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JAPAN'S PARTICIPATION IN SPACE STATION DESIGN - FEASIBILITY STUDY OF GaAs SOLAR CELLS FOR SPACE STATION APPLICATIONS

National Space Development Agency of Japan

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16. Abstract The report gives the results of feasibility studies and a cost analysis done on GaAs solar battery cells for space stations. The studies and their results are as follows: 1) Cell size - The 2 x 4 cm cell size was found superior to the 4 x 4 cm cell; 2) Manufacturing technology - Overal, LPE crystal growth was found more suitable than MO-CVD. Current technology for post-growth processes and applying large-area cover glass can be used with few or no modifications; 3) - Cell assemblies - Tests for mechanical and thermal stresses encountered from assembly through operation are recommended; 4) - Procuring materials - Steps should be taken to avoid sharp price increases due to a speculative gallium market. There are no problems with arsenic materials; 5) Production facilities - The capital investment needed remains to be determined, but a working area of 4000 m^2 will be required; 6) Cell costs - to be determined; 7) Cell development-supply plan - Two-year lead time will be needed to develop the necessary technology and prepare for production. Delivery will begin 3 years after receipt of contract.

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SUMMARY

We made technical and production feasibility studies, and did a cost analysis of the GaAs solar cells used for NASA's space station. The results of this study are as follows:

1. Studies on cell size

We are in the process of manufacturing 2 x 2 cm cells for CS-3 communications satellites. Based on this, we extrapolated the electrical performance of 2 x 4-area cells, and studied their conversion efficiency. As a result, we found that, as far as electrical characteristics and their retention go, 2 x 4 cm was superior to 4 x 4 cm.

2. The studies on manufacturing technology:

There are two methods used in epitaxial growth to obtain even quality in large-area cells: the currently used LPE crystal growth and MO-CVD crystal growth. We studied both to see which is more suitable for volume production, parameter control, cell characteristics, facility costs, schedules, etc.

As a result, we found that LPE crystal growth is superior. Also, with regard to the process after epitaxial growth, we found that basically we can use the processes currently in use because there is no need to change the size of the substrates. We also identified the areas where batch process should be improved or newly adopted.

We also studied the technology for applying large-area cover glass, and found that the current technology used for 2 x 2 cm can also be applied here with a few modifications.

3. Technical studies on cell assemblies

Basically, we see no basic problems with respect to the cell assembly for space stations, but feel that some evaluation tests should be performed assuming mechanical and thermal stress that may occur during the period from assembly to the actual use of the cells.

4. Studies on procuring materials

Concretely speaking, we studied the availability of GaAs single crystal substrates, Gallium (the materials for single crystal and liquid phase epitaxial growth) and Arsenic (materials for GaAs single crystal).

As a result, we found that we need a capital investment [of] (blank) with one year lead time to put together the necessary equipment and facilities for the GaAs crystal growth.

Gallium is in increased production at present; therefore, we see little problem. However, Gallium belongs to a speculative market. Therefore, we must take every precaution to avoid drastic increases in price during our procurement cycle.

There is no problem with the Arsenic materials.

5. Studies on production facilities

Investment in production facilities, buildings and working area of approx. 4000 m^2 are necessary.

6. Analysis of cell costs:

- Cell cost: (Excludes depreciation and development costs)
    - 2 x 4 cm cell:
    - 4 x 4 cm cell:
- Capital investments:
- Development costs:

In applying GaAs solar cells to Space Stations, our detailed study of the specifications and our design optimum cell based on radiation environment data (types/quantity of rays, etc.) and the expected life at the space station orbit may result in a price reduction.

7. Cell development-supply plan

Items that require technical development:
- Technology to increase LPE capability
- Manufacturing large area cells
- Manufacturing large volume cells.

Two years are required for developing these technologies.

In preparing for production, the following items are required:

- Procurement of materials:	one year
- Space and facilities/installation:	two years
- Personnel recruitment and deployment:	one year.

Production and delivery shall take place three years after receipt of order and the delivery shall be complete in three years after the first delivery.

As stated above, we forsee no major issues either of technical or manufacturing nature.

Finally, we understand that the overall evaluation must be made with regard to space station plan, such as cost, schedule, etc., but we feel very strongly that GaAs solar cells have sufficient adaptability to the space station project.

In the field of GaAs single crystal manufacturing, we feel we are the leader in the world, occupying 60% of the total market volume.

We are very proud of our design and manufacturing technology of GaAs solar cells for space use, which is exemplified in our development and production of 2 x 2 cm solar cells for the CS-3 satellite program.

CONTENTS

JAPAN'S PARTICIPATION IN SPACE STATION DESIGN - FEASIBILITY STUDY OF GaAs SOLAR CELLS FOR SPACE STATION APPLICATIONS

Introduction /1 *

The GaAs solar battery cell, developed in our country and now in production for use in the payload of Communications Satellite No. 3 (CS-3), scheduled for launch in 1988, has extremely good conversion efficiency, radiation resistance and temperature-related properties. Therefore, our country's GaAs solar battery cell was used to illustrate increased electrical power generation in a space station in America's current plans for a manned space station. As a result, a feasibility study on GaAs cell technology was carried out at NASA's invitation, as an option study on solar battery cells, .

The National Aerospace Development Agency (NASDA), hoping to enhance the conversion efficiency of solar battery cells as /2
part of the enlargement of man-made satellites, upon which space development plans depend, began to develop a GaAs solar battery cell for use in space in 1982. To date, the GaAs solar battery cell has been commercialized for consumer use, and a superior production technology has been established for it. Therefore, within a relatively short time, a highly efficient (17.5% TYP) GaAs solar battery cell (cell size = 2 cm x 2cm) has been developed, along with the production technology for it. In 1984 it was recognized as a highly reliable component for general use in space, and production of it for use in the payload of the CS-3 was begun that same year.

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*Numbers in the margin indicate pagination in the foreign text.

GaAs solar battery cells, when compared to Si solar battery cells, have far superior conversion efficiency, radiation resistance, and temperature-related properties. This difference in performance is essentially a function of the physical differences between GaAs and Si crystals. Specifically:

(1) GaAs crystals have high sensitivity in the region where the solar spectrum is strongest;
(2) Their band gap is wider and the change in properties due to temperature is smaller; and
(3) Since their light absorption coefficient is larger, their effective crystallization thickness, that is, their movement region (p-n contact region) is shallower, resulting in superior radiation resistance.

These are qualities that make GaAs solar batter cells ideally suited to use in space.

This report deals with the development, the design technology for current production, and the volume production of GaAs solar battery cells, as well as studies on their applications, technology, production and cost.

2. Studies on Cell Size /2

2.1 Projections of electric properties and property retention as cell surface is enlarged.

A study of changes in properties and property retention was made using 2 x 2 cm, 2 x 4 cm and 4 x 4 cm GaAs solar batteries cells now in production for use in the CS-3. The results are described below:

(1) Change in Electric Properties (I_{LD})

The GaAs solar battery cell currently in production for the CS-3 uses a 5 x 4.5 cm substrate. Accordingly, the combined properties of any two of four cells on the same substrate may be said to have the properties of a 2 x 4 cm cell, and four cells may be said to have the properties of a 4 x 4 cm cell.

Moreover, considering I_{LD} from among all the properties, the value for two cells placed in series is simply the sum of the I_{LD} value for each of the cells.

In this way, cell properties for every size cell could be calculated for a set with varying property retention levels. The cell properties (I_{LD}) for acceptable cells are shown in Table 2-1. Furthermore, the standard I_{LD} value for 2 x 2 cm cells according to NASD-QTS-1013D/301A ($I_{LD} \geq 105.0$ mA) was met.

Results clearly showed that going from 2 x 4 cm to 4 x 4 cm cell size caused a change in I_{LD} of less than -1%, and that, especially in the case of the 2 x 4 cm size, a value of around -0.5% was within the range defined by measurement error.

(2) Changes in Retention

Property retention was calculated for each cell size using the same method as in (1). The results are shown in Table 2-1, as are those of (1).

Since comparison with a 2 x 2cm cell shows an average property retention change of -1% for the 2 cm x 4 cm size, with a maximum of -5%, the results indicate that a change of more than -10% could be anticipated for the 4 x 4 cm size.

The above observations of electric properties and property retention lead to the conclusion that the 2 x 4 cm is superior to the 4 x 4 cm size.

Table 2-1 I_{LD} and Property Level for GaAs Solar Battery Cell Size /3

	1) 良品平均 I_{LD}					2) 特性歩留 (I_{LD}≧105.0 mA)				
	2×2 cm cm	2cm×4cm		4cm×4cm		2×2 cm cm	2cm×4cm		4cm×4cm	
	I_{LD} (mA)	I_{LD}/2 (mA)	変化率 3)(%)	I_{LD}/4 (mA)	変化率 4)(%)	歩留 5)(%)	歩留 6)(%)	変化率 7)(%)	歩留 8)(%)	変化率 9)(%)
Case1	113.37	113.16	-0.2	112.81	-0.5	75.1	72.0	-4.1	67.4	-10.3
Case2	113.41	113.23	-0.2	112.99	-0.4	77.0	75.4	-2.1	73.3	-4.8
Case3	111.80	111.26	-0.5	111.06	-0.7	81.7	80.0	-2.1	73.5	-10.0
Case4	114.18	114.03	-0.1	113.42	-0.7	88.7	84.0	-5.3	78.4	-11.6
Case5	113.12	112.34	-0.7	111.87	-1.1	91.4	95.3	4.3	96.9	6.0
Case6	113.73	113.21	-0.5	113.38	-0.3	94.7	98.3	3.8	96.4	1.8
Case7	115.06	114.32	-0.6	113.59	-1.3	98.7	98.7	0.0	100.0	1.3
10) 平均	113.52	113.08	-0.40	112.73	-0.71	86.76	86.24	-0.79	83.70	-3.94

Key: 1) - Average I_{LD} for Acceptable Cells; 2) - Property Retention; 3) - Rate of change; 4) - Rate of change; 5) - Property retention; 6) - Property retention; 7) - Rate of change; 8) - Property retention; 9) - Rate of change; 10) - Average.

