

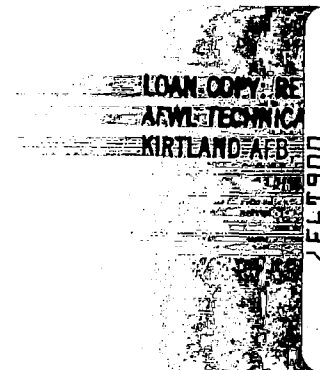
NASA Contractor Report 3361

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GaAlAs/GaAs Solar Cell Process Study

David W. Almgren and Katinka I. Csigi

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GaAlAs/GaAs Solar Cell Process Study

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I. SUMMARY

This study was conducted to collect information on (AlGa)As/GaAs fabrication processes which could produce single crystal solar cells for use in space and to assess the relative merits of the different processes for pilot line production in the early 1980's. The production rate assumed for this study was based on the launch of one 500 watt array per year, approximately 5,000 to 10,000, 2cm x 2cm, space-qualified cells (18% AMO).

Discussions with several potential solar cell suppliers indicated that this production rate could be satisfied with existing facilities. The current production of gallium arsenide solar cells is typically only a small part of the total current production of gallium arsenide devices. For example, more than 100 times the current budget for solar cells is being spent on microwave devices by at least one company. This situation is the result of the very small current market for (AlGa)As/GaAs solar cells and the small future market perceived for space-qualified cells of this type.

Three basic growth processes were identified which could be used to fabricate the epitaxial layers on a single crystal, (AlGa)As/GaAs solar cell. The processes are: 1) Liquid Phase Epitaxy (LPE), including infinite melt and finite melts, 2) Metal-Organic Chemical Vapor Deposition (MO-CVD) and 3) Molecular Beam Epitaxy (MBE). Table 1 summarizes the major direct costs per cell for growth of the epitaxial layers by three processes for a production quantity of 10,000, 2cm x 2cm solar cells.

The infinite melt LPE process, with 100% yield, has the lowest per cell cost because of its ability to fabricate all of the cells in a time period of 4 months, thereby reducing labor costs. This production rate requires holders with a capacity to hold 32, 2cm x 2cm substrates at one time.

The current MO-CVD process, with an enlarged growth station and 100% yield, has the potential to produce cells at the same cost per cell as the infinite melt LPE process. A significant uncertainty with the MO-CVD process is the yield of the growth system, i.e., the fraction of the active material in the input gas stream that ends up in the epitaxial layers.

The MBE process is capable of producing well defined epitaxial layers but it is a slow and expensive process because of the associated labor and capital equipment costs.

Additional work is needed in the area of defining and documenting the detailed process parameters and yield for the MO-CVD system so that a more accurate determination of its economic potential to produce space quality (AlGa)As/GaAs solar cells can be made.

TABLE 1
SUMMARY OF MAJOR DIRECT COSTS PER CELL FOR GROWTH
OF THE EPITAXIAL LAYERS OF 10,000, 2cm x 2cm (AlGa)As/GaAs SOLAR CELLS

● Excluding overhead and profit

Process	Yield (%)	Time to Fabricate (months)	Material Costs	Unburdened Labor Costs	Capital Equipment Costs	Energy Costs	Cost per Cell ¹
LPE — Infinite Melt	100	4	\$.006	\$ 1.54	\$.32	\$.016	\$ 1.88
— Finite Melt	100	63	\$.006	\$14.11	\$ 2.00	\$.015	\$ 16.13
	10	63	\$.06	\$14.11	\$ 2.00	\$.015	\$ 16.19
	1	63	\$.62	\$14.11	\$ 2.00	\$.015	\$ 16.75
MO-CVD	100	31	\$.23	\$ 6.94	\$ 3.88	\$.002	\$ 11.05
	10	31	\$ 2.29	\$ 6.94	\$ 3.88	\$.002	\$ 13.11
	1	31	\$22.94	\$ 6.94	\$ 3.88	\$.002	\$ 33.76
	100	3	\$.23	\$ 1.15	\$.38	\$.002	\$ 1.76
	10	3	\$ 2.29	\$ 1.15	\$.38	\$.002	\$ 3.82
	1	3	\$22.94	\$ 1.15	\$.38	\$.002	\$ 24.47
MBE	50	344	\$.03	\$77.06	\$25.00	\$.79	\$102.88
	5	344	\$.30	\$77.06	\$25.00	\$.79	\$103.15
	50	31	\$.03	\$ 6.94	\$12.92	\$.72	\$ 20.61
	5	31	\$.30	\$ 6.94	\$12.92	\$.72	\$ 20.88

1. Does not include a \$1.24/cm² purchase price for polished substrates.

II. INTRODUCTION

A. PURPOSE AND SCOPE

The purposes of this study were 1) to collect and organize available information on major crystal growing processes that could be used to fabricate single crystal, heteroface, gallium arsenide solar cells and 2) to assess the potential of these processes to produce space — qualified cells in the early 1980's. The specific cell configuration that was examined (see Figure 1) has a three layer structure, namely a p-Ga_{1-x}Al_xAs window, a p-GaAs layer and a n-GaAs layer (which includes the n-GaAs substrate).

A similar study was performed in 1975 by the Air Force with the consulting assistance of A. E. Middleton⁽¹⁾. At that time only a limited amount of experience had been accumulated using Mg and Be as dopants and results from the metal-organic chemical vapor deposition and molecular beam epitaxy growth techniques were not available. Since that time, additional measurements have also been made on the radiation resistance of the heteroface cell. The earlier work was concerned with a production rate of 10,000, 1 cm² (AlGa)As/GaAs solar cells per day of which 100 cm² were space qualified cells.

The production goal assumed for the current study was the fabrication of enough single crystal, gallium arsenide solar cells to support the launch of one 500 W, space-qualified, solar cell array per year. For a nominal (unconcentrated) solar constant of 1353 W/m² and an 18% AMO (25°C) cell, the production goal translates into a minimum of 5200, 2cm x 2cm, space-qualified cells per year. Additional cells will be needed to account for production and handling losses and spares, as well as any decrease in operating cell efficiency due to elevated temperatures or radiation damage on-orbit. We assumed, therefore, an annual production capacity of 10,000, 2cm x 2cm cells per year (40 cells per day for 250 working days per year).

The successful fabrication of space-qualified solar cell arrays involves additional steps after growing the epitaxial layers such as metallization, bonding to the array structure, interconnecting the cells and testing. The objective of this study was an assessment of the epitaxial growth processes so that a suitable cell fabrication process could be selected by NASA for further development of the necessary additional steps leading to space-qualified, gallium arsenide, solar cell arrays.

B. METHODOLOGY

The methodology established in the Statement of Work for the assessment of the various cell fabrication processes was to quantify, where possible, the following process parameters:

- materials usage
- energy usage
- manpower required
- degree of control and repeatability
- process yields
- problems and potential for scale up and automation
- cost.

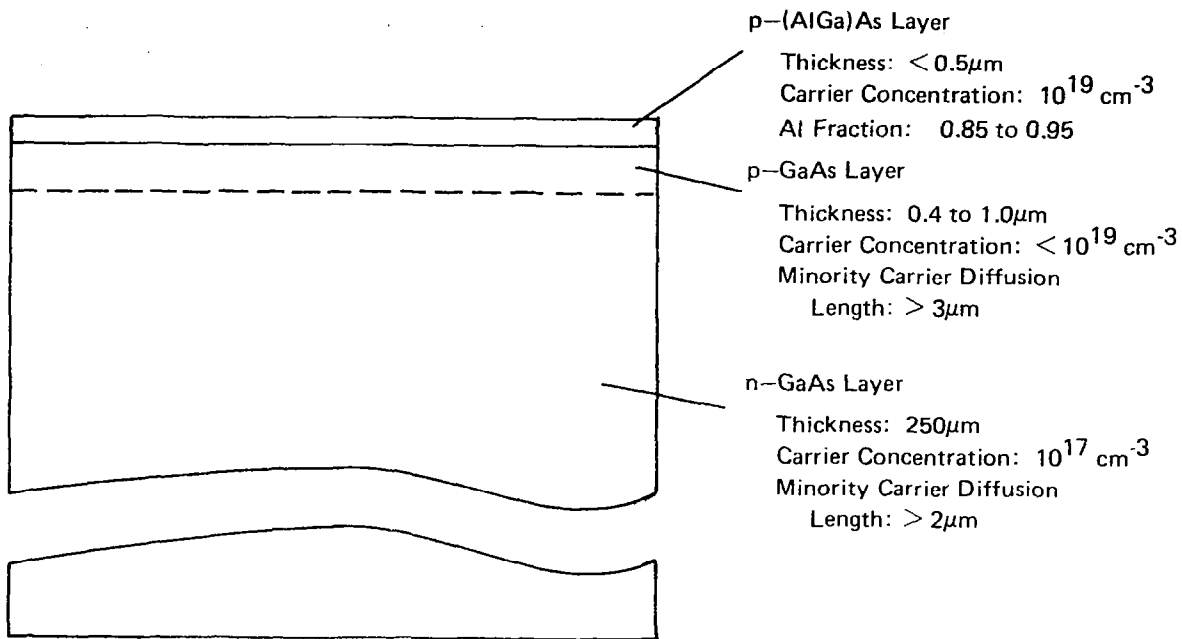


FIGURE 1 PHYSICAL CHARACTERISTICS OF SPACE DESIGNED (AlGa)As/GaAs SOLAR CELL CONSIDERED IN THIS STUDY.

Because of the differences in funding levels that have been allocated to develop the various cell fabrication processes, it was assumed that today's best documented cell efficiencies do not define a quality factor for comparing the different processes. The approach was to assume that all cell fabrication processes could produce an equally efficient cell (18-20%) and then define current and projected costs for these cells and additional development necessary to achieve these costs

A study of this type is limited by the uncertainties inherent in trying to quantify production type data, e.g., process yields, from laboratory scale experiments. Much of the published literature on gallium arsenide solar cells deals with the fabrication of individual cell structures of small size. The investigators were primarily interested in defining cell growth parameters that would lead to more perfect crystalline structures and optimum doping profiles. Problems associated with materials and energy usage, manpower requirements, control of process parameters over large areas and economics of higher production rates were not typically considered. Our methodology was to document the available process parameters and to parametrically examine significant uncertainties when process data was not available.



III. THE SINGLE CRYSTAL GALLIUM ARSENIDE SOLAR CELL

The purpose of this section is to define the basic cell structure before discussing the various cell fabrication procedures in Section IV.

A. PRINCIPLES OF OPERATION

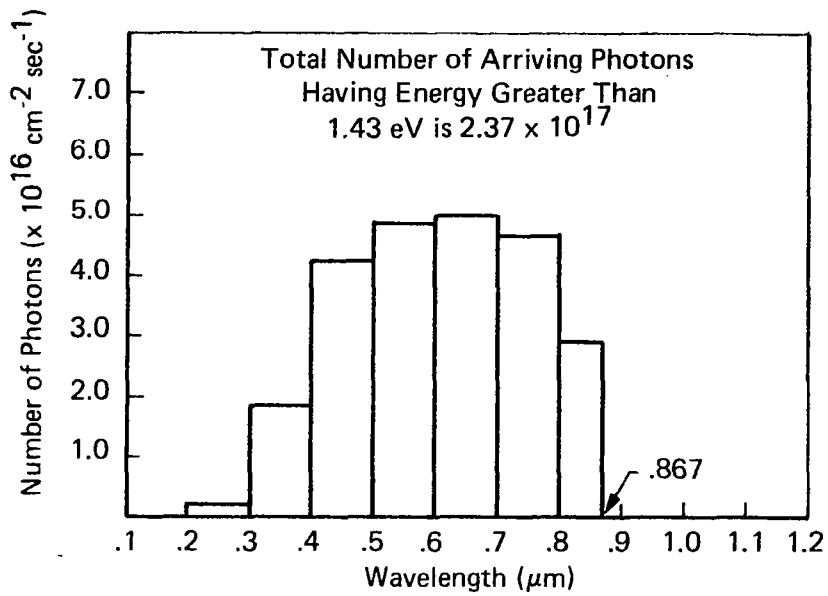
The space-type, gallium arsenide solar cell under consideration for this study would be used to convert an unconcentrated, AM0 solar spectrum into electrical energy. The basic structure of the GaAs solar cell is a GaAs p-n junction covered by a window layer of (AlGa)As (to reduce surface recombination losses), covered by an anti-reflection coating and provided with ohmic electrical contacts. GaAs has a direct band gap of 1.43eV (300K) and, based on NASA's standard AM0 solar spectrum data⁽²⁾ there are 2.37×10^{17} photons/(cm²-second) incident on a normal surface capable of creating a hole-electron pair in GaAs. Once the electron-hole pair has been created, the collection of these photogenerated carriers by movement across the p-n junction is in competition with the loss of these carriers by bulk and surface recombination. If every electron-hole pair were collected by the p-n junction, a maximum short circuit current, I_{sc} , of 38 ma/cm² would be realized.

Figure 2 shows a histogram of the number of incident photons in the AM0 solar spectrum having an energy of at least 1.43eV, broken down into discrete wavelength bands of 0.1 μm width. Using the absorption coefficient shown in Figure 3 for GaAs⁽³⁾, the number of electron-hole pairs created in the material as a function of depth is shown in Figure 4. The data in Figure 4 assumes no reflection losses at the surface or absorption losses in the Ga_{1-x}Al_xAs window layer.

The lifetime of a minority carrier (L_n for electrons, L_p for holes) in doped GaAs is in the range of 0.1 to 6.0×10^{-6} sec. depending on the level of doping and method of crystal growth.⁽⁴⁾ Experimentally, the lifetime in GaAs decreases with increasing doping level but, in practice, there is no unique lifetime at a given doping level. For a finished device, the realized lifetime depends on the surface treatment during fabrication, the diffusion temperature, the rate of cooling and the presence or absence of annealing steps.⁽⁴⁾ Closely associated with the lifetime of a minority carrier is the distance a free charge carrier can diffuse in one lifetime period (termed the diffusion length).

Typical values for diffusion lengths in a space type GaAlAs/GaAs solar cell are 2 μm for the n-GaAs bottom or substrate layer and 3 μm for the p-GaAs middle layer. The longer diffusion lengths obtained for the electrons in the p-type GaAs material is a reason to design the cell so that the majority of the hole-electron pairs are created in the p-type material. An n⁺ on p-type GaAs cell, with a top n⁺ layer thickness of only 200 Å (without a GaAlAs window layer) has also been fabricated so that the majority of the electron-hole pairs are created below the junction in the p-type material.⁽⁶⁾

As shown in Figure 4, for a junction depth of 0.5 μm below the surface of a GaAs cell (neglecting any absorption by the window layer), 78% of the incident photons would be absorbed in the p-type material before reaching the junction. As the junction depth is decreased to enhance the radiation resistance of the solar cell, more of the charge carriers will be generated below the junction in the n-type material. With a 0.2 μm junction depth, for example, approximately 57% of the electron-hole pairs would be created above the junction.



