OM-VPE GROWN MATERIALS FOR HIGH EFFICIENCY SOLAR CELLS

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SUMMARY

The versatility of organometallic vapor phase epitaxy (OM-VPE) for the production of photovoltaic materials is reviewed. Organometallic sources are available for all the III-V elements and a variety of dopants; thus it is possible to use the technique to grow a wide variety of semiconductor compounds, e.g., AlGaAsSb and AlGaInAs alloys for multijunction monolithic solar cells have been grown by OM-VPE. While the effort at Varian has concentrated on terrestrial applications, the success of OM-VPE grown GaAs/AlGaAs concentrator solar cells (23% at 400 suns) demonstrates that OM-VPE is suitable for growing high efficiency solar cells in large quantities for space applications. In addition, OM-VPE offers the potential for substantial cost reduction of photovoltaic devices with scale-up and automation and due to high process yield from reproducible, uniform epitaxial growths with excellent surface morphology.

INTRODUCTION

GaAs solar cells for space applications are attractive for a number of reasons. These include high conversion efficiencies as compared to Si solar cells, capability of high temperature operation without significant loss in efficiency, and less radiation damage in space compared to Si cells owing to a much shorter absorption length for sunlight with a direct bandgap material, which with smaller diffusion lengths can withstand greater radiation flux and defect densities before significant performance degradation takes place [1]. In addition, recent studies show promise of in-situ annealing of radiation damage when GaAs cells operate at temperatures circa 250°C [2]. It has been suggested that GaAs cells would find increased use in space applications if large-scale production of "space qualified" cells is demonstrated [3]. Thus the major problem area is considered to be a reliable high-throughput epitaxial growth technique.

Organometallic vapor phase epitaxy (OM-VPE) has proven to be a highly successful method of growing GaAs/AlGaAs solar cells for concentrator systems applications. Efficiencies of 23.2 ±0.2% at 400 AM2 suns have been achieved in packaged devices [4]. The pilot production facility has demonstrated yield of 65% for packaged OM-VPE-grown cells with efficiency in excess of 20%. The electrical contacts have been examined in detail and contact resistances about 1×10^{-6} ohm-cm^2 are achieved for both n- and p-type contacts. In addition, accelerated aging studies have been done and are currently in progress. The lifetime studies have shown that OM-VPE cells have superior environmental stability compared to LPE-grown solar cells [5].

This paper will discuss the advantages of the OM-VPE technique for growing high efficiency GaAs/AlGaAs solar cells. The growth of multijunction solar cells will also be discussed. Finally, the application of the technique for GaAs space solar cells will be described.

OM-VPE

Organometallic vapor phase epitaxy derives its name from the use of organometallic source compounds for the column III and V elements and the dopants for epitaxial growth of compound semiconductors. The epitaxial growth of GaAs and AlGaAs, for example, is done using trimethylgallium, trimethylaluminum and arsine. Arsine is used in place of the organometallic source trimethylarsenic, since it is much cheaper compared to TMAs and is available in electronic grade purity because of its long-standing usage in the semiconductor industry.

A schematic diagram of the OM-VPE reactor used for the experiments discussed here in shown in Fig. 1. An rf generator is used as the source of power to heat the graphite susceptor on which the wafers are placed. The organometallic compounds decompose at elevated temperatures and the III and V species combine for epitaxial growth. Although the use of vertical reactors has been reported, the horizontal geometry was chosen to simplify later scale up of the system and to avoid problems associated with thermal convection in a vertical cold-wall system.

OM-VPE-grown epitaxial layers have been shown to exhibit excellent thickness and doping uniformity over a large area (about 8 sq.in. in the present system). Also, abrupt GaAs/AlGaAs heterojunctions (<40 Å) have been demonstrated using Auger profiling technique [6,7]. OM-VPE has significant advantage over LPE in its capability of high throughput production and automation, superior surface morphology and control of growth rates down to 0.01 microns/min. Conventional chloride transport VPE is not suitable for growing Al-containing alloys due to thermodynamic constraints and MBE equipment is much more complex and difficult to be set up for high throughput production.

OM-VPE growths usually take place in the mass transport-limited regime so growth rates are easily controlled by changing the input fluxes. In addition, close to one to one correspondence is observed between input gas ratios and incorporation in solid for ternary and quaternary alloys [6].

GaAs/AlGaAs SOLAR CELL

OM-VPE and LPE-grown solar cell fabrication has been pursued in parallel at Varian for a number of years. Conversion efficiencies at 50°C of 23% for LPE cells [8] and 19% for early OM-VPE cells were demonstrated [9]. Both types of cells were unpackaged with 0.566 cm^2 active area. The OM-VPE solar cell was subsequently redesigned, taking full advantage of the capability of the technique and 23.2% efficiency for packaged cells with 1.25 cm^2 active area at 400 suns and 50°C has been obtained [4].