2.2 Electrode Pattern Design

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2.2.1 Theory and analysis of electrode patterns

In order to calculate the optimized design for electrode patterns, Moor's[1] calculation method for series resistance in solar battery cells according to electric loss was used to find the grid square count with the highest conversion efficiency. The electrode pattern used for calculation, shown in figure 2-1 has a comb-like structure with cell size La x Lb, bar electrode width W_B, grid width W, intra-grid gap Lg, and grid square count n.

Using Rs as the sheet resistance of the p-layer, Rc as the contact resistance of the p-electrode, Rm as the comparative resistance of the electrode metal, and Jph as the photo-activated current density, the electric loss, Pspr, due to the sheet resistance of the p-layer, is:

$$P_{spr} = 2n \int_0^{Lg(1-S)/2} \{(Lb - W_B) \cdot y \cdot Jph\}^2 \cdot \frac{Rs}{Lb - W_B} dy \qquad (2\text{-}1)$$

the electric loss due to the contact resistance of the p-electrode is:

$$Pc = n \{(Lb - W_B) \cdot Lg \cdot (1-S) \cdot Jph\}^2 \cdot \frac{Rc}{(Lb - W_B) \cdot W} \qquad (2\text{-}2)$$

and the electric loss Pg from the electrode metal resistance is:

$$Pg = n \int_0^{Lb - W_B} \{Lg \cdot (1-S) \cdot x \cdot Jph\}^2 \frac{Rm}{W \cdot t} dx \qquad (2\text{-}3)$$

S is the grid electron coating ratio, and t, electrode metal thickness.

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(1) A.R. Moor, RCA Rev., vol. 40, p. 153

The electric loss from contact resistance of the inner electrodes and the bulk resistance of the substrate are quite small, and if we ignore them, total electric loss Pr for the solar battery cell is

$$P_R = P_{spr} + P_c + P_g \tag{2-4}$$

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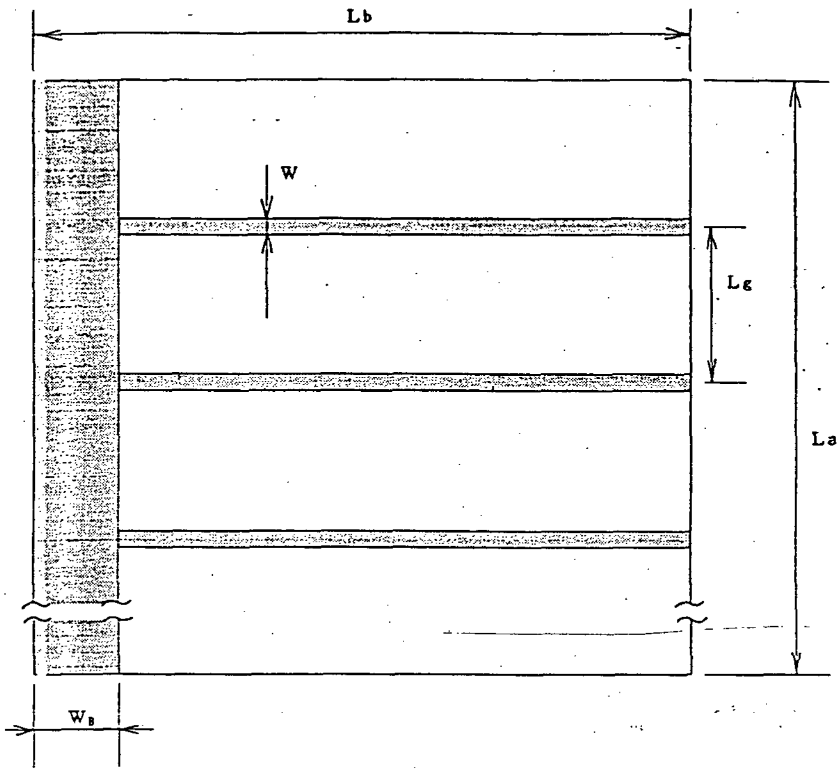


La, Lb:	Solar battery cell dimensions
W_B:	Bar electrode width
W:	Grid width
L_g:	Grid gap

Fig. 2-1 Electrode pattern used in calculations

On the other hand, since total electric current I is: /6

$$I = La \cdot (1-S) \cdot (Lb - W_B) \cdot J_{ph} \tag{2-5}$$

and $P_R = RI^2$, solving formulas (2-1) through (2-5) for R, total series resistance, gives:

$$R = \frac{La - n \cdot W}{12n^2 \cdot (Lb - W_B)} Rs + \frac{1}{n \cdot W \cdot (Lb - W_B)} Rc + \frac{Lb - W_B}{3 \cdot n \cdot W \cdot t} R_m \tag{2-6}$$

Further, the solar battery cell's V-I property is shown by:

$$I = I_{ph} - I_0 \cdot [\exp(\frac{q \cdot (V + I \cdot R)}{B \cdot k \cdot T}) - 1] \tag{2-7}$$

and the electricity produced, P, is

$$P = I \cdot (-I \cdot R + \frac{B \cdot k \cdot T}{q} \ln(\frac{I_{ph} - I}{I_0}) + 1) \tag{2-8}$$

By substituting the maximum value for P is formula (2-8), and finding Im and Vm, conversion efficiency η becomes:

$$\eta = \frac{I_m \times V_m}{E_{in} \times La \times Lb} \times 100 \quad (\%) \tag{2-9}$$

Here Ein is 135.3 mW/cm^2.

By substituting the grid square count that will provide the maximum value for η into formula (2-9), we obtain the optimum pattern design.

2.2.2 Application to large-area cells /7

The methods set forth in 2.2.1 were applied to several cell sizes (La x Lb) -- 2 x 2 cm, 4 x 2 cm, 2 x 4 cm, and 4 x 4 cm -- based on the average properties of the 2 x 2 cm GaAs solar cell now in production for the CS-3.

Electrode bar width W_B and electrode metal thickness should each be determined by how well those dimensions lend themselves to assembly. Here, as is the case for the CS-3, W_B = 0.1 cm, t = 5 μm, and the electrode metal is silver. Grid widths of 10, 20, 30, 40 and 50 μm were evaluated based on their relation to grid square count n and conversion efficiency η, with results shown in Figures 2-2 through 2-5.

In figures 2-2 through 2-5, when grid width W is fixed, a decrease in grid count leads to an increase in series resistance, with a subsequent decrease in conversion efficiency. An increase in grid count leads to an increase in conversion efficiency until a certain grid count value is exceeded, after which there is a decrease. This is due to an increase in the rate of electrode covering of the cells as the grid count increases and a reduction of the effective light absorption surface. Consequently, it is possible for a small grid width to attain a comparatively high efficiency.

2.2.3 Pattern design and observations on large-area cells

Since GaAs solar battery cells produced by liquid phase epitaxial growth have the uneven surface characteristic of liquid phase epitaxy, grid width for volume production was set at 40 μm. Table 2-2 shows the results of section 2.2.2 for W = 40 μm and each cell size under consideration, in terms of relation to the grid count n and conversion efficiency η.

Table 2-2 Calculation Results for Optimum Number of Grid Units

1) セルサイズ La ×Lb	最適ｸﾞﾘｯﾄﾞ本数n 2)	変換効率 η (%)3)	ｸﾞﾘｯﾄﾞ被覆率S 4)	有効受光面積 5) (cm²)	直列抵抗 6) R (Ω)
2cm×2cm	19	17.55	0.019	3.73	0.190
4cm×2cm	38	17.55	0.019	7.45	0.095
2cm×4cm	21	17.82	0.011	7.65	0.118
4cm×4cm	42	17.82	0.011	15.43	0.059

Key: 1) - Cell size; 2) - Optimum number of grid squares n; 3) - Conversion efficiency η (%); 4) - Grid coating ratio S; 5) - Effective light-receiving surface (cm^2); 6) - Series resistance R (Ω).

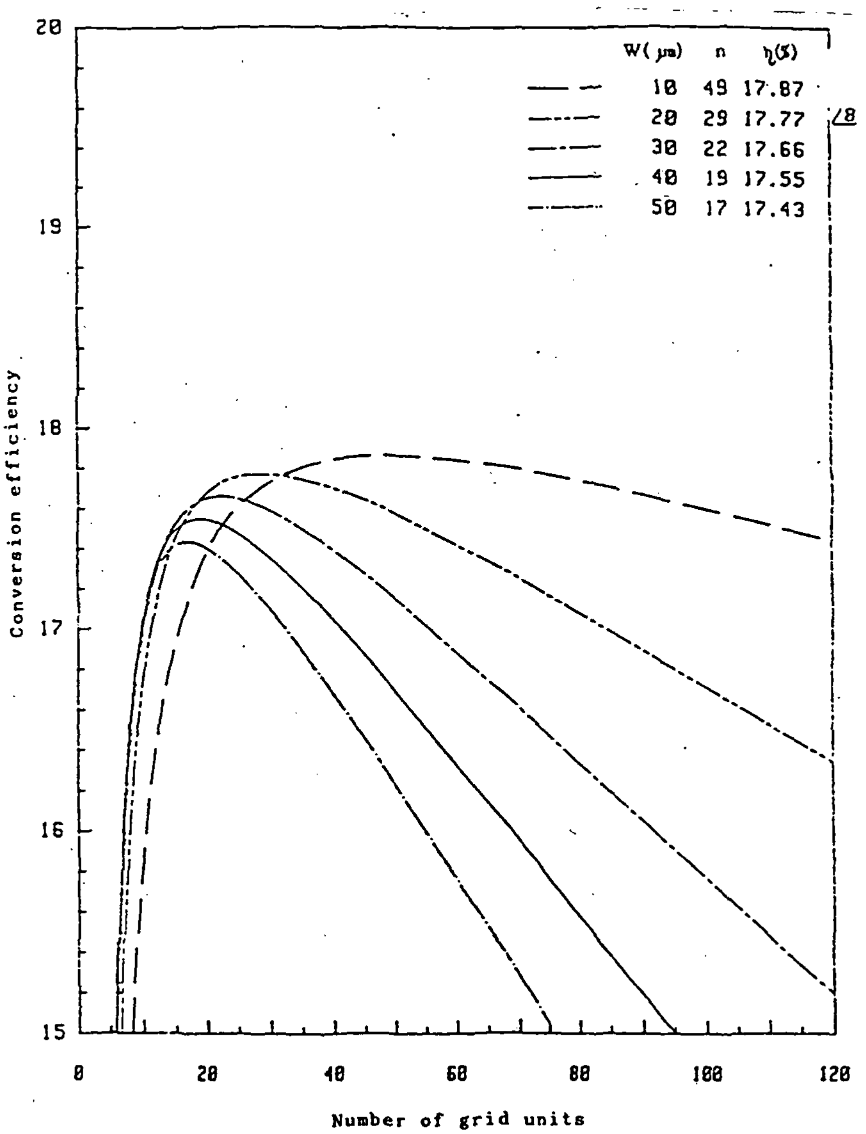


Figure 2-2 Conversion efficiency as a function of the number of grid squares (2 cm x 2 cm cell)