- Divided into discrete spectral bands

FIGURE 2 NUMBER OF PHOTONS IN AMO SOLAR SPECTRUM HAVING ENERGIES GREATER THAN 1.43 eV.

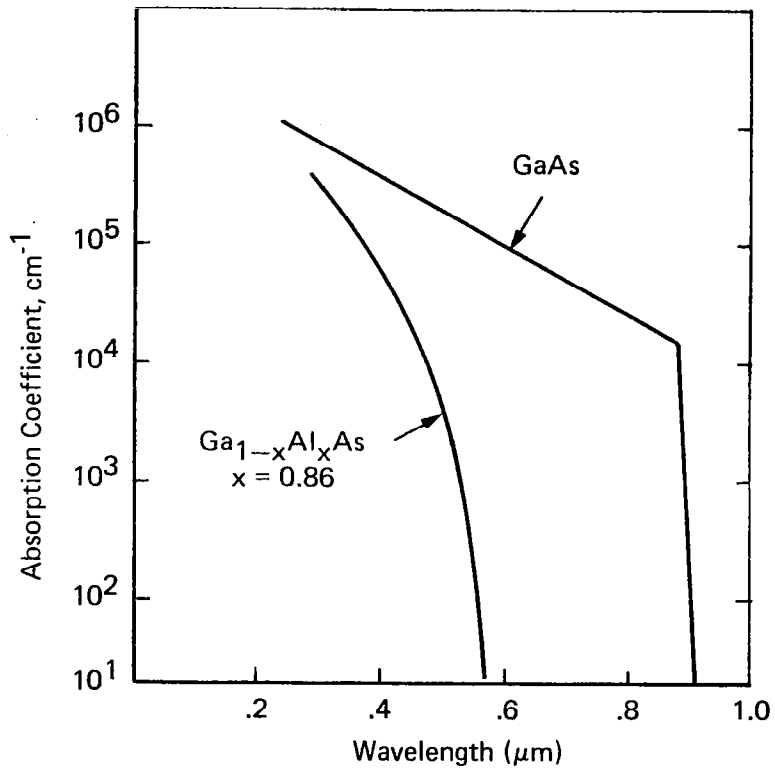
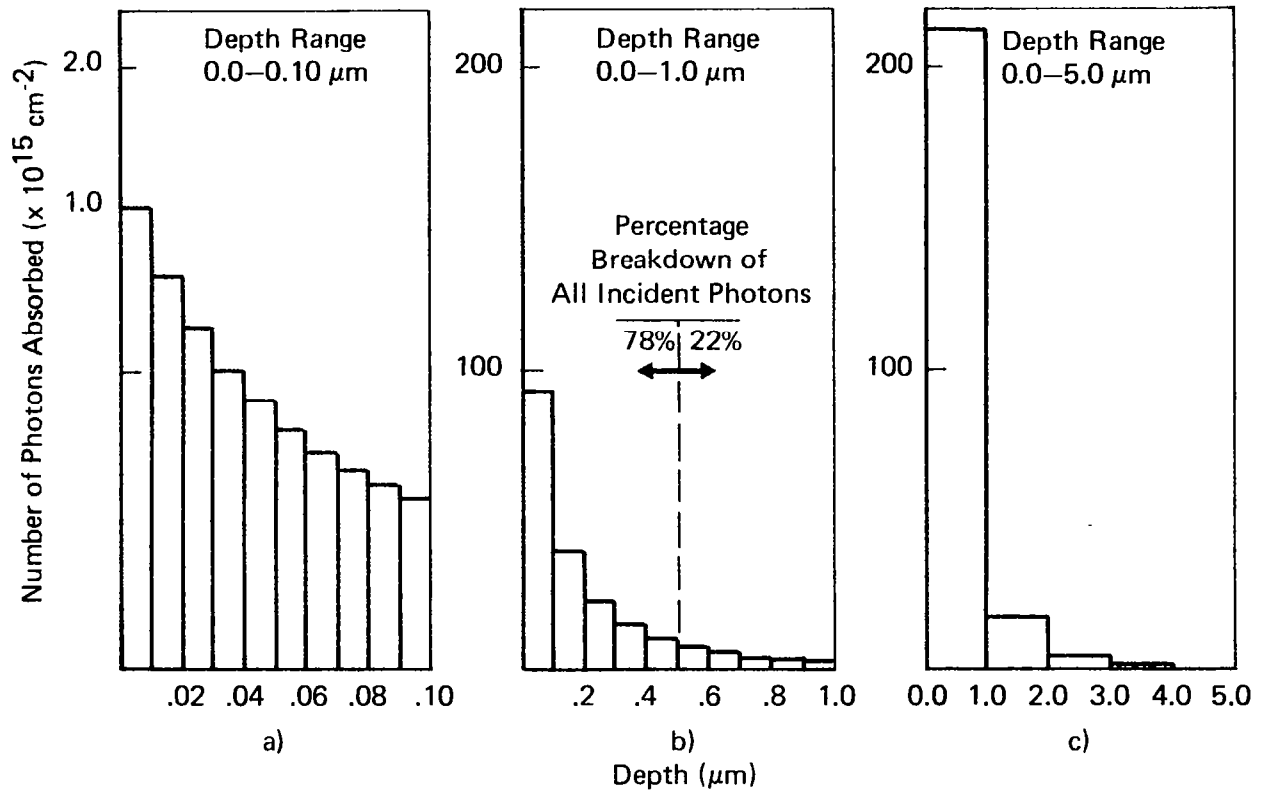


FIGURE 3 ABSORPTION COEFFICIENT FOR GaAs AND Ga_{1-x}Al_xAs AS A FUNCTION OF WAVELENGTH.



- All incident photons are assumed to enter GaAs material
- No window layer

FIGURE 4 NUMBER OF AM0 PHOTONS ABSORBED IN DISCRETE LAYERS OF GaAs AS A FUNCTION OF DEPTH (300K).

For non-space applications the actual junction depth, i.e., the width of the p-GaAs region is not as an important parameter when the window layer is very thin.⁽⁶⁾ Only for a deep junction solar cell, $>1.0 \mu\text{m}$, is the short circuit current, I_{sc} , significantly reduced as the electron diffusion length is decreased. For space application it has been shown that the p-GaAs thickness is an extremely important parameter for radiation damage control.⁽⁷⁾ At a given fluence of $1 \text{ MeV electron/cm}^2$, the short circuit current is higher for cells with shallower junction, e.g., $0.5 \mu\text{m}$. This situation is due to the shorter diffusion lengths caused by the radiation damage. The significance of this requirement for shallow junctions in the space-type cells is in the relative ability of the different cell fabrication processes to control the thin layer thicknesses and dopant profiles uniformly over large areas so that optimized (AlGa)As/GaAs solar cells can be produced in significant quantities with a high yield.

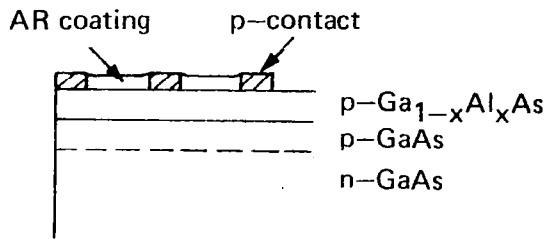
The primary purpose of the p-GaAlAs window layer on the p-GaAs material is to reduce the recombination velocity at the GaAs "surface" (the interface between the two materials). Surface recombination is a significant cause of low power conversion efficiencies in conventional GaAs solar cells, an effect that is augmented by the high absorption coefficients of GaAs to the AM0 solar spectrum. The recombination velocity at the front of a standard GaAs solar cell is in the range of $10^5 - 10^6 \text{ cm/sec}$. At the $\text{Ga}_{1-x}\text{Al}_x\text{As-GaAs}$ heterojunction the recombination velocity is typically 10^4 cm/sec or lower.

Increasing the Al fraction in the $\text{Ga}_{1-x}\text{Al}_x\text{As}$ increases the overall efficiency of the cell because of reduced optical absorption in the (AlGa)As. It is therefore desirable to fabricate cells with as much Al incorporation as is compatible with other factors which determine overall cell efficiency. When $x > .96$, for example, a visible oxide forms on the cell surface immediately upon removal from H_2 . When $x \sim .95$, several hours are required before the oxide film becomes visible; for $x \sim .92$, several days are needed.⁽⁸⁾

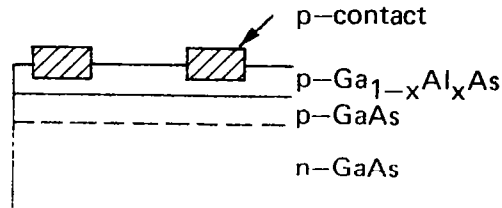
Increased doping of the $\text{Ga}_{1-x}\text{Al}_x\text{As}$ window lowers its sheet resistivity and thereby decreases the series resistance in the cell. The level to which the window layer can be doped while maintaining the desired junction depth in an LPE process is a function of the choice of dopant, the concentration of dopant in the melt and the time-temperature growth procedure. With Be, for example, there is an initial high diffusion rate of Be into the GaAs material until a few hundred angstrom thick layer of (AlGa)As forms on the surface.⁽⁹⁾

The junction depth is particularly sensitive to solution concentration when slow growth rates are used. Slow growth rates are important to allow for orderly growth of the window layer to maintain good crystal perfection as well as avoiding dopant segregation at the growth interface. An increase in the dopant concentration in the (AlGa)As melt will cause a deeper junction and a decreased average lifetime in the p-type material.

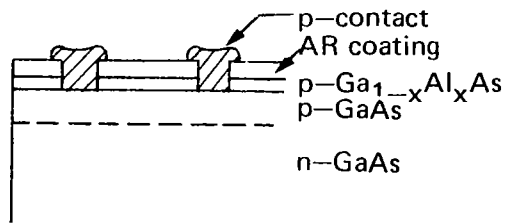
An approach to minimizing the effect of too high a doping level in the (AlGa)As layer, while also making low resistance metallic contacts directly to (AlGa)As, is to grow an additional heavily doped layer of GaAs on top of the (AlGa)As.⁽⁶⁾ During the growth of this p-type GaAs contacting layer, diffusion occurs from that layer into the window layer underneath, thereby substantially reducing the (AlGa)As sheet resistivity without increasing the junction depth in the GaAs. After metallization is applied to the contacting layer, the uncovered p-type GaAs contacting layer is selectively etched away, stopping at the (AlGa)As layer (see Figure 5).



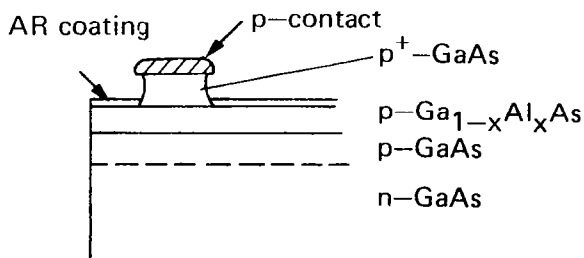
AMO
(Same grid pattern
as used with
2cm x 2cm silicon cell)



Terrestrial
Concentrator
Cell



Terrestrial
Concentrator
Cell



Terrestrial
Concentrator
Cell

● Not to scale

FIGURE 5 SUMMARY OF CONTACTING GEOMETRY BEING USED WITH GaAl As LAYER.

B. CHOICE OF DOPANTS

Table 2 summarizes the p-type and n-type dopants that could be used with GaAs. N-type substrates are typically manufactured by the horizontal Bridgman technique with Si, Se, Te or Cr as the n-type dopant. The solar cell business of the substrate suppliers typically represents less than 15% of their total business so that generally the photovoltaic community buys the same material that is being made for FET's or LED's.

TABLE 2
SUMMARY OF DOPANTS USED WITH GaAs

P-Type	Amphoteric	N-Type
Be	Ge	Cr
Cd	Si	Se
Mg	Sn	Te
Mn		
Zn		

Many fabricators of GaAs solar cells believe that the less than perfect quality of the n-type substrate material as purchased will degrade cell efficiency unless steps are taken to mask the substrate defects with a n-type buffer layer or to leach out the substrate impurities as a first step in the cell fabrication process.

The GaAs solar cells fabricated by one organization use Te doped substrate material having a dopant concentration of $5 \times 10^{17} \text{ cm}^{-3}$.⁽⁹⁾ This material was chosen for economic reasons in that it was already developed for use in LED's. The highly doped substrate also makes contacting with Au-Ge-Ni easier. A $\geq 10 \mu\text{m}$ buffer layer of n-GaAs is then grown on the substrate, doped to a level of $1 \times 10^{17} \text{ cm}^{-3}$ using tin. Tin has a low vapor pressure and well behaved segregation coefficient and was chosen over Te because of the somewhat higher vapor pressure of Te. The level of doping was chosen to maximize the open circuit voltage as a function of carrier concentration in the n layer. The thickness of $\geq 10 \mu\text{m}$ was chosen because results have indicated that substrate "effects" are minimized at this thickness. This thickness is about three times the minority carrier diffusion length. The p-GaAs layer is then formed ($2 \times 10^{18} \text{ cm}^{-3}$) by diffusion of the Be dopant from the melt used to grow the (AlGa)As window layer.⁽⁹⁾

An alternative approach, used by another organization, is to grow their own high quality substrate material by a liquid encapsulation Czochralski technique which has been doped with either Sn or Te to a level of 10^{18} cm^{-3} . A $30 \mu\text{m}$ thick, n-GaAs epitaxial layer (doped with Sn to a level of $8 \times 10^{17} \text{ cm}^{-3}$) is then grown as a buffer layer. The p-GaAs layer is then formed by diffusion of Mg from the melt used to grow the (AlGa)As layer. Mg was chosen over Be because it is a less toxic material. Typical Mg concentrations are $7 \times 10^{17} \text{ cm}^{-3}$ in the p-GaAs layer and $5 \times 10^{17} \text{ cm}^{-3}$ in the (AlGa)As window layer. The p^+ -GaAs layer grown on top of the window layer to receive the metallization is doped to a level of 10^{18} cm^{-3} with Mg.⁽⁹⁾

The LPE growth techniques being studied at a third organization were typically done with n-GaAs substrates doped to a level of $1.5\text{-}2.0 \times 10^{17} \text{ cm}^{-3}$. Zn was a dopant used for many experimental runs however the incorporation of Mg as the p-type dopant in early 1978 allowed for

the growth of both p-type and n-type layers in the same run without appreciable cross doping effects. The use of Mg doping was considered to be very desirable since there is not an appreciable evaporation of Mg from the melt during growth. This is in contrast to the noticeable amount of Zn evaporation during growth.