The epitaxial structure of the current design solar cell is shown in Fig. 2. The modified structure utilizes a thin (about 1500 Å) $Al_{0.9}Ga_{0.1}As$ window layer. Computer modeling calculations show that the collection efficiency increases as the window layer thickness is reduced. The results of the model are shown in Fig. 3. The short circuit current increases as the window layer thickness is reduced. Also, the junction depth is a critical parameter and a value of 0.5 micron is used in our design. The p-type doping level is increased halfway into the active layer to provide a drift field that helps in collecting the photo-generated carriers and for reduced series resistance. The cap GaAs layer is used to protect the AlGaAs window layer against oxidation in air and is etched away just prior to depositing Si_3N_4 antireflection coating. The metallization and packaging of these cells is discussed in the paper by Borden et al at this conference.

MULTIBANDGAP SOLAR CELLS

The conversion efficiency can be significantly increased over single p-n junction cells by utilizing multibandgap schemes. The feasibility of the concept was demonstrated at Varian using a spectral splitter approach [10]. A spectral splitter module of 10 Si and $Al_{0.2}Ga_{0.8}As$ cell pairs has recently been completed for Sandia, and greater than 20% system efficiency was measured [11]. The system operates at 37°C and the efficiency includes losses due to the fresnel lens, the dichroic filter, and wiring interconnects. The efficiency of the average cell pair unit is 27.5% at 840 W/m^2 insolation. With improved design for the fresnel lenses and the spectral splitting filter, higher system efficiency can be obtained, as discussed by Borden et al at this conference.

The monolithic structure calls for series-connected p-n junction solar cells grown epitaxially on a substrate. Conversion efficiency of 30% or better is expected from an optimized structure. Although many III-V material systems can be used, the work at Varian has concentrated on the AlGaInAs pseudo-quaternary system [12]. This system encompasses materials with bandgaps varying from 0.4 to 2.1 eV. The proposed structure is shown in Fig. 4.

AlGaInAs

Extensive experimentation has been done to develop techniques for growing alloys in AlGaInAs material systems. It was discovered early in the work that In organometallic compounds react with arsine at room temperature and the In incorporation in the epitaxial layer is not obtained. This problem can be bypassed by employing a concentric tube input design so that the gases do not mix until just before deposition. This scheme is not suitable for reproducible growths, particularly in a scaled-up version of the reactor. It has been reported that growths at low pressures avoid this problem by pyrolyzing PH_3 before it enters the reactor [13]. The solution at Varian has been chemical in nature. It has been demonstrated that trimethylarsenic (TMAs) and In organometallic compounds do not react with each other, and InGaAs layers can be grown on GaAs substrates [14]. This solution makes it possible to retain the advantages of a one atmosphere reactor system.

The first set of experiments for grading InGaAs layers on GaAs were done using TMAs, TMGa, and TEIn. The growths were found to be nonuniform in In content and growth rates across the wafer. This problem was solved by using trimethylindium in place of TEIn and uniform In incorporation and growth rates were obtained [15]. It is thought that since the mechanism of epitaxial growth involves diffusion of species across the boundary layer and breaking the organometallic molecules, the presence of common organic radicals for both In and Ga is helpful. Similar results have been observed in low pressure systems where TEIn and TEGa are used for uniform growth of epitaxial layers of InGaAs.

The doping levels in graded InGaAs have been investigated in detail both as a function of the growth temperature and the input flux of dopant. Zinc p-type dopant and selenium n-type dopant have been investigated in this work. The incorporation of the dopants increases at lower temperatures due to the reduced probability of the dopant atoms escaping from the surface. It is considered preferable to develop techniques for controlled growth at lower growth temperatures, since that reduces the extent of Zn diffusion in a multilayer structure. It has so far not been possible to obtain mid-$10^{17}cm^{-3}$ p-type doping levels at 600°C growth temperature.

Considerable progress has been made in determining conditions for the growth of AlGaInAs alloys. It is found that with a fixed TMIn and (TMGa + TMAl) flux the bandgap can be varied by changing the TMGa/TMAl input ratio while the lattice constant remains unchanged. The growth conditions have been established for the growth of 6% and 20% In compounds over a wide range of bandgaps.

Various grading schemes have been investigated for InGaAs layers grown on GaAs substrates. Dislocation etch pit studies show that with step grading the etch pit density reduces compared to ungraded and linearly-graded layers. A few low-bandgap solar cells have been fabricated using an AlGaInAs window layer. The best spectral response to date is observed in a sample grown with a large number of closely spaced steps. In this respect, the results are similar to previously-reported work with chloride transport VPE-grown InGaAs/InGaP low-bandgap solar cell [16]. Experiments are underway to investigate the effect of various grading schemes on the performance of the cell and optimize the structure.