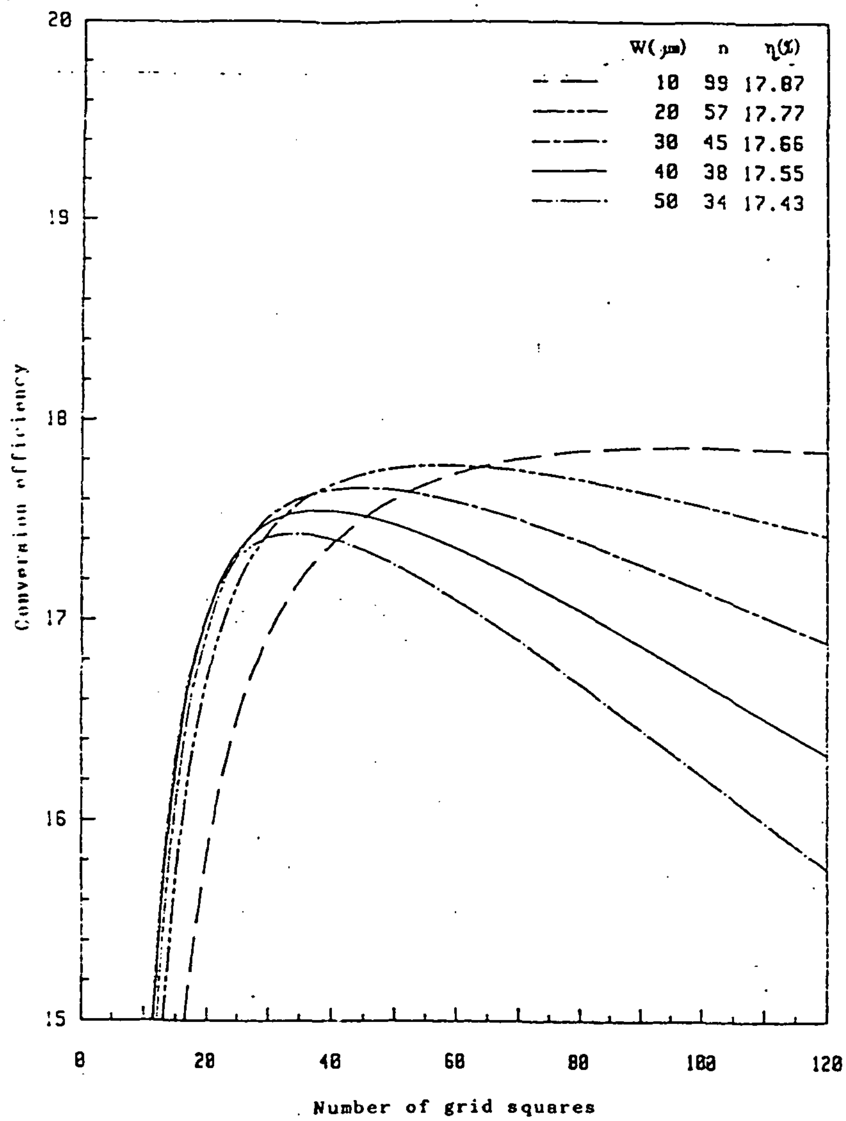


Figure 2-3 Conversion efficiency as a function of the number of grid squares (4 cm x 2 cm cell)

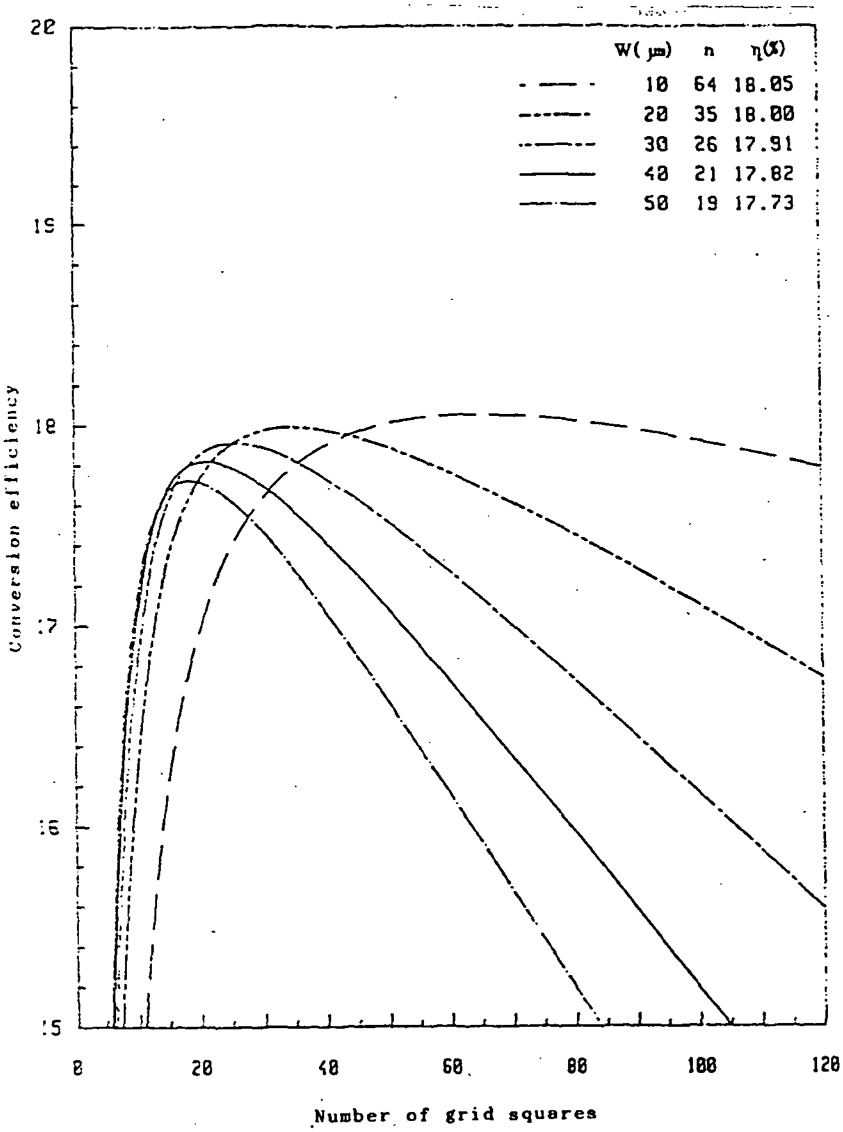


Figure 2-4 Conversion efficiency as a function of the number of grid squares (2 cm x 4 cm cell)

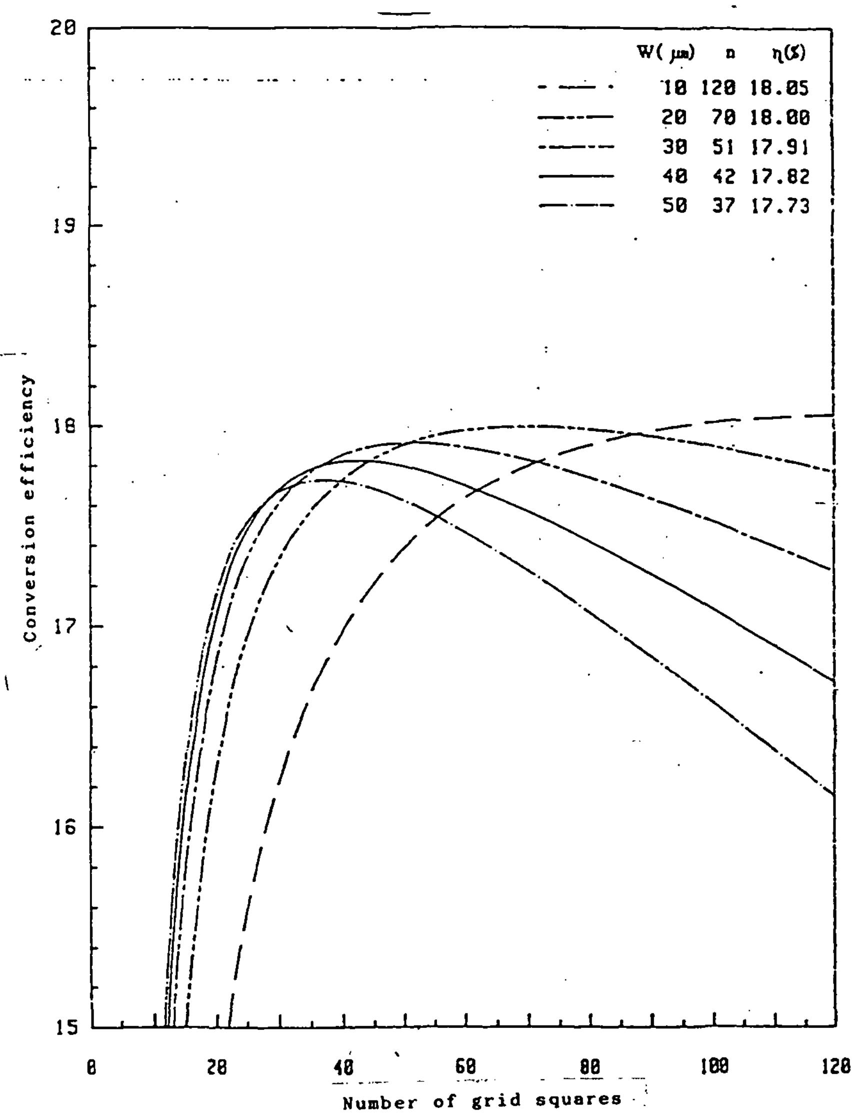


Figure 2-4 Conversion efficiency as a function of the number of grid squares (4 cm x 4 cm cell)