C. CONTACTING

The methods currently used to provide ohmic contacts to the top and bottom of a $Ga_{1-x}Al_xAs/GaAs$ solar cell show several variations, due primarily to difficulty in making contacts that would adhere to $(AlGa)As$. Reference No. 10 tabulates sixty different materials that have been used as ohmic contacts to GaAs and Table 3 summarizes the materials currently being used in the United States for the fabrication of GaAs solar cells.

TABLE 3
SUMMARY OF CONTACTING MATERIALS CURRENTLY BEING USED WITH
 $(AlGa)As/GaAs$ SOLAR CELLS

Back Contact	Front Contact
Au-Ge-Ni ($\sim 5000\text{\AA}$)/Ag ($10\ \mu\text{m}$)	Au-Zn ($3000-4000\text{\AA}$)/Ag ($10\ \mu\text{m}$)
Mg(20\AA)/Ti(2000\AA) Mg($20-50\text{\AA}$)/Ti(300\AA)/Pd(300\AA)/Ag(5000\AA)	Mg(20\AA)/Ti(300\AA)/Pd(300\AA)/Ag
Au-Ge (2000\AA) Au-Ge	Au(2000\AA)/Zn(1600\AA)/Au(200\AA) Ag-Zn/Ag($5\ \mu\text{m}$)
Au(100\AA)/Sn(500\AA)/Ag(4000\AA)	Au(500\AA)/Mg(250\AA)/Au(3000\AA)

The back ohmic contact generally covers the full area of the cell and is relatively easy to fabricate as compared to the front contact. (The use of Ni in the contacting material, however, degrades the diffusion lengths in VPE grown, n-GaAs.) By making the back contact out of Au-Sn, which exhibits a low contact resistance over a wide range of alloying temperatures and times, the contact alloying temperature cycle can be optimized specifically for the front contact.

The front contact has the specific problems of difficult adhesion to the p- $(AlGa)As$ and diffusion of the contact material to the shallow junction. Figure 5 shows some of the techniques used to solve the problems associated with the front contacts.

For their space and terrestrial cells, one organization contacts directly to the $(AlGa)As$ layer with a sputtered Au-Zn layer ($.3-.4\ \mu\text{m}$). The finger thickness is then built up to $10\ \mu\text{m}$ with a subsequent plating of silver. Annealing of the contacts on the space type cell at 450°C for three minutes caused a lowering of the V_{oc} that was traced to a migration of either Au or Zn to the junction in localized areas of the cell. This problem did not occur when the junction depth was greater than $\sim .25\ \mu\text{m}$ below the window layer.⁽⁹⁾

Another organization selectively etched through their ultrathin ($< 500\text{\AA}$) window layer and contacted directly onto relatively thick p-GaAs layer. Ag-Zn was the contacting material that was

evaporated onto the cell. The thickness of each finger was subsequently increased to 5 μm by electroplating with Ag.⁽⁶⁾

Researchers at a third organization solved the problems of front contacts by growing an additional p^+ -GaAs layer (1 μm thick) on top of the window layer prior to metallizing. Au and Mg were used as the contacting material. To avoid a high Mg concentration at the GaAs surface, (known to cause surface damage), a 500 Å layer of Au was first applied, followed by a 250 Å layer of Mg and capped by a 3000 Å layer of Au. Annealing at 450°C for 10 seconds in hydrogen causes the Mg to diffuse through the Au to the GaAs.⁽⁶⁾

The production of reliable front contacts with a low contact resistance will be a significant problem in scaling up the production quantity of (AlGa)As/GaAs, space-type, solar cells (with shallow junctions). Difficulties have been noted by personnel at several organizations in this specific area. Variations in measured solar cell parameters from cells produced by one group did not correlate with (AlGa)As thickness or diffused junction depths leaving personnel to believe that the observed scatter may be due to variations in either GaAs diffusion lengths or specific contact resistance.⁽⁸⁾

D. RADIATION DAMAGE EFFECTS

One of the important concerns for space-type solar cells is their resistance to radiation damage. The end of life (EOL) efficiency of the cells determines the total array area that must be launched to satisfy payload power requirements for the lifetime of the mission. On-orbit radiation damage is caused by the high energy protons and electrons trapped by the earth's magnetic field and by solar proton flares whose frequency is tied to the sun's eleven year activity cycle. Protons and electrons create different types of damages in semiconductor materials. A proton interacts more strongly with the lattice because of its large size and, therefore, will not penetrate very deeply into the material unless it initially possesses very high energy. It creates considerable damage near the surface that it initially enters. The electron, because of its smaller size, penetrates more deeply into the cells and the damage it creates, therefore, is spaced more uniformly across the cell.

For (AlGa)As/GaAs solar cells the most important location for radiation damage is in the vicinity of the shallow junction. Because GaAs has a large optical absorption coefficient and a short diffusion length, radiation damage beyond the active region near the surface of the cell has a negligible effect on cell performance.

Work has been performed by personnel at several organizations to test the degradation in cell response for a limited range of electron and proton fluences. Figure 6 shows the reduction in maximum power of 2cm x 2cm, deep junction cells, not optimized for resistance to electron radiation damage, that were exposed to 1 MeV electrons at fluences in excess of $4 \times 10^{14} \text{ cm}^{-2}$.⁽⁷⁾ Using a computer model to predict cell performance, short circuit current, I_{sc} , was predicted as a function of fluence of 1 MeV electrons for a range of junction depths. Figure 7 shows the significant beneficial effect of a shallow junction on resistance to electron radiation damage. Experimental data for a junction depth of .5 μm using 1 MeV electrons verified the analysis.⁽⁷⁾

The (AlGa)As solar cells exhibited a higher maximum power output over the range of proton fluences (15.4 MeV and 40 MeV) than the deep junction (AlGa)As cells or the silicon cells that were also tested.

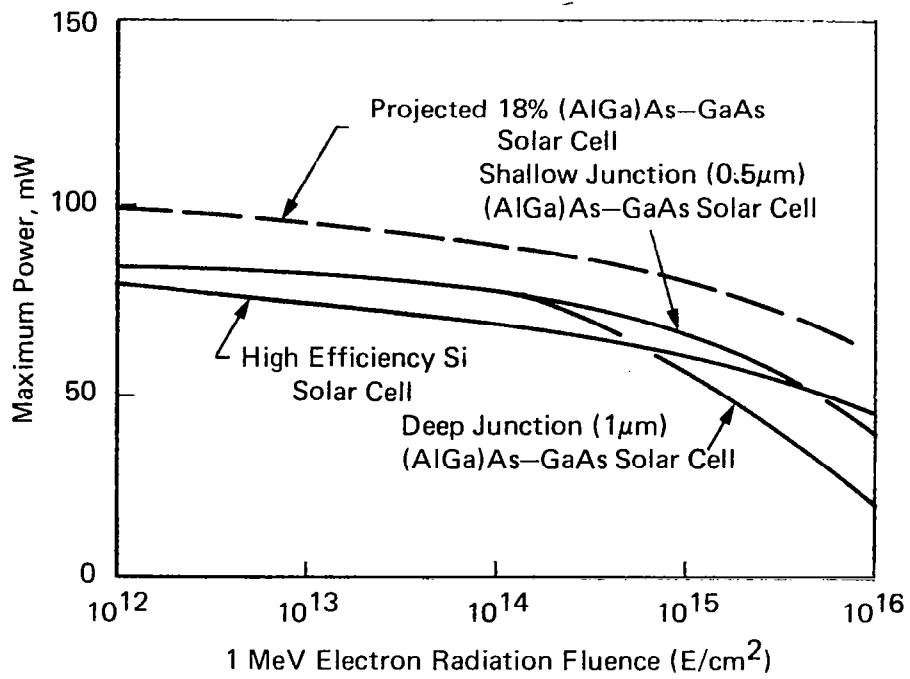


FIGURE 6 MAXIMUM OUTPUT POWER (4 cm^2) VERSUS 1MeV ELECTRON FLUENCE.

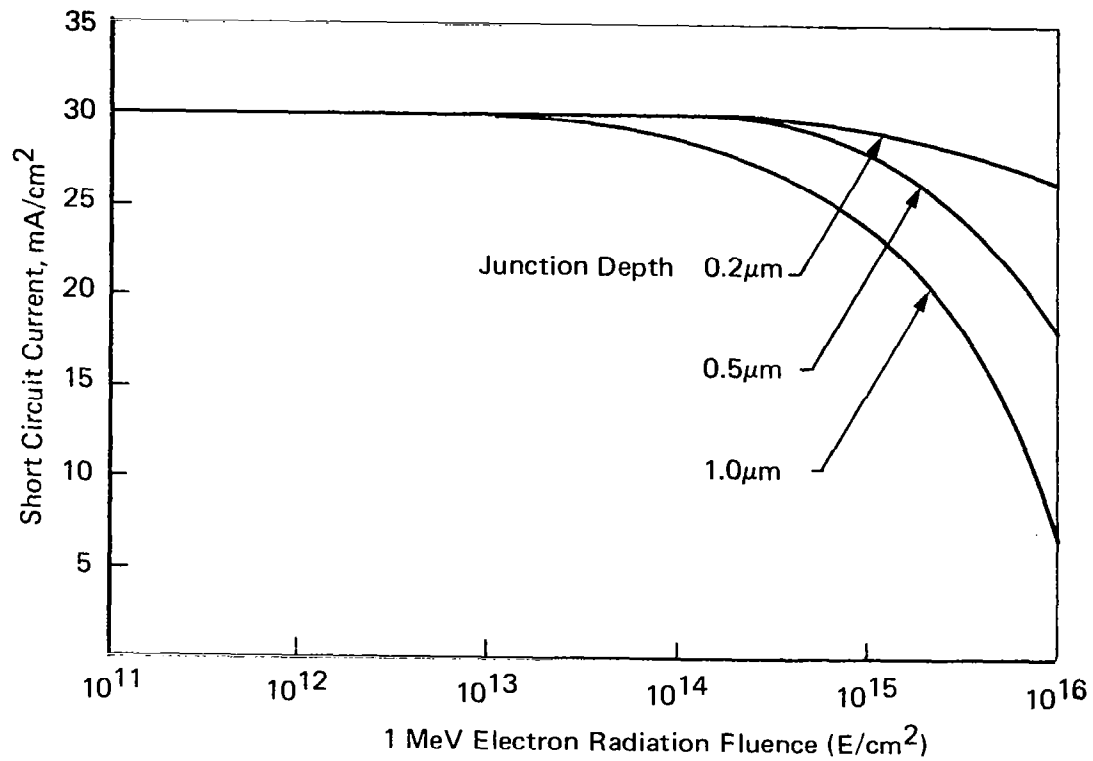


FIGURE 7 PREDICTED (AlGa)As-GaAs SOLAR CELL SHORT CIRCUIT CURRENT DENSITY VERSUS 1MeV ELECTRON RADIATION FLUENCE AS A FUNCTION OF JUNCTION DEPTH.

E. SUMMARY OF SIGNIFICANT CELL DESIGN PARAMETERS

The significant design parameters which must be closely controlled during the cell fabrication processes include: 1) dopant concentration profiles, 2) junction depth and 3) thickness of the window layer. Because of the large absorption coefficient for GaAs, the p-n junction depth is on the order of $0.5 \mu\text{m}$. A shallow junction depth is also beneficial from the viewpoint of increasing the resistance of the cell to radiation damage. The various epitaxial growth processes which could be used to fabricate the active layers of the cell will be discussed and compared in the following sections.

IV. DEFINITION OF EPITAXIAL GROWTH PROCESSES

A. INTRODUCTION

The purpose of this section is to briefly describe the three basic crystal growing procedures that have been used to epitaxially grow doped GaAs and AlGa/As layers on a GaAs substrate. The three techniques are: Liquid Phase Epitaxy (LPE), Vapor Phase Epitaxy (VPE) which includes the Metalorganic Chemical Vapor Deposition (MO-CVD) process, and Molecular Beam Epitaxy. Because of the difference in funding levels that have been applied to develop (AlGa)As/GaAs, heteroface solar cells by the three different techniques, cell conversion efficiencies achieved to date are not being used as a measure of the potential of each process to produce an optimized, space quality solar cell.

B. LIQUID PHASE EPITAXY

Liquid-phase epitaxy (LPE) has become an established technique for the growth of devices based on GaAs and other III-V compounds. The basic growth process is to saturate a melt of Ga m.p. with GaAs at a temperature of around 900°C and to bring this saturated solution in contact with a GaAs substrate. The substrate and solution are cooled at a rate of 0.1-0.5°C/min. to cause the epitaxial layer to grow and the melt and substrate are decoupled when the desired layer thickness has been obtained. A dopant can be added directly to the melt and will be incorporated in the crystal structure in accordance with diffusion rates in the melt and its segregation coefficient.

Variations in the LPE process include both 1) the design of the oven apparatus which holds the melt and substrate and controls contact between the two, and 2) the time-temperature profile followed during the growth process.

The three basic growth techniques used in LPE are: 1) the "dipping" technique in which the substrate(s) are lowered and raised vertically into and out of a melt, 2) a rotating or sliding boat process in which, through the use of a multi-bin system the layers are grown by bringing the substrate into contact with different melts, or 3) a "tipping" technique in which the melt-substrate contact is achieved by tilting the furnace to cause the solution to flow over the substrate. The "dipping" and "rotating or sliding" processes (will be discussed here) because they have been used to grow (AlGa) As/GaAs solar cells. The "dipping" process is typified by the infinite melt LPE process which is currently in use to grow space and terrestrial type (AlGa) As/GaAs solar cells.

In the infinite melt LPE process, two separate furnaces are needed to maintain two growth melts at equilibrium conditions (near 800°C) continuously. A 5000 melt would be maintained for the n-type GaAs melt, used to grow a 10 μ m buffer layer on the as-received GaAs substrate, and a 3000gr melt would be separately maintained for growing the $\leq 0.5\mu$ m, p-type window layer. The infinite melt LPE technique is currently being used in a limited production mode and has demonstrated the advantages of long term stability of the growth solution, a single melt having been maintained for a period of two years.⁽⁹⁾ Once the solution is prepared, it is maintained in an ambient of palladium-diffused hydrogen. All operations for layer growth or maintenance of the melt are performed by passing the appropriate material through an entry chamber. The entry chamber can be independently evacuated and fitted with hydrogen before it is opened to the quartz growth tube. (See Figure 8).

