooled at a very slow cooling rate of 0.1°C/min or less, while the temperature gradient is kept constant at 10°C/cm during the crystal growth. A thick GaAs layer of 120 ± 5 μm has been obtained with a growth duration of 6 h, which value corresponds to the growth rate of 20 μm/h.

The (GaAl)As/GaAs multi-layers were grown by the temperature gradient LPE as shown in fig. 7. Nine (GaAl)As layers and ten GaAs layers were grown on the GaAs substrate. In this case, the temperature gradient in the Ga melt was 7°C/cm, and the growth duration 1 h for each layer. The total thickness was 248 μm, and the average GaAs thickness was 18 μm for nine GaAs layers. Thus it is clear that (GaAl)As/GaAs thick multi-layers can be grown by the temperature gradient method because of the high growth efficiency.

A further detailed study in multi-layer growth by the temperature gradient LPE method is in progress.

5. Summary

GaAs thin film concentrator solar cells were fabricated by Peeled Film Technology. The efficiency of a p-GaAs/n-GaAs concentrator solar cell is 9.4% at a concentration ratio of 109. The maximum output power density obtained from the cell is 1.0 W/cm^2. The radius of curvature of a (GaAl)As/GaAs thin film was theoretically analyzed. The fabricated n-$Ga_{0.5}Al_{0.5}As$/p-GaAs thin film solar cells showed efficiencies of up to 13.5% in sunlight.

Furthermore, it is proposed that Multi-PFT will give numerous GaAs thin films by a selective etching process. The (GaAl)As/GaAs multi-layers were grown by the temperature gradient liquid phase epitaxial technique.

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