Based on Table 2-2, the following may be said: /12

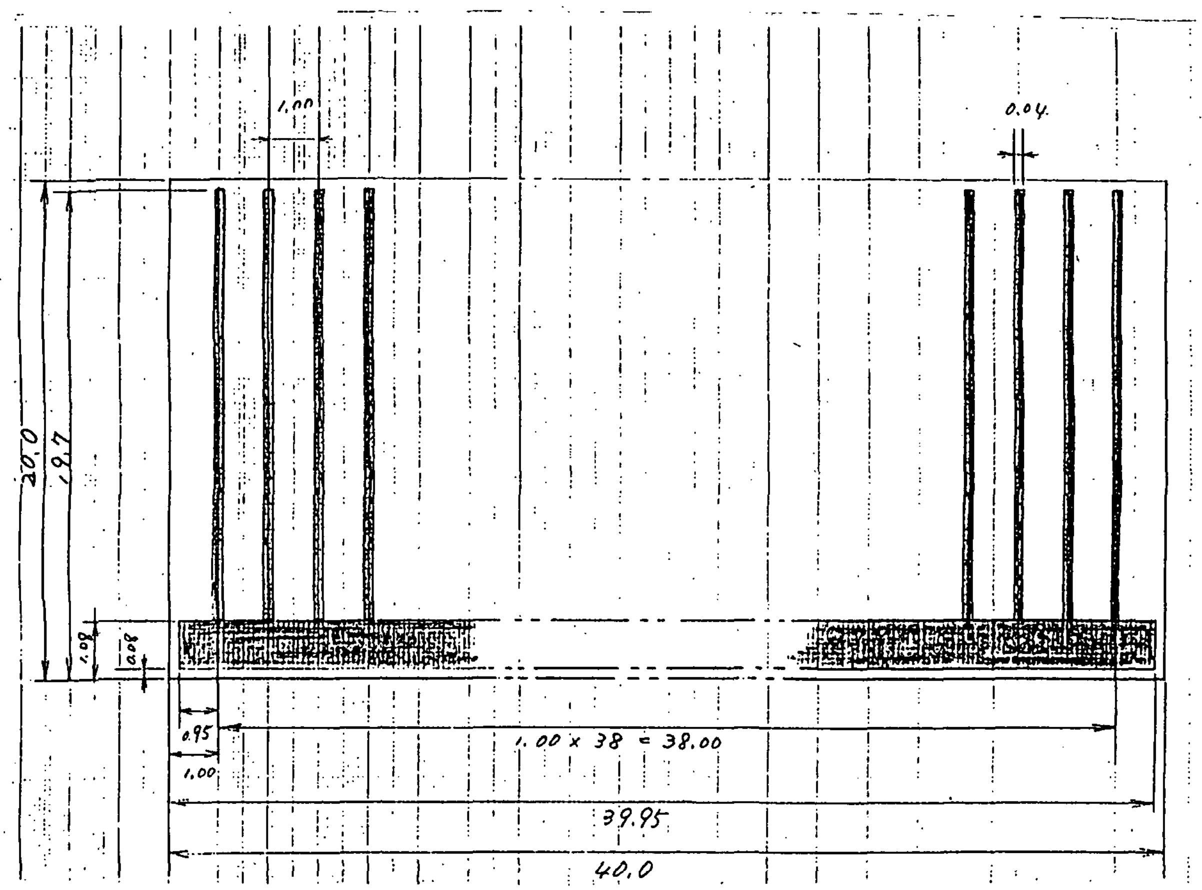
(i) 4 x 2 cm cells achieve maximum conversion efficiency on a 38-unit grid, as do 2 cm x 2 cm cells.

(ii) 2 x 4 cm cells achieve their maximum on 21-unit grid, while 4 x 2 cm cells achieve a maximum approximately 1.5% higher. This is because the 2 cm x 4 cm cells' series resistance R is 24% higher than that of the 4 x 2 cm cells, and since the bar electrode surface area is one-half that of the 4 x 2 cm cell, and its light-receiving surface is 2.7% more, the effects of series resistance are eliminated.

(iii) 4 x 4 cm cells achieve maximum conversion efficiency on a 42-unit grid, and the 2 x 4 cm cells are capable of the same level of efficiency.

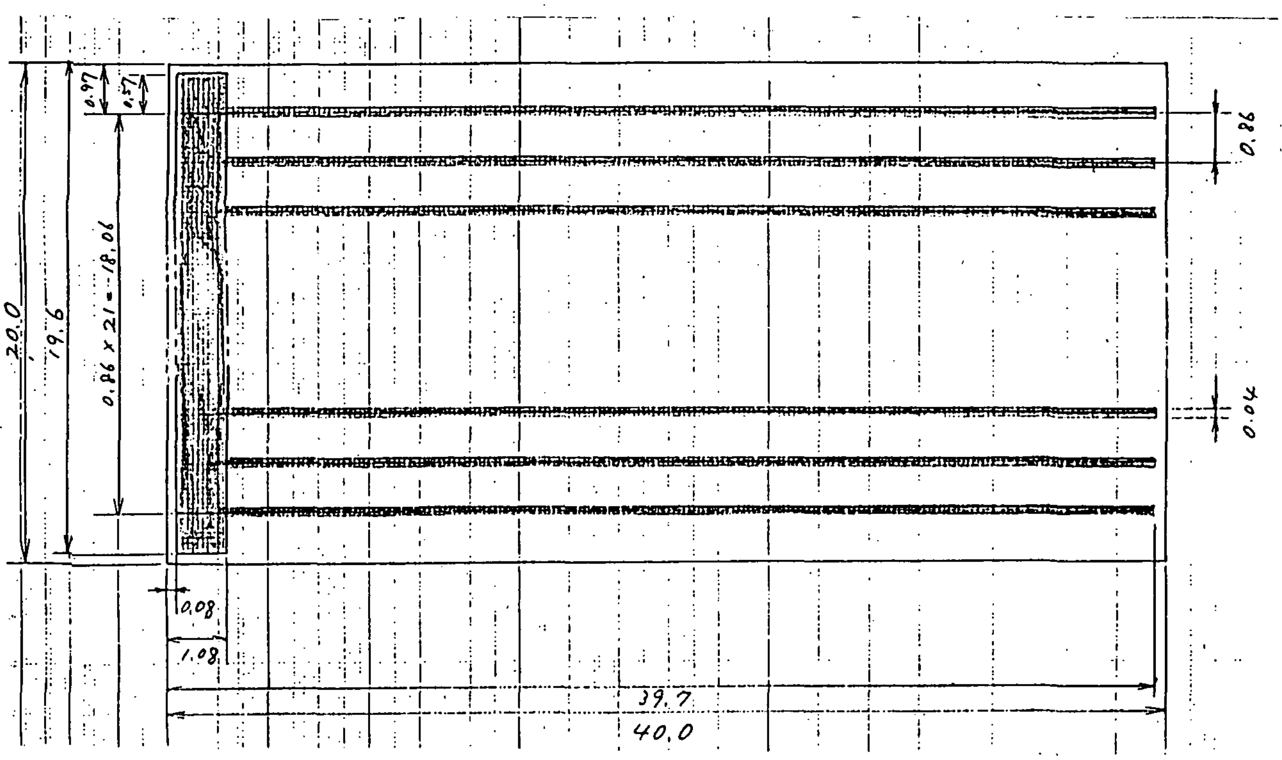
These are the results of calculating the optimum number of units in a grid. For the final stage of deciding on the electrode pattern, stability in production process and assembly method, etc., had to be considered, and so it was necessary to compare several patterns experimentally.

Figures 2-6 through 2-8 show the interaction of cell size and electrode pattern.