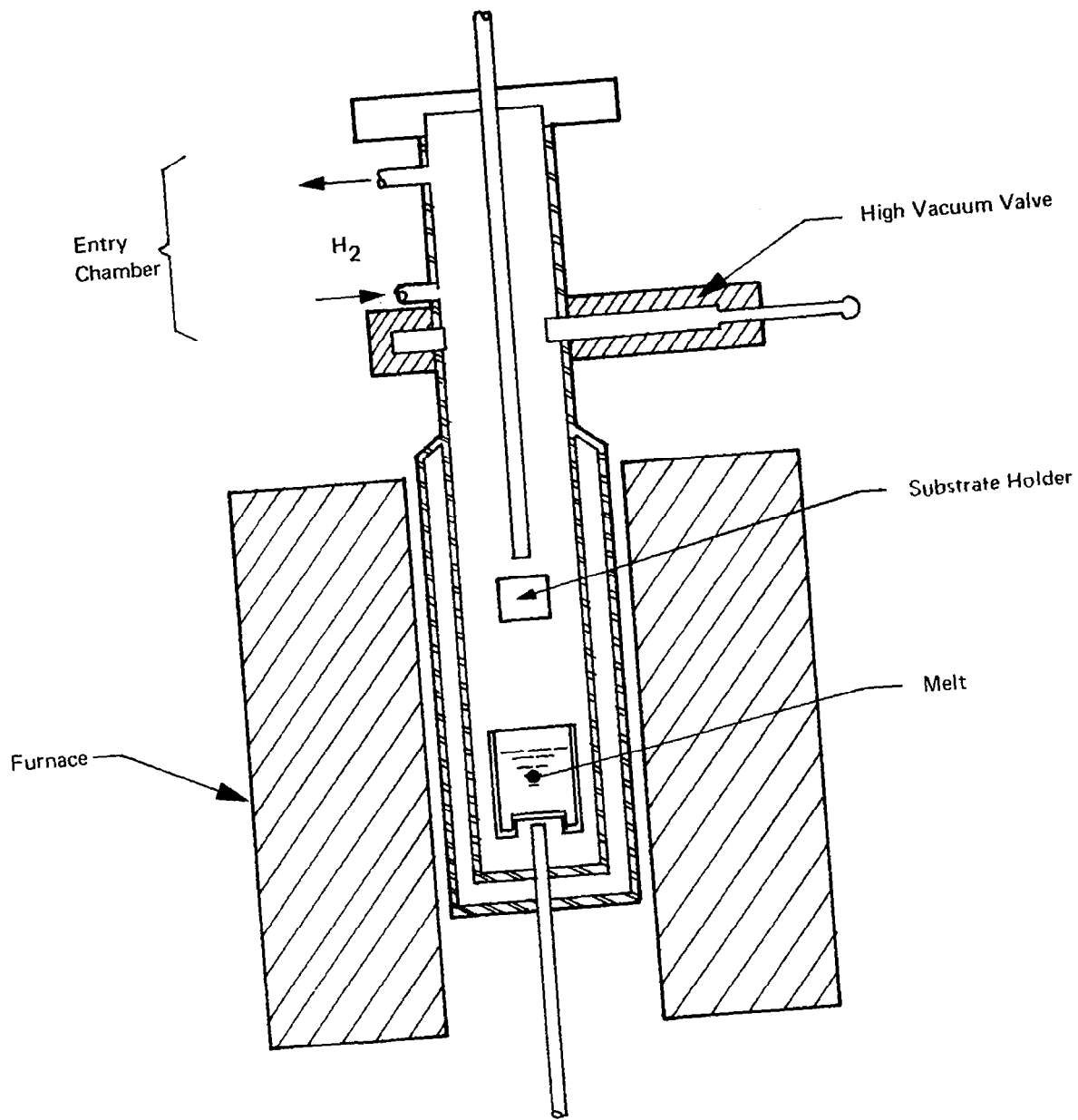


FIGURE 8 TYPICAL GROWTH APPARATUS FOR INFINITE MELT LIQUID PHASE EPITAXIAL PROCESS.

A graphite substrate holder, used to hold the GaAs substrates while they are being dipped into the saturated GaAs solution, serves two basic purposes. First, it provides a backing for the substrate, thereby exposing only one side to the solution. Second, its retractable cover protects the substrate while the substrates and holder are equilibrating with the temperatures of the furnace.

In the limited melt LPE process a rotating or sliding multiple-bin boat allows for sequential deposition of several layers during one growth cycle. (See Figure 9). The GaAs substrate is placed in a recessed area of the slide which, prior to initiation of layer growth, is not in contact with the reservoirs containing the melts. The various reservoirs are fitted with the components of the desired melts, as solids, and the whole apparatus is placed in an evacuated quartz tube which is located in a furnace. A bake-out at 900°C in hydrogen for 12 hours may be necessary prior to initiation of the growth process.

Many different, carefully controlled, time-temperature profiles have been utilized to grow the epitaxial layers on the GaAs substrates.

C. VAPOR PHASE EPITAXY

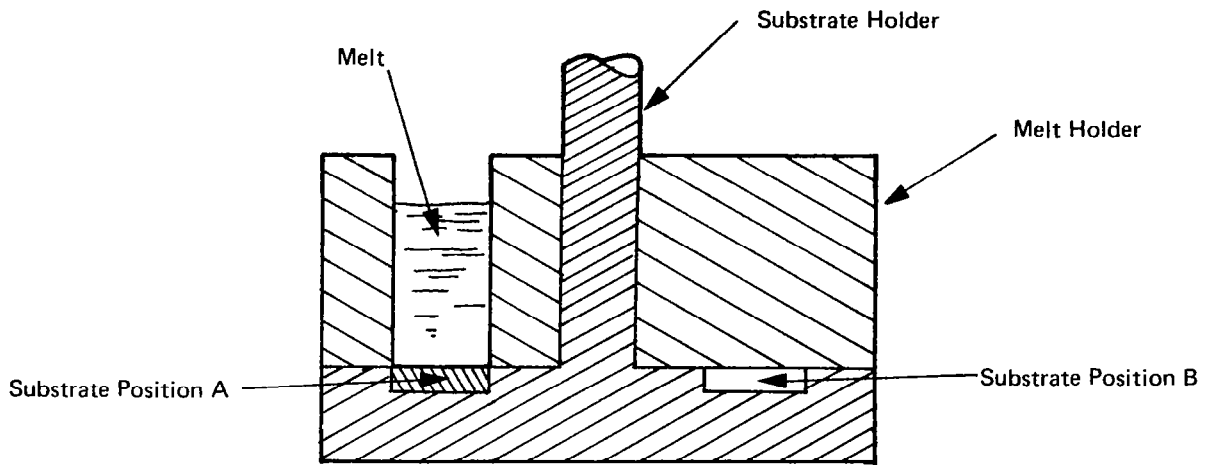
The Vapor Phase Epitaxy (VPE) processes can be broadly subdivided into those that utilize inorganic compounds (HCl , AsCl_3 , AsH_3 , H_2 , etc.) and those that utilize the organometallic compounds ($\text{Ga}(\text{CH}_3)_3$, $\text{Al}(\text{CH}_3)_3$, $\text{Zn}(\text{C}_2\text{H}_5)_2$). The processes that use the inorganic compounds have demonstrated their ability to fabricate thin, n-type GaAs, and AlAs layers. These processes could be used as part of an overall process to fabricate space type GaAs solar cells. The inorganic processes can be further subdivided based upon the materials used as input to the system. There was some early work (1966) in which single crystal layers of AlAs-GaAs were grown by an iodide-disproportionation-type, closed-tube, vapor transport system⁽¹⁰⁾.

Another early process to grow n-GaAs on n+-GaAs substrate utilized a H_2 - H_2O transport system with both the source and substrate were located in a fused silica reactor tube.⁽¹¹⁾ The 15 mm diameter substrate was maintained at 1000°C-1050°C and the upstream source was held at a temperature 50°C higher, the hottest location in the reactor tube. Growth rates of .11 to .75 μ /min were recorded.

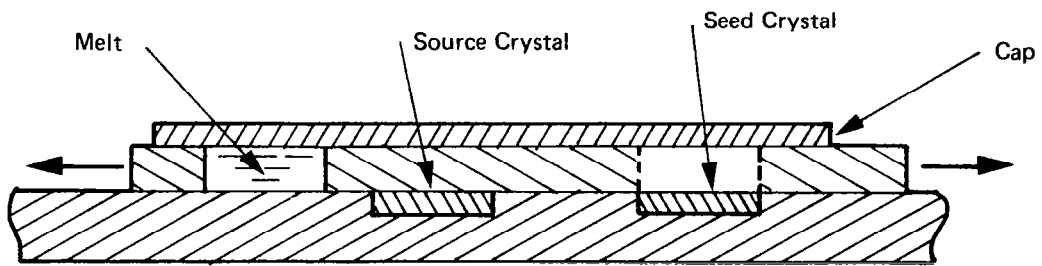
At about the same time (1966), vapor phase epitaxial growth was achieved using the complete hydrogen reduction of GaCl_3 in the presence of arsenic.⁽¹²⁾

Growth rates ranged from .07 μ m/min to 0.45 μ /min depending on the flow rate of GaCl_3 and it was observed that for the higher gas flow rates, the downstream substrates showed a lower growth rate than the upstream substrates. The growth rates were more uniform at the lower flow rates. This effect was believed to be caused by the greater time available for the reaction products from the upstream substrates to diffuse away from the vicinity of the substrates with the lower flow rates.

More recent work (1976) with a HCl transport VPE process has demonstrated the ability to grow n-type AlAs on p-GaAs substrates of a quality comparable to that grown by an LPE system⁽¹³⁾. Figure 10 shows a schematic diagram of the reported system. The temperature of the reactor varies along the length with a 1000°C — 1100°C temperature environment in the vicinity



(a) Rotating Substrate and Melt Holders.



(b) Horizontal Sliding Boat.

FIGURE 9 TYPICAL GROWTH APPARATUS FOR FINITE MELT LIQUID PHASE EPITAXIAL PROCESS.

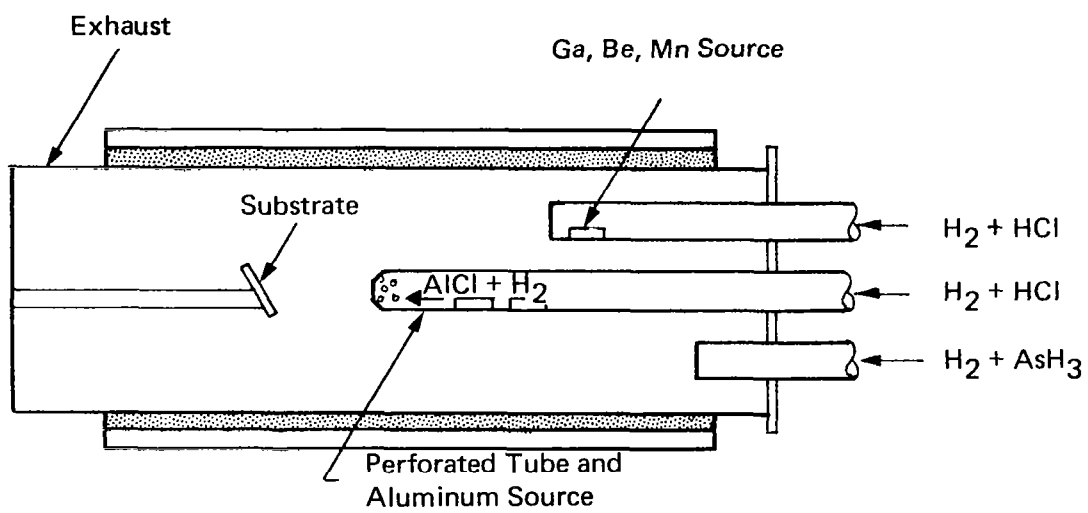


FIGURE 10 SCHEMATIC DRAWING OF A VPE GROWTH REACTOR.

of the end of the tube containing the aluminum. Growth of alternating layers of GaAs and AlAs as accomplished by drawing the substrate to an appropriate position in the 600-800°C range and switching the HCl flow from the Al source to the Ga source. Typical epitaxial growth rates were 0.2 to 1.0 $\mu\text{m}/\text{min}$.

Planar layers as thin as .05 μm have been grown and variations in thickness over the 4cm x 4cm substrate were less than 10%. Growth of 20 μm thick layers at an area rate of 50 cm^2/hour were reported and it was believed that the size of the apparatus could be readily expanded to allow 600 cm^2/hour using commercially available components.

Using the HCl transport process, n-AlAs/p-GaAs solar cells were fabricated on Zn doped, 10 cm^2 , GaAs substrates. A 20 μm layer of n-AlAs was grown after which the AlAs surface was anodized. AM1 conversion efficiencies were in the range of 13-18%. Work is continuing to fabricate more efficient contact grids and to increase the open circuit voltage.

Another VPE process being utilized to grow a homojunction n+/p/p+ GaAs solar cell uses AsCl_3 -Ga-H₂ as reactants.⁽⁶⁾ The H₂ flows through a AsCl_3 evaporator (15°C) and over a Ga boat (820°C) prior to arriving at the heated growth position (730°C). Dopants are introduced in the vapor phase by using $\text{n}(\text{CH}_3)_2$ and H₂S respectively. The initial n+ layer thickness is about 2050 Å and, after the anodization process, final n+ layer thicknesses as small as 200 Å were obtained. A reported advantage of this cell structure is that the surface n+ layer is sufficiently thin so that most of the hole-electron pairs are created below the junction in the p-type material thereby reducing surface recombination losses without using a $\text{Ga}_{1-x}\text{Al}_x\text{As}$ window layer. AM1 efficiencies of 20% have been reported using GaAs and Ge substrates.

The use of organometallic (metalorganic - MO) and hydride sources has permitted the growth of both p and n doped layers of GaAs and $\text{Ga}_{1-x}\text{Al}_x\text{As}$ on a GaAs substrate by a vapor phase epitaxy process, i.e., chemical vapor deposition (CVD). Figure 11 is a simplified schematic diagram of a laboratory type MO-CVD apparatus for the growth of GaAs and (AlGa)As.

A successfully grown three layer structure consisted of GaAlAs:Zn/GaAlAs:Zn/GaAs:Se on a GaAs:Si substrate.⁽¹³⁾ Typical layer thicknesses were GaAlAs:Zn ~ 500 Å; GaAs:Zn ~ 1-2 μm ; GaAs:Se 4-6 μm . The layers are grown at 750°C at a rate of ~ 0.25 $\mu\text{m}/\text{min}$ over areas greater than 12 cm^2 . Scaling of the process to large-area growth on 200 cm^2 of substrates in a single run is believed possible.

The compounds used in the reaction are trimethylgallium (TMGa), trimethylaluminum (TMAI) arsine (AsH_3) and H₂Se or Zinc (DEZn), for the source of dopant. The organometallic compounds require care in their handling in that they will ignite and may detonate on exposure to air. Trimethylaluminum, however, is in common use in industry as a catalyst in the preparation of polyethylene.