The other two components for the multijunction cell are the high bandgap cell and a suitable connecting junction. The work on the high bandgap cell is expected to proceed smoothly now, since the basic materials experiments are successfully in progress. The connecting junction can be a tunnel junction in the high bandgap material. To demonstrate the feasibility of a tunnel junction by OM-VPE, we have attempted to fabricate a tunnel junction in GaAs. This work is still in progress and alternate approaches are also being considered.

AlGaAsSb

We have investigated the basic materials growth of alloys in AlGaAsSb quaternary system. This system covers a wide range of bandgaps and is suitable for multibandgap solar cell structures. GaSb growth conditions have been optimized and ternary GaAsSb and AlGaSb and quaternary AlGaAsSb alloys have been grown.

The GaSb growth experiments were done on InAs substrates, since they are nearly lattice matched and InAs substrates are easily available. It is found that the growth morphology is quite sensitive to the III/V ratio and unlike GaAs which grows best in our system with a III/V ratio of 1/10, the growth of GaSb requires a III/V ratio of the order of or greater than 1 [18]. This might be due to the low melting of Sb compared to As.

Graded GaAsSb layers have been grown and it has been possible to grow GaAs-graded GaSb/InAs substrate and vice versa, GaSb-graded GaAs/GaAs substrate layers. It is found that as with AlGaAs alloys, Al can be substituted for Ga without changing the lattice constant. Thus, quaternary AlGaAsSb alloys have been grown on graded GaAsSb layers. Ternary AlGaSb layers have also been grown on InAs substrates.

CONCLUSION

The OM-VPE technique has matured in the past few years and a wide variety of III-V semiconductor alloys have been grown using this technique. It has proven to be a potentially high-throughput epitaxial technique which produces the highest efficiency packaged GaAs/AlGaAs solar cells to date. It is expected that monolithic multibandgap solar cells with 30% and greater efficiencies will be attainable with OM-VPE in the future. The application of this technique to growing solar cells for space use is currently under investigation and is expected to lead to greater use of GaAs-based solar cells in space.

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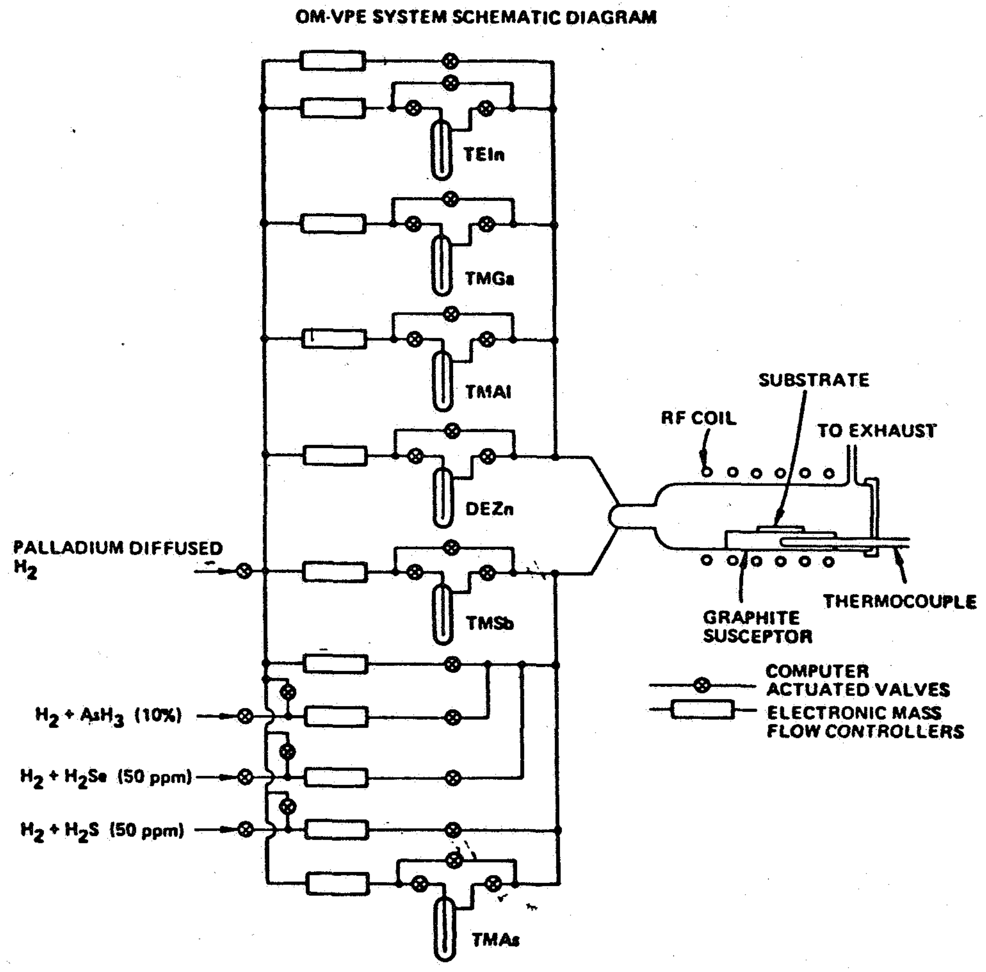