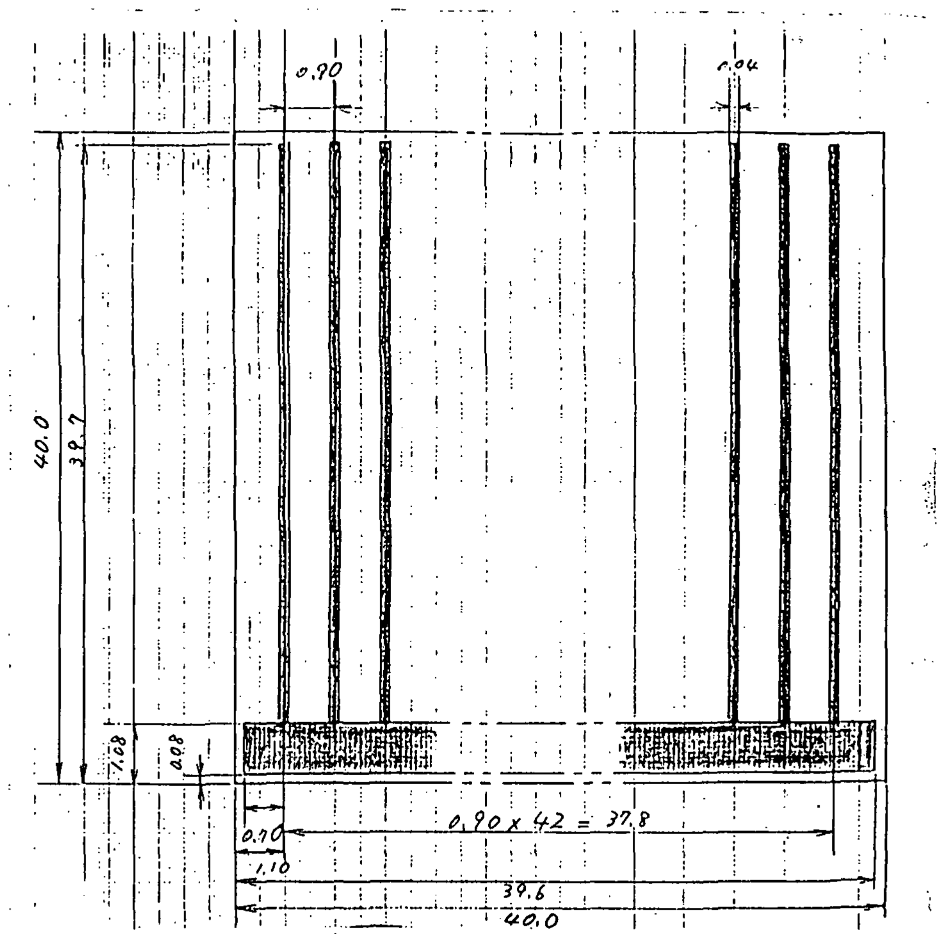
Unit

Figure 2-6 Electrode pattern for a 4 x 2 cm cell



Unit

Figure 2-7 Electrode pattern for a 2 x 4 cm cell



Unit

Figure 2-8 Electrode pattern for a 4 x 4 cm cell

3. Studies on Manufacturing Technology /16

3.1 A study on crystal growth technology

Methods for making crystals for solar battery cells now generally include LPE (Liquid Phase Epitaxy) and MO-CVD (Metal Organic-Chemical Vapor Deposition).

While studying applications of GaAs solar battery cells to space stations, these two methods for crystal growth were examined and compared in terms of technology, suitability for volume production, expenditures for manufacturing equipment and scheduling considerations.

3.1.1 State of LPE and MO-CVD technologies for making GaAs solar battery cells

(1) State of LPE technology

LPE gives superior crystallization in crystalline growth layers, and the GaAs solar battery cell developed by NASDA for use in space was made with this technology. In the development stage, important parameters for determining cell properties -- binding depth (x_j), the uniformity the AlGaAs layer's thickness, and the remanifestation characteristic -- were enhanced. Furthermore, a VSTC (Vertically Separated Three-Chamber) LPE Boat made it possible to manufacture fifty (50) .5 cm x 5 cm substrates at once. Equipment included a sequencer which permitted automated temperature control, gas control and insertion and removal from the boat furnace during volume production.

As a result of this development, the 50,000 GaAs solar battery cells (2 cm x 2 cm) mass-produced annually for use in space achieve 17.5% conversion efficiency.

Figures 3-1 and 3-2, respectively, show the structure of the volume production boat currently used and the essentials of the LPE system.

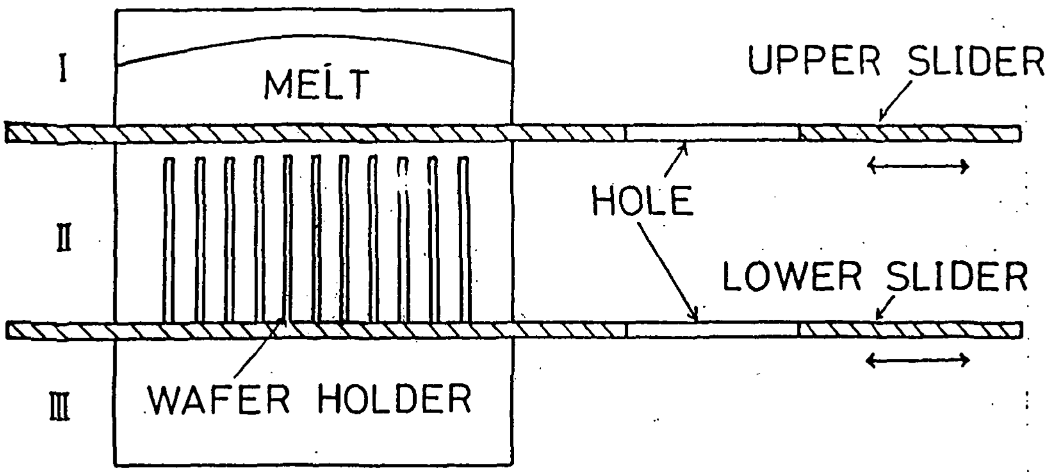


Fig. 3-1 Structure of the Existing Volume Production (VSTC-LPE) Boat

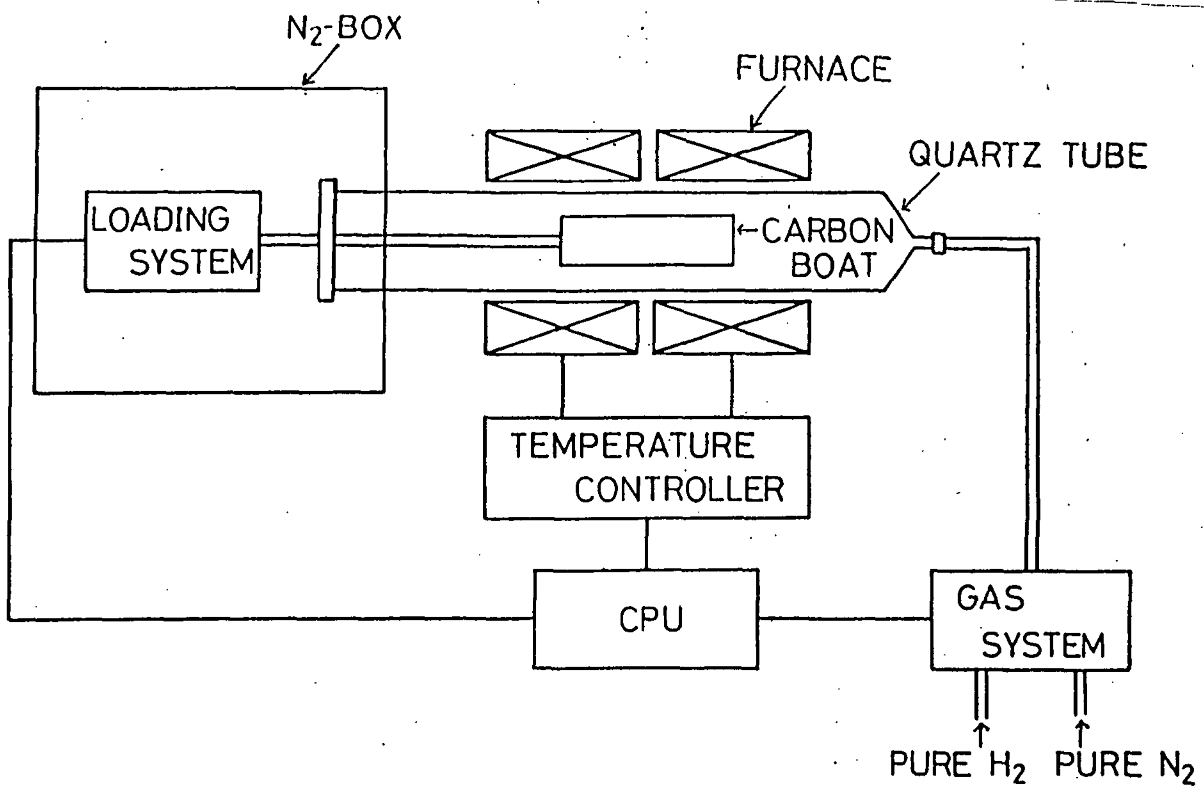


Fig. 3-2 LPE System

In order to enhance the processing capability of crystal formation for the GaAs solar battery cell, the current processing capability (one run of epitaxial growth produces fifty (50) 4.5 wafers) should be approximately doubled by adopting the large LPE system under consideration. To accomplish this, the following problems will have to be solved. /19

(a) Enlarging current volume production LPE equipment

(1) Enlarging furnace diameter;
(2) Extending the uniform heat area of the furnace;
(3) Automating the boat loader-unloader.

(b) Enlarging the current LPE boat's capacity

(1) Design of the large-capacity LPE boat;
(2) Selection of materials for the boat from the standpoint of mechanical strength.

2. State of MO-CVD Technology

MO-CVD is a thin-film crystal formation method which gives superior parameter control and surface evenness. Recently, manufacturers have been actively developing the use of MO-CVD for GaAs solar battery cells. Table 3-1 shows the status of several manufacturers.

Table 3-1 Status of GaAs Solar Battery Cell Manufacture Using MO-CVD

Manufacturer	Development Stage		Notes
	Cell Size	Efficiency (Conditions) (Top Data)	(References)
Sprire Corporation	1 cm × 1 cm	20.3% (AM1)	S.M.Vernon et al.,17th IEEE PVSC,p434(1984)
Varian Associates Inc.	2 cm × 2 cm	18.7% (AM0)	J.G.Werther,17th IEEE PVSC,p141(1984)
Applied Solar Energy Corporation	2 cm × 4 cm	16.8% (AM0)	Y.C.M.Yeh et al.,17th IEEE PVSC,p145(1984)
Mitsubishi Electric Corporation	1 cm × 1 cm	19.7% (AM0)	K.Mizuguch et al.,12th Int'l Sym.on GaAs,1985

As shown in Table 3-1, the GaAs solar battery cell, which has a high efficiency near 20% as top data during production, had an average efficiency of 15-16%[1]. /20

Adapting MO-CVD to volume production of GaAs solar battery cells is a matter of achieving stable production of highly efficient solar battery cells and enhancing crystal quality.