Layers grown by the CVD process have shown small variations in thickness due to boundary layer effects in the gas stream, and the only reported growth efficiency (amount of material in layer/amount of material available in gas stream) was in the range of 1-3% (for very small substrates).⁽¹⁴⁾

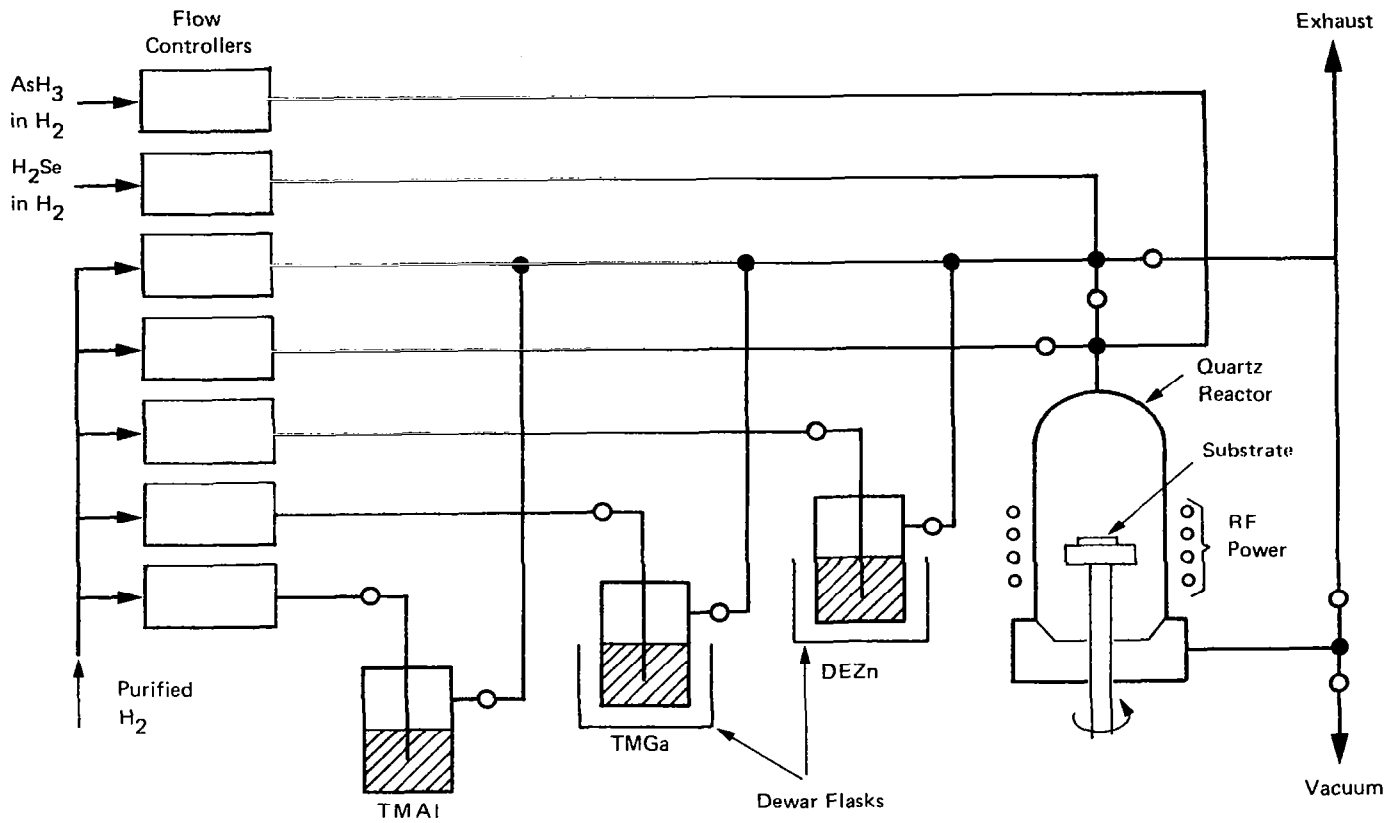


FIGURE 11 SIMPLIFIED SCHEMATIC DIAGRAM OF LABORATORY TYPE MO-CVD APPARATUS FOR GROWTH OF GaAs and GaAlAs.

Experience in fabricating periodic structures using the MO-CVD process has shown that it is possible to grow individual layers at least as thin as 30-40 Å⁽¹⁶⁾

The various VPE processes offer the capability of growing thin epitaxial layers over large substrate surface areas and, in the case of the organometallic compounds, growing both p and n doped layers of Al_xGa_{1-x}As. The inorganic VPE processes using an HCl transport process would appear to be a technique for growing the 10 μm thick, n-GaAs, buffer layer on large area, n-type GaAs substrates as the p-(AlGa)As window layer has not been grown by this process.

D. MOLECULAR BEAM EPITAXY

The Molecular Beam Epitaxy (MBE) process achieves epitaxial growth in an ultra high vacuum through the reaction of multiple molecular beams of differing flux density and chemistry with a heated, single crystal substrate. An MBE system for the growth of doped (AlGa)As is shown schematically in Figure 12. The temperature of each furnace is chosen so that the vapor pressures of the materials are sufficiently high for free evaporation generation of thermal energy, molecular "beams." The furnaces are arranged so that the central portion of the beam flux distribution from each furnace intersects the substrate. Individual shutters are interposed between each furnace and the substrate, permitting abrupt cessation or initiation of any given beam flux to the substrate. Figure 13 shows a typical temperature-time-shutter operation sequence for a graded band-gap, p-Al_xGa_{1-x}As/n-GaAs, heterojunction solar cell.⁽¹⁶⁾

The MBE technique is characterized by a relatively slow growth rate, approximately 1 μm per hour (one monolayer per second) and a low growth temperature for GaAs (500-600°C for MBE as compared to 700-900°C for LPE and ~750°C for VPE). The slow growth rate makes precise thickness control possible and the low temperature minimizes thermally activated processes such as diffusion. The use of different beams for the constituent components, each with its own shutter, allows abrupt changes in composition or doping.

The beams are created from sources contained in effusion ovens where thermal equilibrium is maintained. The deposition process at the substrate, on the other hand, is not a thermal equilibrium situation and is governed mainly by complex kinetic reaction processes; it not being obvious that growth of stoichiometric material is possible. It has been shown, however, that the growth of stoichiometric III-V compounds is possible because of the surface chemical dependence of the sticking coefficient of the Group V elements (As). For temperatures at which epitaxial growth occurs, only that amount of the Group V element is absorbed which satisfies the available Group III bonding orbitals at the surface.⁽¹⁷⁾ The growth rate is therefore determined by the arrival rate of Group III elements while the condition of stoichiometry is satisfied by growing in an excess flux of the Group V elements.

Another advantage of the MBE process, as compared to the LPE and VPE processes, is that the vacuum environment allows in situ analytical instrumentation to 1) monitor surface crystallographic and topographical characteristics prior to and during growth, 2) monitor gas composition in the work chamber including a portion of the actual molecular beam flux as well as background gases and 3) identifying the elemental composition of the films grown by the MBE process, including surface contaminants.

The MBE process offers a procedure for fabricating (AlGa)As/GaAs heteroface solar cells with a high degree of uniformity and reproducibility of structure (layer thicknesses and doping profiles).

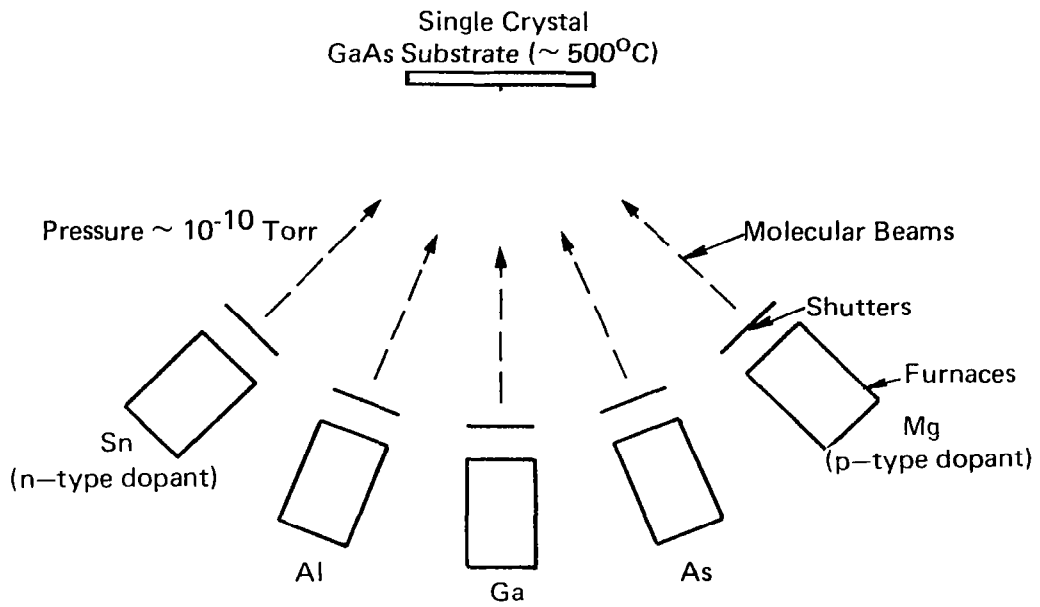
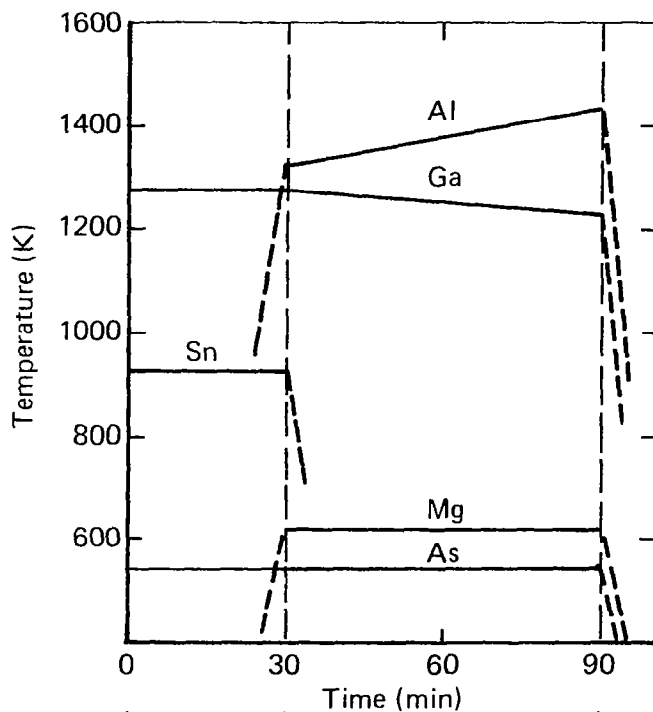


FIGURE 12 SCHEMATIC DIAGRAM OF A MOLECULAR BEAM EPITAXY SYSTEM FOR THE GROWTH OF A $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ SOLAR CELL (1 Torr = 133.3 Pa).



n-GaAs substrate	n-GaAs 0.5 μm	graded p-AlGaAs 1.1 μm
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- Dashed line shows temperature of cells when shutters are closed.

FIGURE 13 TEMPERATURE-TIME SCHEDULE FOR EACH EFFUSION CELL FOR FABRICATING A GRADED BAND-GAP $\text{Al}_x\text{Ga}_{1-x}\text{As}$ SOLAR CELL BY MOLECULAR BEAM EPITAXY.

E. OTHER GROWTH PROCESSES

Other processes for the fabrication of compound semi-conductors include flash evaporation and sputtering.⁽¹⁰⁾ In flash evaporation, the material to be evaporated is fed into the system as very fine grains. The temperature of the evaporator on which the grains fall is set high enough to evaporate the least volatile component, and the temperature of the substrate is kept low enough to prevent the re-evaporation of the more volatile component. GaAs has been grown by this technique using an evaporation temperature of approximately 1300°C and a range of substrate temperatures (300°C-600°C). No reference to the preparation of solar cells by this technique was found.

Sputtering is a process in which an electrical discharge is passed between electrodes at a low gas pressure and the cathode electrode slowly disintegrates under the bombardment of the ionized gas molecules. Some of the liberated atoms are then condensed on surfaces surrounding the cathode. 1-12 μ m GaAs films have been grown on Ge substrates by this technique, with substrate temperatures of 560-580°C and argon as the gas component (2.5-12x10⁻²Torr). No reference to solar cell fabrication using this technique has been found.

Ion implantation is a process that has been used to fabricate p-n junctions in GaAs. Early work examined the use of Zn and Be as implanted p-type dopants.

The energy of ions used for implantation in GaAs generally ranges from 20 to 400 keV and the amount of damage generated is dependent on the temperature of the substrate. For GaAs, there appears to be an appreciable in situ annealing in samples implanted above 150°C.

Even with the use of heated substrates, temperatures in the range of 800-900°C are generally required to achieve maximum electrical activation of the implanted ions. At these temperatures, it is necessary to encapsulate the GaAs to prevent 1) out diffusion of the implanted species and 2) decomposition of the GaAs surface. During the high-temperature annealing step, there is diffusion of the implanted ions which can broaden and lower the distribution.

Electrodeposition of thin film, polycrystalline GaAs has been demonstrated on various substrates, industry indium tin oxide-coated glass. Although electrical characterization has yet to be completed for the GaAs films or devices made from them, the process is believed to hold promise of lowering manufacturing costs and achieving reasonably high efficiencies. No reference to the preparation of single crystal solar cells by this technique was found.

F. CHOICE OF EPITAXIAL GROWTH PROCESSES FOR FURTHER COMPARISON

The three epitaxial growth processes chosen for further comparison of their relative merits for pilot line production are: LPE, MO-CVD and MBE. These processes are capable of fabricating the required epitaxial layers and are sufficiently documented in the literature so that a comparison can be made.

V. COMPARISON OF EPITAXIAL GROWTH PROCESSES

A. COMPARISON METHODOLOGY

A significant factor currently restricting the increased use of gallium arsenide solar cells for space applications is the initial cost per cell, particularly in small quantities. An accurate assessment of the economic benefits of using gallium arsenide solar cells in space will require a system level study to trade off the initial cost per cell against the advantages of total array size. The total array size with gallium arsenide solar cells benefits from the inherent cell advantages of beginning of life (BOL) efficiency and resistance to radiation damage (with prospects for thermal annealing of incurred damage).

The comparison between the several processes for fabricating single crystal (AlGa)As/GaAs solar cells developed in this report is primarily a cost comparison, resulting in a tabulation of the major direct costs per cell for the growth of the epitaxial layers on 10,000, 2cm x 2cm (AlGa)As/GaAs solar cells. The elements of the total cost are: 1) material usage 2) energy consumption 3) labor hours required and 4) capital equipment. In addition to these cost elements two additional comparison factors are also discussed: 1) the degree of control or reproducibility and 2) problems and potential for scale up and automation.

This section of the report contains a discussion of the cell fabrication comparison factors and concludes with a comparative summary of the direct costs associated with each of the cell fabrication processes.