Fig. 1 Schematic diagram of the OM-VPE system.

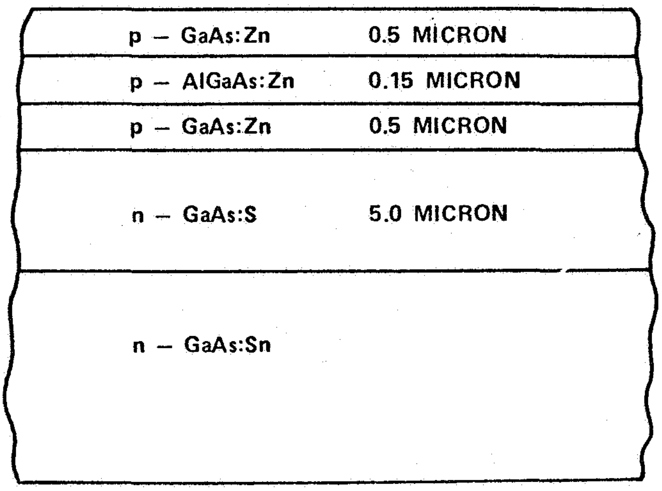

Fig. 2 Epitaxial structure of GaAs/AlGaAs concentrator solar cell.

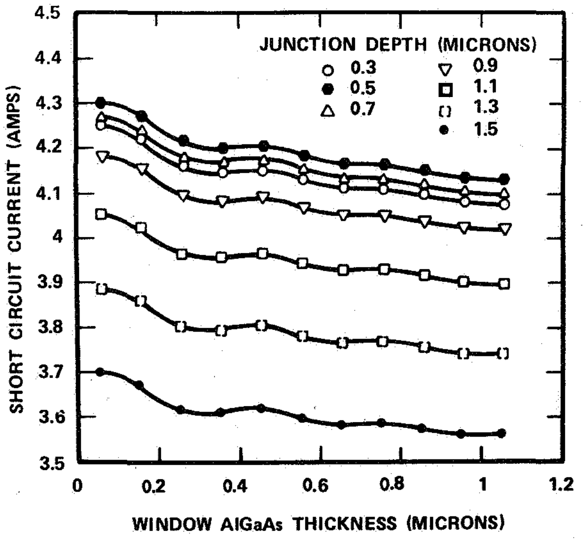

Fig. 3 Predicted AM2 short circuit current as a function of window layer thickness for different junction depth values.

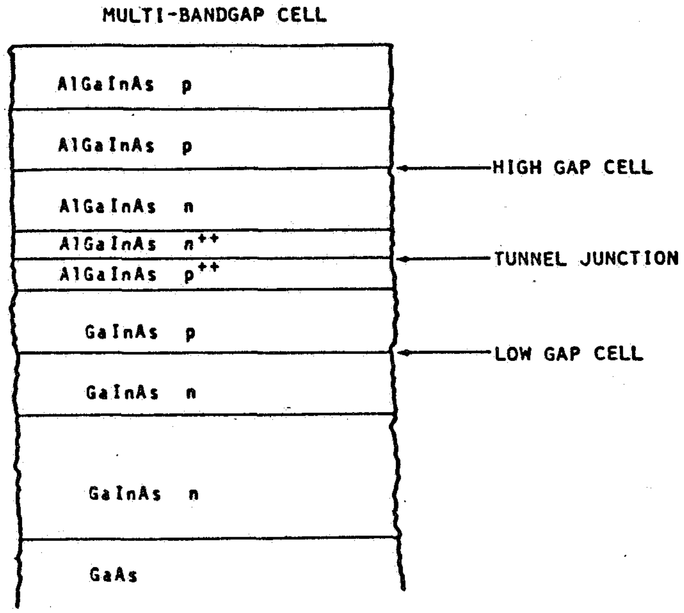

Fig. 4 Multibandgap cell epitaxial structure.