(1) Y.C.M Yeh et al., 19th IECEC, p. 205 (1984)

3.1.2 A Comparative Study of LPE and MO-CVD

The main equipment used for manufacturing GaAs solar battery cells with LPE and MO-CVD is shown in Table 3-2, (1)-(3). Apart from the epitaxial process, the process and equipment used for LPE and MO-CVD are almost identical.

Table 3-3 shows comparative results for the GaAs solar battery cells produced by LPE and MO-CVD, in terms of epitaxial layer properties, adaptability to production, safety, economy, and cell properties (efficiency).

Generally, MO-CVD is superior to LPE in terms of uniform film thickness and surface evenness of the epitaxial layers, while LPE is superior to MO-CVD in terms of crystal properties.

With regard to safety, since the MO-CVD process uses highly flammable organic-metal materials and large amounts of highly toxic AH_3, extremely thorough safety procedures are needed to assure safety and prevent pollution from exhaust materials. Consequently, equipment expenditures for this process tend to be higher than for LPE, as shown in Table 3-4.

With regard to cell properties: MO-CVD, when produced in quantity, has an average efficiency of about 15-16%, which is lower than the 17.5% provided by LPE. Therefore, improved cell properties and stability are problems for the future development of MO-CVD.

Results of the comparative studies on LPE and MO-CVD mass production of GaAs solar battery cells show that, in terms of improved cell properties and stability, GaAs solar battery cells currently made with the LPE process are superior to those made with MO-CVD for volume production.

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Table 3—2—(1)

MANUFACTURING PROCESS FLOW OF GaAs SOLAR CELL (1)

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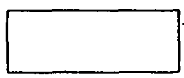
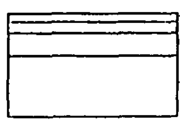
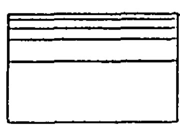
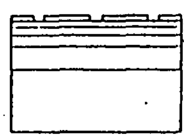
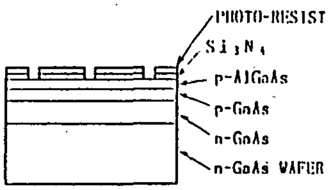
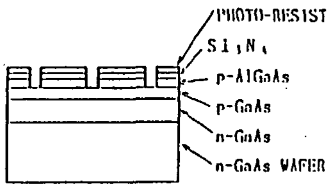
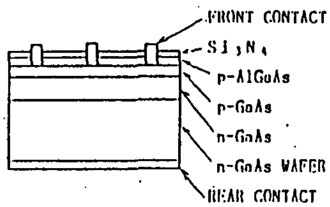
NO	PROCESS	STRUCTURE	MAIN PRODUCTION EQUIPMENTS FOR LPE AND MO-CVD METHODS	
			LPE	MO—CVD
1	· STARTING MATERIAL	 n-GaAs WAFER		
2	· EPITAXIAL GROWTH	 p-AlGaAs p-GaAs n-GaAs n-GaAs WAFER	· LPE SYSTEM (12) · SAFETY SYSTEM (1) · EPITAXIAL LAYER EVALUATION SYSTEM (1)	· MO-CVD SYSTEM (20) · SAFETY SYSTEM (1) · GAS SCRUBBER (20) · EMERGENCY FAN SYSTEM (2) · EPITAXIAL LAYER EVALUATION SYSTEM (1)
3	· ANTI-REFLECTION COATING	 Si_3N_4 p-AlGaAs p-GaAs n-GaAs n-GaAs WAFER	· CVD SYSTEM (4)	· CVD SYSTEM (4)
4	· PHOTO-LITHOGRAPHY	 PHOTO-RESIST Si_3N_4 p-AlGaAs p-GaAs n-GaAs n-GaAs WAFER	· MASK ALIGNER (11) · RESIST COATER (5) · DICING SAW (12) (FOR CUTTING OFF WAFER PERIPHERY)	· MASK ALIGNER (11) · RESIST COATER (5)

( ) APPROXIMATE QUANTITY IN THE CASE OF CELL SIZE : 2cm×4cm

Table 3-2-(2)

MANUFACTURING PROCESS FLOW OF GaAs SOLAR CELL (2)

NS003A

NO	PROCESS	STRUCTURE	MAIN PRODUCTION EQUIPMENTS FOR LPE AND MO-CVD METHODS	
			LPE	MO-CVD
5	· ETCHING OF Si_3N_4		· PLASMA ETCHER (6)	· PLASMA ETCHER (6)
6	· ETCHING OF AlGaAs		· CHEMICAL ETCHER (4)	· CHEMICAL ETCHER (4)
7	· METALLIZATION		· SPUTTERING SYSTEM (5) · ELECTRON BEAM EVAPORATOR (10) · SINTERING FURNACE (2)	· SPUTTERING SYSTEM (5) · ELECTRON BEAM EVAPORATOR (10) · SINTERING FURNACE (2)

( ) APPROXIMATE QUANTITY IN THE CASE OF CELL SIZE : 2cm×4cm

Table 3-2-(3)

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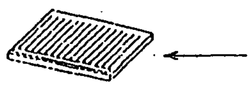
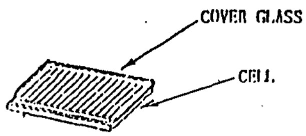
MANUFACTURING PROCESS FLOW OF GaAs SOLAR CELL (3)

NS004A1

NO	PROCESS	STRUCTURE	MAIN PRODUCTION EQUIPMENTS FOR LPE AND MO-CVD METHODS	
			LPE	MO-CVD
8	·DICING		·DICING SAW (9)	·DICING SAW (9)
9	·COVER GLASS ADHESION		·ADHESION SYSTEM (1)	·ADHESION SYSTEM (1)
10	·INSPECTION		·INSPECTION SYSTEM (1)	·INSPECTION SYSTEM (1)

( ) APPROXIMATE QUANTITY IN THE CASE OF CELL SIZE : 2cm×4cm

Table 3-3 A Comparison of the Application of MO-CVD and LPE to Volume Production of GaAs Solar Battery Cells /25

Characteristics		LPE	MO-CVD
Epitaxial Layer	Even Surface		●
	Uniform Film Thickness		●
	Crystallization	●	
Can be produced in quantity		●	●
Safety (flammability and toxicity of ingredients)		●	
Economy (equipment expenditures)		●	
Solar battery cell (conversion efficiency)		●	

● : good

Table 3-4.

ESTIMATION OF THE EXPENSE OF EQUIPMENTS FOR LPE AND MO-CVD

UNIT : MILLION YEN

METHOD / PROCESS	L P E	M O - C V D
EPITAXIAL GROWTH		
ANTI-REFLECTION COATING		
PHOTO-LITHOGRAPHY	TBD	
METALLIZATION		
INSPECTION		
OTHERS		
TOTAL EXPENSE		

NOTE : THE EXPENSES OF EQUIPMENTS IN EACH PROCESS WERE ROUGHLY ESTIMATED BY USING THE MARCKET PRICES IN 1985, AND SO THEY ARE CHANGEABLE.

3.2 A Study on Production Process. Technology Applied to Mass Processing /27

A study on the crystal growth process was described in section 3-1. This section deals with studies made on the technology of subsequent production processing stages.

The substrate size currently in production is 4.5 x 4.5 cm, and with the current crystal growth technique, the edges are incompletely formed. In the current manufacturing process, after the anti-reflection coating is formed, irregularities in the edges are cut away with a dicing saw, which trims dimensions to 4.3 x 4.3 cm. Subsequent processes are set up to handle these dimensions. The same process can be applied to 2 x 4 cm or 4 x 4 cm cells, with dicing being set up just like a production line. Consequently, even the GaAs cell used in space stations may also be thought of basically in terms of the production line concept.

However, if the scale of production is increased to ten times that of the present, then we need equipment which gives uniform quality and improved processing performance; we must also design and develop treatment tools, review process content for suitability for automation, and develop automated equipment.

Results of studies on problems of automation and technology involving main processes are shown in Table 3-5.

Table 3-5 Issues Involving Technology and Automation /28

Process	Type of Equipment	Technological Issues	Automation Issues
Formation of Anti-reflection film	CVD equipment	Increase batch processing figures (Enlarge CVD equip.)	Automated movement of angled substrate
Photographic Plate	Exposure equip. Resist-coating equipment Image equipment Baking equipment Dicing saw	Optimizing alignment mark	Automated movement of angled substrate Automatic alignment technology
Etching anti-reflection film	Plasma etcher	Increase batch processing figures (Enlarge equip.)	Automated movement of angled substrate
Etching AlGaAs layer	Etching equipment	Increase batch processing figures Uniform etching	Automated movement of angled substrate Develop automated etching equip.
Metallizing	Sputter equip. Electronic beam deposition equip. Sintering oven	Increase batch processing figures	
	Ag etching equipment	Uniform silver coating etching	Develop automated etching
Dicing	Dicing saw	Increase speed	Automated alignment technology
Adhesion of Cover Glass	Cover glass adhesion equipment	Uniform thickness of adhesive resin	Must study each according to assembly method
Inspection	Measuring equip.		
	Exterior viewing inspection equipment	Mechanical detection of microcracks	

3.3 Large-Area Cover Glass Adhesion Technology

/29

Anticipating problems in the transition from cover glass adhesion technology for the 2 x 2 cm size to technology for the 2 x 4 cm and 4 x 4 cm sizes, a study of surface enlargement was made. The points listed below are considered the main issues involving adhesion of cover glass to solar battery cells.