B. COMPARISON FACTORS

1. Material Usage

The various solar cell fabrication processes utilize different amounts of input materials to grow the same 11 μ m thick epitaxial layers, (including the 10 μ m buffer layer). The relative differences are reduced, however, because of the amount of material contained in the 250 μ m thick substrate common to all processes.

An annual production rate of 10,000, space-qualified, 2cm x 2cm solar cells would require 40,000 cm² (6200 in²) of single crystal GaAs substrates per year. The substrate material is typically grown by a horizontal Bridgman technique and sawed to a thickness of 500 μ m (with 50% saw kerf losses), polished to a thickness of 300 μ m (with 40% polishing losses) and cleaved to a 2cm x 2cm solar cell shape (with 45% cleaving losses). Therefore, approximately 73,000 cm² (11,300 in²) of polished, boat shaped wafers (250 — 300 μ m thick) would need to be purchased per year to support an annual production rate of 10,000 2cm x 2cm cells. Because only 17% of the GaAs material in the original boat grown crystal ends up in the final substrates for the flight qualified cells, 15.1 kg of high purity gallium and 16.2 kg of high purity arsenic would be required as input material (assuming 250 μ m thick substrates polished from 417 μ m thick wafers). Total material requirements for the fabrication of the substrates is reduced by recovery of the various material losses.

The additional gallium and arsenic material contained in the 10 μ m thick, n-GaAs, buffer layer, the 0.5 μ m thick p-GaAs and the 0.5 μ m thick p-(AlGa)As epitaxial layers, for 40,000 cm² of

cell area, is 108 grams of gallium, 121 grams of arsenic and approximately 2 grams of aluminum. The total required input of high purity gallium and arsenic (or compounds containing Ga or As) for growing the epitaxial layers is then dependent on the yield of the specific epitaxial growth process.

The infinite melt LPE growth system is the most conservative of material in that the only material that intentionally leaves the growth chamber is in the epitaxially grown layers. The annual consumption of material is approximately 108 grams of Ga and 121 grams of As. An infinite melt growth chamber contains approximately 5000 grams of a high purity Ga solution in inventory and two growth solutions are needed, one for the n-GaAs buffer layer (5000 grams) and one for the p-(AlGa)As window layer (a 3000 gram melt which also forms the p-GaAs layer by diffusion).

The limited melt LPE process has a high consumption of Ga and As material because of the additional losses associated with "disposing" of the solutions remaining in the small melt chambers after the epitaxial layers are grown. Because these additional losses have not been quantified in the literature we treated this uncertainty in material consumption as a variable. Yield is defined as the ratio of the amount of material in the epitaxially grown layers to the amount of material used as input to the growth process. For a 10% yield, limited melt LPE process, 1080 grams of high purity gallium and 1212 grams of high purity arsenic would be consumed per year. For a 1% yield process, 10,800 grams of Ga and 12,122 grams of As would be needed annually. The advantages of 1) conservation of material and 2) reproducibility of solution composition from run to run favor the infinite melt LPE system over the limited melt LPE growth system.

The MO-CVD process uses high purity trimethylgallium [$\text{Ga}(\text{CH}_3)_3$] and arsine (AsH_3) as the input compounds to produce the GaAs material. It has been experimentally observed that better surface morphology and higher electron mobility are obtained when the ratio of AsH_3 to $\text{Ga}(\text{CH}_3)_3$ in the input stream is in the range of 5-10. We've assumed a ratio of 10 for our computation of material requirements. Therefore, 108 grams of gallium in the epitaxial layers requires at least 178 grams of $\text{Ga}(\text{CH}_3)_3$ and 121 grams of arsenic requires a minimum of 1260 grams of AsH_3 . A significant uncertainty in determining the total amount of input material required is the yield of the MO-CVD process, i.e., the fraction of the Ga and As in the input compounds that ends up in the epitaxially grown layers.

The arsine uses purified hydrogen as a transport gas and a purchased concentration of 10% AsH_3 in hydrogen was used for our cost computations. (L.E.D. purity).

Material losses with a cold wall reactor include the portion of the gas stream that flows past the substrate without reacting, as well as gas losses associated with starting, stopping and venting the system. Because of a lack of published information on process yield, we treated this uncertainty as a variable. For a 10% yield MO-CVD process with a As/Ga ratio of 10, 1779 grams of $\text{Ga}(\text{CH}_3)_3$ and 12,600 grams of AsH_3 would be needed per year. For a 1% yield process, 17,790 grams of $\text{Ga}(\text{CH}_3)_3$ and 126,000 grams of AsH_3 would be needed annually.

Additional experimental effort would be needed to quantify and optimize the process yield with the MO-CVD and to determine the feasibility of collecting, repurifying and/or recycling the exhaust gas stream. Current practice is to burn the exhaust gas stream as it is vented to the

atmosphere. The collection of the organometallic compounds from the exit gas stream would have to be done with care because the compounds are pyrophoric, i.e., they will burn spontaneously, or may even detonate on exposure to air. There is a difference in the boiling points of the compounds that could be utilized for separation of the active materials from the exhaust stream.

The MBE growth process has a potential for low consumption of cell material depending on the ratio of the total cross sectional area of the molecular beams to the area of the substrate measured at the plane of the substrate. Without properly designed crucible nozzles, economical use of the source material and good flux uniformity over the substrate are not obtained simultaneously and the emphasis has generally been placed on uniformity. With properly designed crucible nozzles, however, collimation of the molecular beams can be achieved in a predictable pattern. Good uniformity then becomes a matter of crucible engineering. An additional loss comes from the intentional excess of As at the growing surface. For growth of device quality films, the accepted As/Ga ratio at the substrate is in the range of 5-10.

If the MBE process were to be used to grow only the $0.5\mu\text{m}$ thick p- GaAs layer and the $0.5\mu\text{m}$ thick p-(AlGa)As window layer, and assuming that the total molecular beam area is twice the substrate area, with an As/Ga ratio of 10, then the annual consumption of material would be 21.3 grams of Ga, 220 grams of As and less than 1 gram of Al. If the MBE process were used to also grow the 10 m thick n-GaAs buffer layer, the total annual consumption of cell material would be 216 grams of Ga, 2424 grams of As, and less than 1 gram of Al. These MBE material consumption figures do not include any losses associated with replenishing the crucibles between runs.

The MBE process also requires the consumption of approximately 0.044m^3 (13 gallons) of liquid nitrogen per 8 hour day for the LN_2 cryopump.

Table 4 summarizes the annual consumption of cell materials for the various cell fabrication processes.

2. Energy Consumption

Starting with cut and polished substrates and purified input materials, the basic energy consuming processes associated with fabricating the crystalline structure for (AlGa)As/GaAs solar cells, are the: 1) melting (vaporizing) and subsequent temperature control of the input material plus any associated heating of the chamber(s) holding a liquid melt, 2) heating of the substrate, substrate holder and other parts of the furnace region, i.e., the walls of the furnace in a hot wall CVD reactor, 3) maintaining of a high vacuum in an MBE system and 4) operating the process control system, e.g., control electronics or mass flow controllers.

In the infinite melt LPE process, which maintains 5000 grams of Ga solution in a molten state for an extended period of time, the continuous power required is dependent on the designed thermal isolation of the heated region. An order of magnitude calculation based on three radiation shields in a vacuum shows an operating power requirement of 500 W for an 800°C melt in a three-inch diameter chamber. The initial energy consumption to melt the 5000 grams of Ga solution and raise it to 800°C (4.5 kWh) plus the energy required to simultaneously bring the furnace hardware up to operating temperature is neglected in this comparison of processes because the amount of energy is small when compared to the 360 kWh of energy required monthly to maintain the melt at 800°C . At a production rate of 32, $2\text{cm} \times 2\text{cm}$ cells every 2 hours during an

TABLE 4

SUMMARY OF MATERIAL REQUIREMENTS TO FABRICATE
10,000 2 cm x 2 cm GaAs SOLAR CELLS ASSUMING
NO RECOVERY OF LOST MATERIAL

- 250 μm n-GaAs Substrate
- 10 μm n-GaAs Buffer Layer
- 0.5 μm p-GaAs Layer
- 0.5 μm p-(AlGa) As Window Layer

Process	Yield (%)	Gallium or Gallium Containing Compound (g)	Arsenic or Arsenic Containing Compound (g)
Substrate Preparation	17	15,084	16,210
LPE - Infinite Melt	100	108	121
- Limited Melt	100	108	121
	10	1,080	1,212
	1	10,800	12,120
CVD-- Ga (CH ₃) ₃	100	178	126
- AsH ₃	10	1,779	1,261
	1	17,790	12,611
MBE - As/Ga = 10	50	216	2,424
	5	2,160	24,240

eight hour work day, five days per week (512 cells/week), .16 kWh of energy is required per cell, per melt, assuming each melt is maintained at 800°C for the full week. At least two melts (5000 grams and 3000 grams) are required, one for the n-doped buffer layer and one for the p-doped window layer, yielding a total energy requirement of .32 kWh per cell. This assumes that the furnace for the 5000 gram melt is identical in construction to the furnace holding the 3000 gram melt.

For the limited melt LPE process, the energy consumption is related to heating the substrate(s), substrate holder and input materials up to operating temperatures (~800°C), maintaining 800°C "overnight" (12 hours) to bake out the system and then executing a time-temperature growth program near 800°C for approximately 1 hour. This sequence is following by cooling of the apparatus. In this process the p-(AlGa)As layer is being grown directly on the substrate. Assuming a thermal isolation design for the furnace identical to that of the infinite melt apparatus, and neglecting the change in energy stored in the components of the system, the total energy consumption is the 4.4 kWh energy loss during the 13-hour heater power cycle. Assuming a single 2cm x 2cm cell is grown per cycle, the energy requirement per cell is 4.4 kWh. If the 12-hour bake out is not required for subsequent cycles the energy requirement is reduced to .3 kWh per 2cm x 2cm cell.

For the MO-CVD process, with a cold wall reactor, the basic energy input is to the RF system which is heating the substrate holder to approximately 750°C during a growth period of

approximately 30 minutes. In the absence of published experimental data we have assumed an average energy consumption of .1 kWh per 2cm x 2cm cell.

The MBE system has a significant consumption of energy for the maintenance of the high vacuum (10^{-10} Torr). A standard Molecular Beam Epitaxy System uses 14.4 kW of energy continuously while it is operating. With a 3.05cm (1.2 inch) diameter wafer, producing one, 2 cm x 2 cm cell every 11 hours (growing a $10\mu\text{m}$ n-type buffer layer as well as two $0.5\mu\text{m}$ p-type layers at a rate of $1\mu\text{m}/\text{hour}$) 158 kWh of energy would be required per 2cm x 2cm cell. If only the top $1\mu\text{m}$ layers were grown by MBE, 14.4 kWh of energy would be required per cell.

Second and third generation MBE systems will probably reduce the power requirements per cell because of their capability to hold a 5.08-cm (2-inch) or a 7.62-cm (3-inch) diameter wafer at the growing station.

Table 5 summarizes the energy consumption per cell for the various cell fabrication processes as required to maintain the proper thermal and vacuum environment. The smaller power required to operate the process control system has not been included. At an assumed level of 100 W for control systems the additional power requirement would vary from .02 kWh/cell with the infinite melt LPE process (1,024 cells/week) to 1.1 kWh/cell with the MBE process (1 cell every 11 hours).

TABLE 5
ENERGY CONSUMPTION PER 2 cm x 2 cm CELL BY
FABRICATION PROCESS

- Only That Energy Directly Related to Maintaining Thermal and Vacuum Environment is Considered.

Process	Energy Consumption Per Cell (kWh)	Comment
LPE - Infinite Melt	.32	Two melts required/assumed maintained at 800°C continuously.
- Limited Melt	4.4	With 12 hour bake out at 900°C
	.3	Without 12 hour bake out at 900°C
MO-CVD	(.1)	Assumed Value
MBE	158	Growing $10\mu\text{m}$ buffer layer as well as two p-type $0.5\mu\text{m}$ layer.
	14.4	Growing only two, p-type, $0.5\mu\text{m}$ layers.

3. Labor Hours Required

Only the labor hours required for the growth of the epitaxial layers by the different fabrication processes is considered here.

For the production of 10,000, 2cm x 2cm, space-qualified solar cells, the control of the epitaxial growth process parameters is assumed to be automated, e.g., time-temperature profiles, shutter positions and gas flow rates. This assumption is based on the observation that laboratory scale GaAs fabrication processes are being developed by research personnel to operate under microprocessor control. This technique permits the transfer of an optimized production sequence to operating personnel with the research (and more expensive) personnel serving as part time inspectors or monitors. In this production model the operating personnel would be responsible for 1) inspecting the incoming wafers, 2) cleaning the wafers, 3) loading the wafers into the growth chamber, 4) initiating the growth sequence, 5) withdrawing the grown material from the chamber, 6) inspecting the final material and 7) maintaining the apparatus, e.g., replenishing the input materials as needed.

Our manpower model assumes one or two full time operating persons depending on the length of time required to grow the epitaxial layers and one part time (20%) professional person monitoring the production. The basic manpower differences between the epitaxial growth processes are derived from how long it takes to fabricate 10,000 cells.

The fabrication of 10,000 solar cells per year may not require the dedication of personnel and equipment for a full 12 months. The manhours required per cell will depend on production rates with the different fabrication processes and the number of operating and supervisory personnel involved. The optimum number of growth chambers and operating personnel dedicated to the production of space-qualified, GaAs solar cells in a particular company would depend on the availability of equipment and people that are being shared with other contracted and in-house programs. With the capability for one person to operate several growth chambers simultaneously, the manpower required per cell could vary by a factor in the range of 2-10 depending on the availability of equipment. A redesign of a laboratory scale or early production model of a growth chamber could also increase the number of substrates that could be processed simultaneously in a single growth chamber.

The comparison of the manpower requirements for the different epitaxial growth processes initially assumed that one growth chamber would be utilized with each process. The one chamber would have the capacity for holding a number of substrates that was obtained from current information.

For our calculation of the growing time required using the MBE process an MBE system with a growth station capable of holding a 5.08cm (2-inch) substrate was used. At a growth rate of 1 μm per hour on a 5.08-cm (2-inch) diameter substrate, approximately 10 hours would be required to grow a n-GaAs buffer layer (10 μm) plus another hour or two to grow the p-GaAs layer and p-Al_xGa_{1-x}As window. In the area of a 5.08-cm (2-inch) diameter substrate holder, two 2 cm x 2 cm solar cells could be fabricated simultaneously, yielding a production rate of approximately four cells per day from one machine. Scaling up the production would require additional machines or the design of a multiple growing station MBE system. Approximately ten MBE systems working in parallel would be required to satisfy a daily production goal of 40 2 cm x 2 cm cells.

The daily throughput per system could be significantly increased if a higher quality substrate were available, thereby eliminating the need for the 10 μm thick buffer layer. It is also possible that the buffer layer could be grown by another process, e.g., LPE or VPE, and the final

layers added by the MBE process. If only a 1 μm layer were needed to be grown by MBE, the daily production rate, using a single MBE system, would increase to approximately 48 cells per day, sufficient to satisfy an annual production rate of 10,000 cells. If a planned third generation MBE system were available with the capability of growing on a 7.62-cm (3-inch) diameter wafer, epitaxial layers could be grown on seven 2 cm x 2 cm cells simultaneously. If only a 1 μm layer were needed on each cell, a daily throughput of approximately 168 cells/24 hour day or 56 cells/8 hour day could be achieved.

Table 6 summarizes the fabrication times for the different epitaxial growth procedures assuming one growth chamber of current design. It is obvious from the calculation of the number of months required to produce 10,000 cells that only the equipment for the infinite melt LPE process is currently sized to produce the required output within 1 year. The other processes would require more than one growth chamber or an increase in the size of the current reactor. Published data for the MO-CVD system suggests that the current 12 cm^2 of growth area (one 2cm x 2cm cell in an assumed circular wafer) could be increased to 200 cm^2 (thirty-six 2cm x 2cm cells) with a change in reactor size. This would reduce the total time required to grow 10,000 cells by the MO-CVD process to less than 1 month. A commercially available, four loop MO-CVD system has the capability of holding two 7.62-cm (3-inch) diameter wafers simultaneously. This system would reduce the total time required to grow 10,000 cells to 9 weeks using a 1 shift operation.

TABLE 6

SUMMARY OF FABRICATION TIMES FOR DIFFERENT EPITAXIAL GROWTH PROCEDURES USING ONE GROWTH CHAMBER OF CURRENT DESIGN

Process	Cycle Time (hours)	No. of Cells (2 cm x 2 cm)	Time Per Cell (hours)	Time for ¹ 10,000 Cells (months)
LPE - Infinite Melt	2	32 ²	.06	4
- Finite Melt	1	1	1.0	63
MO-CVD	0.5	1	0.5	31
MBE - 11 μm growth	11	2	5.5	344
- 1 μm growth	1	2	0.5	31

1. Based on 160 hours of operation per month.

2. Based on a system that has been developed to satisfy (limited) production requirements.

The potential for scale up and automation of each process will determine the possible reduction in fabrication time per cell that could be achieved. This is discussed in a later section.

4. Degree of Control or Reproducibility

Specific parameters of the epitaxially grown solar cell material that need to be controlled are: 1) thickness of the p-(AlGa)As window layer, 2) junction depth, 3) concentration of desired dopants, 4) contamination and 5) crystal defects. The production of space-qualified solar cells having reproducible performance characteristics will require that these parameters be controlled to within specified tolerances by controlling the applicable process parameters.

All processes require high purity input materials. The infinite melt LPE process has an advantage over the other fabrication procedure in maintaining purified and reproducible material because large volumes of material are maintained under closely controlled conditions as a melt over an extended period of time. The slowly changing state of the melt can then be monitored, and modified as necessary, by testing the characteristics of the solar cell material on a continuing basis.

The limited melt LPE process has a large surface-to-volume ratio for the growth solution, making it more difficult to control contamination of the growth solution. The limited melt LPE process also requires replenishment of the growth material between runs. For these reasons the controllability of the limited melt LPE process is more difficult than with the infinite melt LPE process.

The MO-CVD process will require high purity metalorganic compounds in quantities as high as 18 kg per year for trimethylgallium (assuming a 1% yield process). This quantity of material is approaching the annual production limits of the major U.S. producer at a purity of 99.999%. A purity level of 99.9999% is more difficult to produce and is achieved in approximately only one out of three batches. The availability of high purity metalorganic compounds for the CVD process in increasing larger quantities will require a more detailed examination of the sources for this material and the economic incentives to increase production.

Cleaning of the CVD system may have to be done on a regular basis; however there was no published data on degradation in cell performance as a function of length of time the chamber had been in use.

The MBE process offers the greatest degree of process control because of the low growth rates and the ability to individually control each component of the process (temperatures of ovens and substrates and shutter position). The vacuum chamber will need to be baked out at 200°C for 24 hours every couple of months to minimize the residual vapor pressure of contaminants in the chamber.

Table 7 shows the distribution of cell efficiencies in small lots of space type gallium arsenide solar cells fabricated by an LPE process and delivered to the Air Force. A typical range of variation in conversion efficiency in a size lot is $\pm 0.5\%$ about the mean. Additional efforts would be required to assess the system level effects due to this variation in individual cell efficiency and to determine the range in cell efficiency of all of the cells fabricated in a given production run.

5. Problems and Potential for Scale Up and Automation

The magnitude of the scale up being considered for space qualified gallium arsenide solar cells is going from current production levels ($\sim 0/\text{day}$) to an annual production rate of 10,000, 2cm x 2cm cells. This is equivalent to 40 cells per day for 250 working days per year. The analyses are based on a single 8 hour shift per day.

LPE was the only process identified in the literature as currently being in use for the (limited) production of terrestrial and space quality, heteroface, gallium arsenide solar cells. Approximately 100-200 cells have been delivered under government contracts as of June 1978. The total number of cells fabricated during this time is estimated at being an order of magnitude

TABLE 7

**STATISTICAL SUMMARY OF AMO EFFICIENCIES OF SMALL LOTS OF
(AlGa)As/GaAs SPACE SOLAR CELLS**

- As received by WPAFB under Contract F33615-76-C-2121
- Cell size 2 cm x 2 cm

January 1976:	5 cells		
	Mean AMO η :	14.12%	
	Mode of distribution:	14.0%	(2)
	Range of distribution:	1.30%	
	Standard deviation:	.48%	
June 1976:	8 cells		
	Mean AMO η :	15.58%	
	Mode of distribution:	15.5%	(5)
	Range of distribution:	0.2%	
	Standard deviation:	.1%	
January 1977:	7 cells		
	Mean AMO η :	16.53%	
	Mode of distribution:	15.9%	(2)
	Range of distribution:	1.4%	
	Standard deviation:	.66%	
June 1978:	10 cells		
	Mean AMO η :	16.77%	
	Mode of distribution:	16.50%	(2)
	Range of distribution:	1.40%	
	Standard deviation:	0.43%	

higher (1000-2000 cells). The MO-CVD and MBE processes have been used to produce only a small number of cells for research and development purposes.

A basic decision in scaling up a laboratory sized solar cell production process is whether to duplicate the laboratory hardware or to develop larger pieces of equipment, capable of fabricating more cells at a single growth station. The development of larger area growth stations may, in essence, be only an extension of the original laboratory research and development program.

The basic questions to be answered in making this decision as to how to scale up are: 1) is it technically feasible to develop larger growth stations for a particular cell fabrication process and, if technically feasible, 2) does it reduce the cost of the final, flight qualified, solar cell?

The requirement for an annual production rate of 10,000, 2cm x 2cm, flight qualified, gallium arsenide solar cells to satisfy NASA's assumed future needs does not guarantee that any one company would receive all of NASA's future orders. There are also other government funded programs requiring gallium arsenide solar cells for space (DOD) and terrestrial applications (DOE) that could impact the number of cells a single company would have to produce in a given year.

The economics of allocating the cost of new capital equipment over a limited production run of space qualified solar cells (with a basic uncertainty in market projections for cells of this type) is a business strategy decision affecting the cost and price of each cell. It is to be expected that the two or three companies in a position to bid on the fabrication of flight qualified gallium arsenide solar cells would, if possible, schedule the use of existing facilities to meet near term requirements rather than building or procuring new equipment.

The scope of this section of the report is to compare the LPE, MO-CVD and MBE processes on the basis of their technical problems and potential for scaling up. In a following section, the costs associated with scaling up will be assessed.

The infinite melt LPE process can be scaled up by 1) increasing the volume of the molten solution and 2) increasing the number and size of the substrate holders so that more cells can be fabricated in a single melt at one time. The infinite melt LPE process has already been scaled up to stored solution masses of 5000g and 3000g with holders capable of inserting thirty-two, 2cm x 2cm substrates simultaneously. With the pair of growth chambers, one for the 10 μ m thick n-doped buffer layer and one for the 0.5 μ m thick p-(AlGa)As window layer, the epitaxial layers for 10,000 cells could be grown in approximately 4 months (160 hours per month). The existing equipment could satisfy NASA's assumed annual production requirement with only a 33% annual utilization of the facility. The excess capacity could then be allocated for other uses. Therefore no further scale up would be needed.

The current MO-CVD process typically grows one or two wafers per run with the maximum device size being limited by the size of the reactors employed and the size of the GaAs substrates. It is believed that large area growth on 200 cm² of substrates can be achieved in a single deposition run.

The quality of the MO-CVD grown material depends on such process parameters as temperature, gas phase stoichiometry, quality of the reactant materials and reactor geometry. As part of the development effort to scale up MO-CVD production capacity by increasing the size of the growth station, one has to assess the compositional changes in the boundary layer of the gas flowing over the large area of substrates. The boundary shape and its gas composition are affected by gas pressure, by reactor geometry, i.e., mixing of the gases prior to and surrounding the substrates and by the orientation and spacing of the substrates in the gas stream. The scaling up of reactor size could also affect the yield of the fabrication process, i.e., the portion of the input material that ends up as epitaxially grown layers on the substrates.

The MO-CVD process appears promising for scaling up by increasing the size of the growth station; however, there are development difficulties which need to be quantified. Sales literature lists a commercially available, four loop MO-CVD system with a production capability of two, 7.62cm (3 inch) diameter wafers per run (a maximum of 14, 2cm x 2cm cell substrates). There was no information obtained during the course of this study to validate that larger MO-CVD systems were already in existence. At this point in time no solar cells have been reported in the literature using a large growth area MO-CVD system. A technology development effort to analyze, design, fabricate and/or test the performance of a MO-CVD system with a large area growth station (including continuous or batch feed) is a logical extension of current efforts to understand the effects that variations in growth parameters have on the quality of the grown material.

The basic conclusion is that, if an annual production rate of 10,000, 2cm x 2cm gallium arsenide solar cells were to be achieved using this larger, commercially available MO-CVD equipment, and assuming a growth cycle of 0.5 hour per run, the full production run of 10,000 cells could be completed in less than 3 months at 160 hours per month of running time. This can be compared to the 31 month fabrication time for the MO-CVD process used in the comparison of the different growth processes.

The decision as to how a particular company would allocate personnel and MO-CVD equipment to satisfy the production requirement of 10,000 solar cells would depend on their availability of resources and other commitments at the time the proposal was prepared. The availability of a proven reactor with a large area growth station could lessen the impact on a company's on-going MO-CVD activities due to the receipt of an order for 10,000 2cm x 2cm solar cells. The availability of a large area MO-CVD reactor could also reduce the additional capital equipment costs associated with expanding annual production rates to levels higher than 10,000 cells. The MO-CVD process could also be used to grow only the two, p-type layers while the 10 μ m buffer layer could be grown by another process, e.g., LPE or VPE.

Scale up of the MBE process could use a third generation MBE system currently in the planning stage. This machine will be able to hold a 7.62cm (3-inch) diameter wafer at the growing station and could produce enough material for seven cells after an 11 hour growth cycle, assuming that both the 10 μ m, n-type buffer layer as well as the two, 0.5 μ m, p-type layers are being grown. The cycle time reduces to 1 hour if only the two 0.5 μ m thick layers are grown, however, additional equipment would then be needed to grow the buffer layer. Using this third generation MBE system, at a rate of 7 cells every 11 hours, would require 22 months of continuous running to fabricate 10,000 cells using one growth chamber. The operation of two or more MBE systems in parallel in order to satisfy an annual production rate of 10,000 cells is technically feasible but is an expensive alternative. (Our comparison of the different cell fabrication processes was based on a second generation MBE system which is currently available.)

The advantage of the MBE process over the other process is in its ability to precisely control the thickness and dopant concentration in the two p-type epitaxial layers. A potential alternative to using the MBE process would be to use a continuous or batch VPE process for the 10 μ m thick, n-type, buffer layer and then use the MBE process to grow the closely controlled p-layers. Figure 8 shows a potential solar cell fabrication process based on these two processes. This is an example of a conceptual approach (presently unproven) which may lead to lower cost GaAs solar cells.

In summary, the infinite melt LPE process is the only cell fabrication process which has currently been up to satisfy an annual production of 10,000, 2cm x 2cm (AlGa)As/GaAs solar cells.

6. Cost

In the comparison of the costs associated with the different cell fabrication processes only the major direct costs of materials, labor, capital equipment and energy consumption were assessed. Whereas materials, labor and energy are assumed to be steady state operating costs, the initial capital equipment costs are amortized over the economic life of the facilities. For this cost comparison we assumed that the cost of the final cell must include the amortized cost of the equipment only during the actual time it is being utilized to fabricate cells. The useful life of the equipment can be either the physical life of the hardware or the expected life of the technology. For the limited production of flight qualified gallium arsenide solar cells technical obsolescence will probably occur before physical obsolescence. A 5 year total useful life for the equipment was assumed and then the fraction of that time that was to be allocated to fabricating 10,000 solar cells was determined. During the 5-year period minor modifications to the equipment and process parameters are expected, but with no replacement of the basic components.

There is a difference between the cost numbers developed here for comparing the different processes and the total cost and selling price of the solar cells. There are additional steps in the fabrication of the flight qualified solar cells, e.g., metallization, application of an AR coating and testing, that are not included in our comparison as well as such indirect costs as company overhead and profit. The Solar Array Manufacturing Industry Costing Standards (SAMICS) developed for the Low-Cost Solar Array Project at the Jet Propulsion Laboratory provides a consistent and detailed methodology for estimating array costs and comparing production technology costs. The use of SAMICS was beyond the scope of this present work as detailed process information must be provided for all steps in the production sequences in order to be able to calculate direct costs. The thorough documentation of all direct processes requires a significant initial effort. Also the use of SAMICS is more applicable to dedicated facilities and plants rather than the part time use of laboratory scale equipment.

The cost comparison documented in this section assumes that the facilities and personnel being utilized to fabricate 10,000 2cm x 2cm solar cells are being shared with other company programs. The time required to fabricate the 10,000 cells is an important parameter as it defines the fraction of annual costs, e.g., salaries and depreciation, that are to be paid by the solar cell fabrication effort.

a. Material

Table 8 summarizes the unit cost of the basic chemicals utilized in the fabrication of gallium arsenide solar cells. Based on the quantity of material required for each process (see Table 4), Table 9 summarizes the total material costs for each of the three processes. The conclusion to be drawn from Table 9 is that the process yield with the MO-CVD fabrication procedure is a major uncertainty in material costs. Only the material cost associated with the substrate is comparable to the MO-CVD costs with a 10% or 1% yield factor. The comparisons shown in Table 9 clearly show the material cost advantage of the 100% yield, infinite melt LPE process. The 8000g of melt held in inventory was not included as a material cost factor. Only the cost of replenishing the melt for the fabrication of the solar cells was included.