1. Control of adhesive agent's thickness
2. Control of cell and cover glass positions (avoiding mismatches.
3. Control of the occurrence of bubbles.

These three points were studied with the assumption that surface enlargement might cause problems.

1. Control of the adhesive agent's thickness

   The amount currently applied to 2 x 2 cm cells can be properly controlled, and the control of thickness seems basically unrelated to the surface area, so the method is adequate for large surfaces.

2. Control of cell and cover glass positions

   Control of the cover glass position in relation to the cell is related to glass shape (square or rectangular) but unrelated to the surface area. Therefore, the tools used now could be used for large-area glass.

3. Control of occurrence of bubbles

   When air is not present in the adhesive agent, bubbles are thought to be due to the inclusion of air when the glass is placed, or the trapping of air when the adhesive is being spread.

When air has been included, it can be eliminated with a vacuum process while the adhesive is hardening, though it is thought that, with large surfaces, the bubbles near the center will need to move over a greater distance and may be difficult to eliminate.

Consequently, operating conditions which make the formation of bubbles unlikely have practical importance, and the multi-point application process currently used for the 2 x 2 cm cells could be extended through studies of number and placement of application points until this and the other problems mentioned above are solved.

Given the studies of the problems mentioned above, there seem to be no special problems involved in cover glass adhesion for large-surface GaAs solar battery cells.

4. Technical Studies on Cell Assemblies /30

The GaAs cells (2 x 2 cm) currently being produced for the CS-3 were tested for thermal stress and mechanical stress which would be encoutered at each stage of panel operation. Results were analyzed and GaAs capacities compared.

The results indicated no basic problems with the use of GaAs solar battery cells in space stations. In the future, however, one can imagine that each phase of panel assembly and deployment will involve mechanical and thermal stress, and a study of the reaction to this stress is necessary.

Furthermore, in order to verify the results of the analysis we think it necessary to construct a portion of a panel and subject it to the experiments shown in Table 4-1.

Table 4-1 Experiments to Evaluate Mechanical and Thermal Stress Applied to the Cells

STAGE	STRESS	EVALUATION EXPERIMENT
Panel assembly	Mechanical and thermal stress from connection	Panel assembly experiment
Panel transportation	Vibration; impact stress	Vibration experiment (sine wave, random vibration)
Blast-off	Vibration (internal, resonance, impact, thermal stress	Impact experiment
Operation	Thermal stress (day-night cycle)	Heat shock experiment

Considering resistance to environment apart from mechanical and heat stress led to the conclusion that there is no relation between this resistance and cell size. Therefore, results of experiments performed on the GaAs solar battery cell (2 x 2 cm) currently in production for the CS-3 were applied, and there are no special technological problems with this area.

5. Studies on Procuring Materials /31

Studies were made on the availability and delivery time for materials essential for the GaAs cell for use in space stations -- the GaAs single crystal substrate, metallic gallium Ga and arsenic As. Results appear below:

1. Single crystal GaAs substrate

The quantity of GaAs single crystal substrates (4.5 x 50 cm, thickness 310 μm) needed to make 1,800,000 2 x 4 cm GaAs cells for use in the space station represents a surface area of 4,000,000 cm^2. Compared to this figure, 1985 production of single crystal GaAs substrates for use in laser diodes, infrared LED and GaAs IC, was about 3,000,000 cm^2. The specifications for substrates used in laser diodes and GaAs IC are somewhat stricter that those for GaAs solar battery cells, so they have a rather low level of monocrystalline properties. Considered in terms of processing equipment currently available, the production capacity needed for GaAs solar cells implies an increase of 7 or 8 times. It is, however, not possible that all available equipment would be used for this purpose, and so we project that an investment of 30 billion yen for equipment will be needed to make this project operational. Furthermore, since it will be necessary to introduce slicing machines, wrapping machines, etc., a year will be needed to fully develop production capacity for this project.

2. Metallic Gallium

The market for metallic gallium is highly speculative, and stable production is difficult to attain. However, based on the situation in 1984 and 1985, supply and demand should be nearly equal.

Production for 1985 was estimated at approximately 50 tons (includes 12 tons from recycling). Sources are shown in Table 5-1.

Table 5-1 Supply of Metallic Ga in 1985 /32

Source of Supply	Supply (Tons)
Japan (Sumitomo Chemicals, Towa Mining	13
France (Rosu Puran*)	7
West Germany (Ingaru*)	7
China	7
Hungary	3
Czechoslovakia	1
Recycling	12
[*Transliterations]	

Viewed from the standpoint of demand, Japan accounts for 30-35 tons of consumption while 80% of the rest is used by America and 20% by Europe.

Metallic Gallium is contained in Cu, Zn and Aluminum bauxite and is produced as a by-product of processing these metals. Aluminum bauxite is particularly important for this type of extraction and, based upon current production levels of aluminum, an estimated 100-200 tons of gallium could be produced.

Highly refined gallium could be produced at a level of about 100 tons, about twice the current production level. Furthermore, the refining equipment represents much lower costs than extraction equipment, so no problem is anticipated in this area. The total amount of gallium needed for the manufacture of 1,800,000 2 x 4 cm GaAs solar battery cells for use in the space station is 53-54 tons. For a three-year production period, this would mean production of 17-18 tons per year. This represents 30-40% of 1985 production and, given the high recovery rate (approximately 90%) for gallium used in Liquid Phase Epitaxy, which constitutes 50% of the demand, and given Japanese manufacturers' plans for increased production and America's plans to join in production, securing an adequate supply is well within the realm of possibility. The market for gallium, however, is highly speculative, so methods of supply which counteract possible sharp price increases should be seriously considered.

3. As /33

Given current levels of Arsenic production in Japan (60 tons annually) and the current level of demand, there should be no problem whatsoever with supply.

Studies of items (1), (2) and (3) above have led to the conclusion that no great problem exists is supplying the material needed for 1,800,000 2 cm x 4 cm GaAs solar battery cells for use in the space station.

Table 5-2 is based upon the essential points set forth above.

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Table 5-2

STUDY OF PROCUREMENT OF SOURCE MATERIALS FOR PRODUCTION OF GaAs SOLAR CELLS

SSNRE001

		Total Consumption (Ton)	Consumption in 1st year of the productin (Ton/year)	Consumption in each following year (Ton/year)	World-wide production capacity in 1985 (Ton/year)	Remarks
GaAs Substrate (4.5cm×5cm)		7 ~ 8	~ 3	~ 3	~20	Lead time (preparation of facilities and production increase of GaAs substrate) will be around one year.
Ga	Virgin Ga	27~28	13~14	6 ~ 7	30~40 *3	Nowadays, the demand and supply of virgin Ga are balanced. But, the amount of Ga in bauxite produced in 1985 is 100~200 tons, and so if the investment for facilities of extracting Ga is carried into effect, production capability of Ga will be enough for this project. The expense of facilities for purifying Ga is less than that for extracting Ga. It will be possible to increase recycling capability after preparatory stage of one year.
	Recycled Ga	25~26	3 ~ 4	10~11	~10 *3 (30~40) *2	
	Total	52~54 *1	16~18 *1	16~18 *1	40~50 *1	
As		25~26	8 ~ 9	8 ~ 9	80~90	There is no problem in the amount of As.

*1. The consumption of Ga contains consumption for melt of LPE and that for substrate.
*2. The estimate of production capacity
*3. The amount of production in 1985

6. Studies on Production Facilities

/35

Studies were made on the equipment, necessary space, expenditures and lead time needed for production facilities. The results are shown in Table 6-1.

At least 2 years' lead time is needed for a large number of LPE devices, exposure devices, dicing saws and electron beam deposition devices, including time for design. Other equipment needed can be procured within the 2-year period. Equipment costs, including development and unanticipated elements, are projected to total something on the order of (to be determined) yen. Space requirements, including working space, are on the order of 4,000 m^2.

As indicated above, a two-year lead time for production equipment, including development, should present no problem.

Table 6-1 Approximate Figures for Main Equipment /36

Main Process	Main equipment	Units Needed	Space Needed	Time needed
Crystal epitaxy	LPE equip. Evaluation equip.	12 1	900 m^2	2 yr 1 yr
Formation of anti-reflection film	CVD equip.	4		1 yr
Photographic plate	Exposure equip. Resist-coat. equip. Image equip. Baking equip. Dicing saw	11 5 5 5 12	250 m^2	2 yr
Etching anti-reflection film	Plasma etcher	6	630 m^2	1 yr
Metallizing	Sputter equip. Electron beam equip. Sintering oven Ag etching equip.	5 10 2 5		2 yr
Dicing	Dicing saw	9	590 m^2	1.5 yr
Cover glass adhesion	Adhesion equip.	1		1.5 yr
Inspection	Measuring equip. Exterior viewing inspection equip.	1 1		1.5 yr
Chemical processing, etc.	Cleaning bench, etc.	---	1,630 m^2	1.5 yr
TOTAL			4,000 m^2	

7. Cell Cost Analysis

Cell cost calculations, based on the study results found on pages 2, 3, 5 and 6 [in the Japanese original] are as follows:

Development costs	To be determined
Capital investment	To be determined
Cell unit cost:	
2 cm x 4 cm cells	To be determ./cell
4 cm x 4 cm cells	To be determ./cell

Cell unit costs are based on the following assumptions:

1. Purchase price for GaAs substrates will be 80% of the current price.
2. Purchase price for Ga will be an extension of the present situation.
3. Standard operation time, given the effects of volume production and automation, should be 50% of the present value.
4. Within the scope of experimentally determined standards, no external inspection standards will be established for aspects which do not affect electrical properties or reliability.
5. Apart from items subject to external inspection, cell specifications will conform to NASDA-1013-301. For example, electric output maintenance during 10 years in stable orbit (1 MeV electron ray 1×10^{15} equivalent) should be 78% TPY, etc.
6. Cell assembly is assumed to be soldered with cover glass.