TABLE 8
UNIT COST OF MATERIALS UTILIZED IN FABRICATION OF
(AlGa)As/GaAs SOLAR CELLS

Material	Quantity	1979 Purchase Price	Source
Arsenic (99.9999%)	10 kg	\$122.20/kg	1
	500 kg	\$ 93.80/kg	1
Arsine (10% concentration in H ₂ L.E.D. purity)	.2 kg	\$723.56/kg	2
	1.8 kg	\$563.61/kg	2
Beryllium (99.95%)	10 g	\$ 10.20/g	3
Diethyl Zinc (99.999%)	25 g	\$ 8.00/g*	3
	100 g	\$ 4.30/g*	3
	500 g	\$ 2.95/g*	3
Gallium (99.9999%)	10 kg	\$534.00/kg	1
	500 kg	\$464.00/kg	1
Germanium (99.9999%)	10 g	\$ 5.00/g	3
Magnesium (99.99%)	50 g	\$.74/g	3
Selenium (99.999%)	25 g	\$ 1.50/g	3
Tellurium (99.999%)	10 g	\$ 2.46/g	3
Tin (99.9999%)	5 g	\$ 5.36/g	3
Trimethyl Aluminum (99.9999%)	25 g	\$ 7.20/g*	3
	100 g	\$ 3.60/g*	3
	500 g	\$ 2.28/g*	3
Trimethyl Gallium (99.9995%)	25 g	\$ 16.00/g*	3
	100 g	\$ 10.80/g*	3
	500 g	\$ 8.90/g*	3
Zinc (99.9999%)	50 g	\$.78/g	3

*Cost to refill cylinder.

Source Code: 1. Cominco American.
2. Matheson.
3. Ventron Corporation, Alfa Catalog 1979-1980.

TABLE 9
COST OF MATERIALS FOR FABRICATING
10,000 2 cm X 2 cm (AlGa)As/GaAs SOLAR CELLS

Process	Yield (%)	Compound	Unit Cost	Total Cost	Cost Per Cell
Substrate Preparation ¹	17	15.1 g Ga	\$464.00/kg	\$ 7,006.40	\$.85
		16.2 g As	\$ 93.80/kg	\$ 1,519.56	
LPE – Infinite Melt	100	108 g Ga	\$.464/g	\$ 50.11	} <\$.01
		121 g As	\$.094/g	\$ 11.37	
LPE – Finite Melt	100	103 g Ga	\$.464/g	\$ 50.11	} <\$.01
		121 g As	\$.094/g	\$ 11.37	
	10	1,080 g Ga		\$ 501.12	} \$.06
		1,212 g As		\$ 113.93	
	1	10,800 g Ga		\$ 5,011.20	} \$.62
		12,120 g As		\$ 1,139.28	
MO-CVD As/Ga = 10	100	178 g Ga(CH ₃) ₃	\$ 8.90/g	\$ 1,584.20	} \$.23
		1,260 g AsH ₃	\$.564/g	\$ 710.64	
	10	1,779 g Ga(CH ₃) ₃		\$ 15,833.10	} \$ 2.29
		12,600 g AsH ₃		\$ 7,106.40	
	1	17,790 g Ga(CH ₃) ₃		\$158,331.00	} \$22.94
		126,000 g AsH ₃		\$ 71,064.00	
MBE As/Ga = 10	50	216 g Ga	\$.464/g	\$ 100.22	} \$.03
		2,424 g As	\$.094/g	\$ 227.86	
	5	2,160 g Ga		\$ 1,002.20	} \$.32
		24,240 g As		\$ 2,278.60	

1. Assuming no recovery of lost material.

b. Energy

The cost of the energy required to fabricate the epitaxial layers was computed based on a cost of electricity of \$.05 per kWh. Table 10 shows the energy consumption per cell by the various fabrication processes and the cost of the energy. With an estimated energy consumption of .1 kWh per cell with the MO-CVD process for running the RF heater, the MO-CVD fabrication procedure is the most energy conservative of all the processes.

TABLE 10

SUMMARY OF ENERGY COSTS BY FABRICATION PROCESS

• Assumed cost of electricity is \$.05 per kWh

Process	Energy Consumption Per Cell (kWh)	Cost of Energy Per Cell
LPE — Infinite Melt	0.32	\$.016
— Finite Melt	4.4	\$.22
	0.3	\$.015
MO-CVD	(.1)	\$.002
MBE	15.8	\$.79
	14.4	\$.72

c. Labor

For each of the fabrication processes we noted that the wafers would have to be cleaned and dried prior to loading into the growth chamber and handled subsequent to removal from the growth station. We assumed that for growth cycle times less than 0.5 hours, (LPE-infinite melt and MO-CVD processes) two operating persons would be needed, one to prepare and remove the wafers and a second to operate the growth chamber. For all other processes a single operating person would have time to perform both functions.

We assumed an unburdened rate of \$10/hour for the operating personnel and \$20/hour for the supervisor. This translates into a monthly unburdened cost of \$1600 for each operator (160 hours) and \$640 for the supervisor (32 hours).

Table 11 summarizes the total unburdened labor costs for each process and the unit labor cost per cell, based on the total time required to fabricate 10,000 cells. The infinite-melt LPE and MO-CVD processes (with a larger area growth station) have the lowest labor cost based on their ability to process a number of wafers simultaneously. The labor costs for the finite-melt LPE process could be reduced by adding more growth chambers in parallel.

d. Capital Equipment

The operating costs due to the utilization of capital equipment were calculated based on a 5 year straight line depreciation schedule. The capital equipment costs charged to the solar cell fabrication processes were then computed as a fraction of the total equipment costs based on the

TABLE 11

SUMMARY OF UNBURDENED LABOR COSTS TO GROW EPITAXIAL LAYERS FOR 10,000 (AlGa)As/GaAs SOLAR CELLS WITH A SINGLE GROWTH CHAMBER

- One or two full time operating persons at \$10.00 per hour
- One part time (20%) supervisor at \$20.00 per hour

Process	Total Time ¹ (months)	No. of Operators	Total Labor Cost	Labor Cost per Cell
LPE – Infinite Melt	4	2	\$ 15,360	\$ 1.54
– Finite Melt	63	1	\$141,120	\$14.11
MO-CVD	31	1	\$ 69,440	\$ 6.94
	3	2	\$ 11,520	\$ 1.15
MBE	344	1	\$770,560	\$77.06
	31	1	\$ 69,440	\$ 6.94

1. Assuming a single 8 hour shift per day.

fraction of the five-year (60-months) depreciation schedule that the equipment was in use fabricating solar cells.

The infinite-melt LPE process requires the use of two growth chambers. The growth chamber for the n-type buffer layer holds 5000 grams of molten solution in inventory and the growth chamber for the p-type window layer, 3000 grams. We estimated, based on duplicating an existing design, that each growth chamber, with substrate holders and associated plumbing and wiring, could be fabricated for \$20,000. The total capital equipment costs for the infinite melt LPE system would be \$40,000, or \$666.67 per month for a 5 year depreciation schedule. The 8000 grams of solution in inventory represents another \$7,424 in fixed costs that we depreciated over five years.

The hardware required for an finite melt LPE process is a relatively simple sliding boat growth apparatus that is positioned in an evacuated, temperature controlled oven. We estimated the total cost of the apparatus including various pumps with associated plumbing and wiring to be \$20,000.00.

A four loop, commercially available, MO-CVD cabinet has a retail price of \$72,000 excluding the RF generator. This number is in relatively close agreement with the cost estimate of \$60,000 provided by several U.S. research organizations who built their own MO-CVD system. We assumed a total capital equipment cost of \$75,000 for the installed MO-CVD hardware including a RF generator and the necessary vent lines to the atmosphere.

The second generation, commercially available MBE system is being produced as a pilot production unit. This basic system currently sells for approximately \$208,000 and accepts 5.08-cm (2-inch) diameter wafers. There is a single growth station with a capability of azimuthal rotation for a more uniform growth over the total substrate area. An optional chamber for substrate

preparation is available (\$45,000) containing a 6 station carousel, 2 of which are heated. For our cost model we assumed a second generation MBE system, at a total capital equipment cost of \$250,000.

Table 12 summarizes the total capital equipment costs, the total cost allocated to the fabrication of 10,000 solar cells and the resulting cost per cell for the different fabrication processes. The high cost of the MBE process in the capital equipment category does not permit a cost savings to be realized by running several chambers in parallel to meet the annual production requirements. The infinite melt LPE process and MO-CVD process with a large area growth station are the most cost competitive from the view-point of capital equipment. This is due primarily to the short period of time in which the equipment is being used.

TABLE 12

SUMMARY OF CAPITAL EQUIPMENT COSTS FOR DIFFERENT SOLAR CELL FABRICATION PROCESSES ASSUMING A MINIMUM NUMBER OF GROWTH CHAMBERS

• Assuming a five year straight line depreciation schedule

Process	Total Capital Equipment Costs	Fabrication Time (months)	Total Equipment Cost Allocated to Solar Cells	Equipment Cost per Cell
LPE — Infinite Melt	\$ 47,424 ¹	4	\$ 3,162	\$.32
— Finite Melt	\$ 20,000	63	\$ 20,000	\$ 2.00
MO-CVD	\$ 75,000	31	\$ 38,750	\$ 3.88
		3	\$ 3,750	\$.38
MBE	\$250,000	344	\$250,000	\$25.00
		31	\$129,167	\$12.92

¹ Includes \$7,424.00 for 8,000 grams of melt held in inventory in two growth chambers

Table 13 summarizes all of the direct costs associated with the growth of the epitaxial layers by the three processes.

TABLE 13
SUMMARY OF MAJOR DIRECT COSTS PER CELL FOR GROWTH
OF THE EPITAXIAL LAYERS OF 10,000, 2cm x 2cm (AlGa)As/GaAs SOLAR CELLS

● Excluding overhead and profit

Process	Yield (%)	Time to Fabricate (months)	Material Costs	Unburdened Labor Costs	Capital Equipment Costs	Energy Costs	Cost per Cell ¹
LPE – Infinite Melt	100	4	\$.006	\$ 1.54	\$.32	\$.016	\$ 1.88
– Finite Melt	100	63	\$.006	\$14.11	\$ 2.00	\$.015	\$ 16.13
	10	63	\$.06	\$14.11	\$ 2.00	\$.015	\$ 16.19
	1	63	\$.62	\$14.11	\$ 2.00	\$.015	\$ 16.75
MO-CVD	100	31	\$.23	\$ 6.94	\$ 3.88	\$.002	\$ 11.05
	10	31	\$ 2.29	\$ 6.94	\$ 3.88	\$.002	\$ 13.11
	1	31	\$22.94	\$ 6.94	\$ 3.88	\$.002	\$ 33.76
	100	3	\$.23	\$ 1.15	\$.38	\$.002	\$ 1.76
	10	3	\$ 2.29	\$ 1.15	\$.38	\$.002	\$ 3.82
	1	3	\$22.94	\$ 1.15	\$.38	\$.002	\$ 24.47
MBE	50	344	\$.03	\$77.06	\$25.00	\$.79	\$102.88
	5	344	\$.30	\$77.06	\$25.00	\$.79	\$103.15
	50	31	\$.03	\$ 6.94	\$12.92	\$.72	\$ 20.61
	5	31	\$.30	\$ 6.94	\$12.92	\$.72	\$ 20.88

1. Does not include a \$1.24/cm² purchase price for polished substrates.

VI. CONCLUSIONS AND RECOMMENDATIONS

The basic conclusions derived from this study are:

1. The infinite melt LPE process currently has the lowest projected cost for the growth of the epitaxial layers on a single crystal, (AlGa) As/GaAs solar cell.
2. The MO-CVD process has a potential for low cost fabrication of (AlGa) As/GaAs solar cells. There currently, however, is a significant uncertainty in the yield of the growth system, i.e., the portion of active material in the input gas stream that ends up as part of the epitaxially grown layers.
3. Additional work is needed to optimize and document the process parameters for the MO-CVD process so that a detailed economic assessment of its potential to fabricate space quality (AlGa) As/GaAs solar cells can be made.
4. The MBE process would be a useful epitaxial growth process for research and development activities related to optimizing the structure of a (AlGa)As/GaAs solar cell for space applications.



APPENDIX A

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APPENDIX B

**LIST OF PERSONNEL INTERVIEWED FOR
GaAlAs/GaAs SOLAR CELL PROCESS STUDY**

1.	AERO PROPULSION LAB	WPAFB, OH	C. Stuerke
2.	CRYSTAL SPECIALTIES	Monrovia, CA	W. Alfred
3.	HUGHES RESEARCH LAB	Malibu, CA	G. S. Kamath R. C. Knechtli
4.	IBM CORPORATION	Yorktown Heights, NY	H. J. Hovel
5.	MIT – LINCOLN LAB	Lexington, MA	J. C. C. Fan
6.	NASA LANGLEY RESEARCH CENTER	Hampton, VA	E. J. Conway J. A. Hutchby G. H. Walker
7.	ROCKWELL INTERNATIONAL/ ELECTRONICS RESEARCH CTR.	Anaheim, CA	P. D. Dapkus R. Ruth
8.	ROCKWELL INTERNATIONAL/ SCIENCE CENTER	Thousand Oaks, CA	J. S. Harris
9.	VARIAN ASSOCIATES	Palo Alto, CA	R. Bell B. Cairns L. W. James

1. Report No. NASA CR-3361	2.	3. Recipient's Accession No.	
4. Title and Subtitle GaAIAs/GaAs Solar Cell Process Study		5. Report Date December 1980	
		6. C-82340	
7. Author(s) David W. Almgren and Katinka I. Csigi		8. Performing Organization Report No. ADL 82340	
9. Performing Organization Name and Address Arthur D. Little, Inc. Acorn Park Cambridge, MA 02140		10. Project/Task/Work Unit No.	
		11. Contract or Grant No. NAS1-15516	
12. Sponsoring Organization Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report Contractor Report	
		14.	
15. Supplementary Notes Langley Technical Monitor: Edmund J. Conway Final Report			
16. Abstract <p>This report summarizes available information on liquid phase, vapor phase (including chemical vapor deposition) and molecular beam epitaxy growth procedures that could be used to fabricate single crystal, heteroface, (AlGa) As/GaAs solar cells, for space applications. A comparison of the basic cost elements of the epitaxy growth processes shows that the current infinite-melt LPE process has the lower cost per cell for an annual production rate of 10,000 cells. The metal organic chemical vapor deposition (MO-CVD) process has the potential for low cost production of solar cells but there is currently a significant uncertainty in process yield, i.e., the fraction of active material in the input gas stream that ends up in the cell. Additional work is needed to optimize and document the process parameters for the MO-CVD process.</p>			
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