Furthermore, in adapting the GaAs solar battery to use in space stations, detailed data on radiation in orbit (types, ray strength, etc.) and life expectancy values were used as a basis for optimizing design and making detailed specifications, which were the basis for cost calculations. If these values were revised, this could results in a cost reduction.

8. Studies on Cell Development-Supply Plans /38

A study was made on plans for technological development, preparation for production, production and shipping of the GaAs solar battery cell for use in space.

8.1 Plan for technological development

(1) Area of technological development

(i) Technology for LPE capacity enlargment

Technology for doubling the current LPE processing capability (one run of epitaxial growth produces 50 wafers, 4.5 x 5.0 cm) needs to be developed.

(ii) Technology for manufacturing large-area cells

Test manufacture and experimental evaluation of large-area cell manufacture are needed.

(iii) Technology for volume production processing of cells

Volume processing techniques and equipment must be developed.

(2) Technological Development Period

Two years will be needed for technological development, equipment development and evaluation for reliability.

8.2 Preparation for Production

(1) Supply of Materials

One year will be needed to procure GaAs substrates and metallic gallium.

(2) Establishing Operations at Production Facilities

Two years will be required for the production facilities to become operational.

(3) Securing Space

One year will be needed to secure land and construct the plant site.

(4) Recruiting Personnel

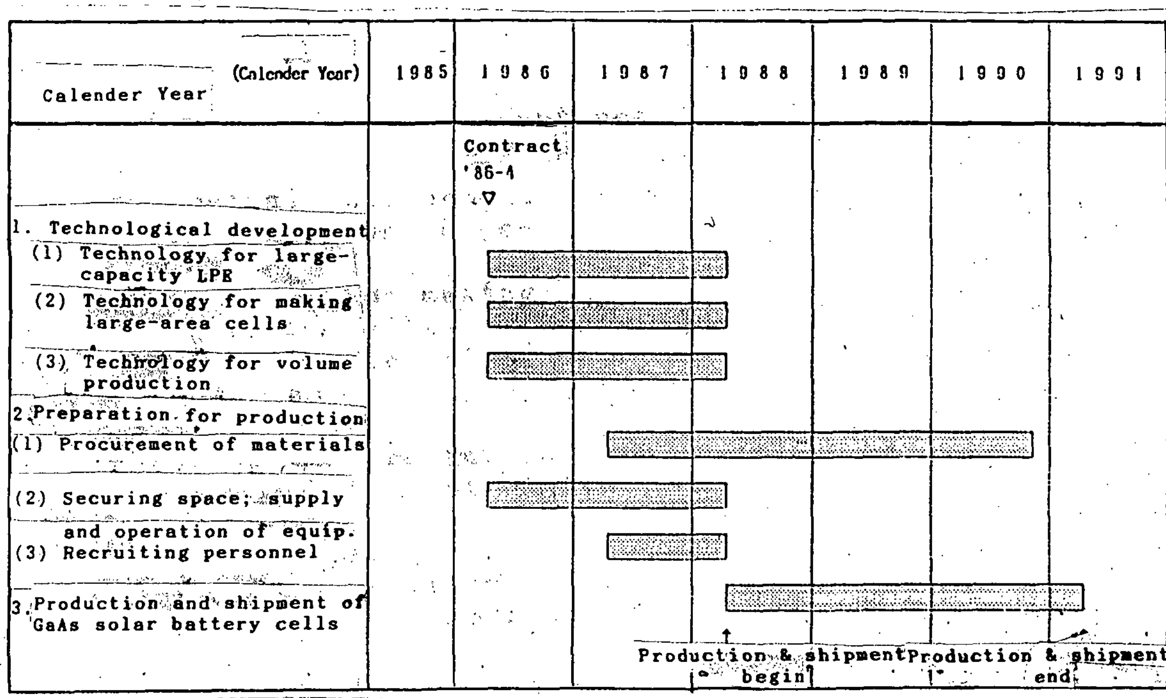
Recruiting personnel (including practical training) will require one year.

8.3 Cell Production and Shipment

Production and shipping of the 1,800,000 GaAs solar battery cells will begin in the third year after receipt of the contract and require three years to carry out.

The bases of plans for technological development and all provision are set forth in Tables 8-1 and 8-2.

Table 8-1 Plan for Development and Provision of the GaAs Solar Battery Cell for Use in Space Stations (Schedule based on initiating contract in 1986) /39



Table

8-2 MANUFACTURING PLAN OF GaAs SOLAR CELL FOR SPACE STATION

1.	PRODUCTION SCALE	: 1,800,000 CELLS/3 YEARS (CELL SIZE: 2cm × 4cm)
2.	PRODUCTION LINE AREA	: 3,000~5,000 m^2
3.	WORKER AND ENGINEER	
	WORKER	: 300~500 PERSONS
	ENGINEER	: 25~35 PERSONS
4.	LEAD TIME FOR GaAs SUBSTRATE	: ONE YEAR
5.	LEAD TIME FOR PRODUCTION EQUIPMENTS	: 2 YEARS
6.	TERM OF PROCESS IMPROVEMENT	: 2 YEARS
7.	PRODUCTION START	: ~3 YEARS AFTER CONTRACT
8.	BEGINNING OF DELIVERY	: ~3 YEARS AFTER CONTRACT
9.	DURATION REQUIRED FOR PRODUCTON OF TOTAL CELLS	: ~3 YEARS

9. Conclusions

/41

In response to the plan for a manned space station being promoted by America, Japan has proposed that GaAs solar battery cells be included in the space station to enhance electricity generating capability.

This report, which constitutes one part of the proposal, is based on the results of investigative studies concerning the applicability of GaAs solar battery cells to space stations.

The purpose of these investigative studies was to deal with the essential technological and manufacturing issues and provide a cost analysis for the materials evaluated in terms of suitability for use in space stations.

These studies were carried out based on Japan's successful development during 1982-1983, and current development and production of GaAs solar battery cells, superior production technology and development of the large-surface cells needed in space stations.

The specific issues dealt with in this report include:

(1) Studies on cell size
(2) Studies on manufacturing tehcnology
(3) Technical studies on cell assemblies
(4) Studies on procuring materials
(5) Studies on production facilities
(6) Analysis of cell costs
(7) Studies on cell development-supply plan

The essential points concerning the study and results are as follows:

(1) Studies on cell size

Studies on cell size were made on the 2 x 2 cm cell currently in production for use in the CS-3 and comparative projections were made concerning the electrical properties and property retention of cells measuring 2 cm x 4 cm. Furthermore, electrode pattern designs developed for 2 cm x 2 cm cell were used to design patterns for larger cells, and comparisons and observations concerning conversion efficiency were made.

The results of this led to the conclusion that, in terms of electrical properties and electrical property retention, among the cell sizes currently under consideration, the 2 cm x 4 cm size is superior to the 4 cm x 4 cm size.

(2) Studies on manufacturing technology /42

Comparative studies of technologies applicable to large-area, uniform epitaxial growth involved an overall comparison of the LPE and MO-CVD methods in terms of volume production, parameter control, cell properties, equipment costs and scheduling, etc.

This revealed the LPE method to be superior to the MO-CVD method under current conditions.

Furthermore, since stages after epitaxial growth in the processing sequence did not require changing the substrate size, the method currently used was clearly shown to be applicable, and issues involving mass production technology such as increased batch size for batch processing, improved automation, etc., were clarified.

Still further, studies on the adhesion of large-area cover glass indicated the possibility of improving cover glass adhesion technology currently in use without any special problems.

(3) Technical studies on cell assemblies

Cell assembly structure for use in space stations seems to present no special problems, though experiments must be done to evaluate the mechanical and thermal stress which may occur at each level, from assembly itself to actual operation.

(4) Studies on procuring materials

A study was made on supply of the main materials: single crystal GaAs substrates, metallic gallium (used in liquid phase epitaxy and in the GaAs substrates) and arsenic (used in the GaAs substrate).

Results were such that, for this project, lead time of a year and an equipment investment of (to be determined) yen were clearly indicated.

Furthermore, requirements for increased production of metallic gallium are considered attainable in terms of quantity, but since the gallium market is highly speculative, a suppy mehtod which would offset sharp price increases needs to be seriously considered. On the other hand, provision of adequate quantities of arsenic presents no problem whatsoever.

(5) Studies on production facilities

Expenditures of (to be determined) yen for equipment, (to be determined) yen for buildings, for a total of (to be determined) yen in capital investment will be required, along with a working space of 4000 m^2.

(6) Cell Cost Analysis

Cell costs (exluding fixed costs for equipment and development)

2 cm x 4 cm cells:	To be determined/cell
4 cm x 4 cm cells:	To be determined/cell

Capital investment (including buildings):	To be determined
Development expenses:	To be determined

Figures could be reduced if the data on the radiation environment in stable orbit (types, ray quantity, etc.) and life-expectancy values, on which cell design and specifications are based, are revised.

(7) Studies on Cell Development and Supply

Issues concerning technological development include:

- Technology for enlarging LPE volume
- Technology for mass-processing cells
- Technology for manufacturing large-area cells.

The period requied for technological development is two years.

Further, time requirements involving preparation for production are as follows:

- Procuring materials:	1 year
- Space and facilities/ installation:	2 years
- Recruiting and deploying personnel	1 year

Production and shipping will start three years after receipt of the contract and require three years to carry out.

The above results indicate no major basic problems with technology and production. Finally, an overall decision concerning cost and scheduling from the standpoint of the space station plan is needed, though the GaAs solar battery cell is considered completely applicable to use in the space station.

Furthermore, our country [Japan] is a leader in development of single crystal GaAs, with a market share of 60%, and a good record in designing and developing the 2 x 2 cm GaAs solar battery cell for use in space.

Given its high conversion efficiency, radiation resistance, and the superiority of its temperature-related properties, the GaAs solar battery cell can make a great contribution to the electricity generating capacity of space stations, and should be adopted for that purpose. /44