TPK

Solar Systems Inc.

GALLIUM ARSENIDE SOLAR CELLS FOR SPACE APPLICATIONS

BY

R.E. THOMAS

AND

C.E. NORMAN

FINAL REPORT

Submitted: 30 June 1983

DSS Contract No:
12ST.36001-1-2-2402

4A-149 BENTLEY AVENUE, NEPEAN, ONTARIO, CANADA K2E 6T7 (613) 225-4403

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EXECUTIVE SUMMARY

This report presents the results of a survey of the present status and future developments in space solar cells from both a technological and market point of view. These results are then extended to propose a development scenario which would realize GaAs solar cells in time to be flown in a satellite by 1988. This would then put Canada in a position to capture a reasonable portion of the space cell market in the decade between 1988 and 1997, and would extend its ability to contract for larger percentages of the total satellite market.

The survey of the technological status of space solar cells shows that silicon solar cells currently dominate the market, and will continue to do so for some time. New technologies are slow to gain acceptance until reliability is adequately guaranteed. Hence only conventional, relatively thick (200 μm) silicon cells are flown despite the readiness or near readiness of ultra-light high efficiency silicon cells with high specific power weight ratios. In terms of development potential silicon is seen to be approaching its limit, so the hope for larger power satellites lies in Gallium Arsenide (GaAs) cells, which are being used in 1983 for the first time to provide the power for a complete satellite. The directions in which GaAs or AlGaAs/GaAs cells will progress are detailed, showing the prospect for 16-18% (AM0 efficiency) cells in the short term, 20-24% in the medium term and greater than 30% in the long term. This should be contrasted with the 18% AM0 limit predicted for silicon cells.

On the basis of the survey it is concluded that any Canadian company entering the space cell market should develop a GaAs cell. A technology based on Metallo Organic Chemical Vapour Deposition (MOCVD) is selected as the direction to follow, and a development scenario proposed to realize 16% efficient cells which could be space flown late 1987 or early 1988. This development is expected to cost of the order of $4.8 M Canadian including purchase of equipment and establishment of facilities.

Assuming the availability of a space-qualified GaAs cell by 1988, the proportion of the space cell market which might reasonably be expected to be captured by the Canadian manufacturer between 1988 and 1997 is estimated. Then, recognizing the inevitable delays in acceptance, an attempt is made to predict the actual dollar value of the market which would be captured by a cell with its first space flight in late 1987 or early 1988. The former is estimated to be $69.25 Million (1980 US dollars), while the latter is predicted at $30 Million (1980 US dollars). With this value and the considerably higher spin-off value for the Canadian Aerospace industry, it recommended that Canada act quickly to fund a GaAs space cell development aimed at first flight in late 1987 or early 1988.

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1.0 INTRODUCTION

1.1 Background and History

The first solar cell array to be used in space was incorporated into Vanguard I, the second U.S. earth satellite launched on March 17, 1958. The array consisted of six panels made up of 18 p on n silicon solar cells of 2 x 0.5 cm size mounted to the outer surface of an approximately spherical spacecraft body. The 10% efficiency cells in the array provided less than 1 watt of power for more than 6 years. From this modest beginning, the USA launched over the next 20 years 791 additional satellites most of which derived their power from silicon solar cells [1]. This number is continually being added to with ever more countries participating in the satellite business.

Accompanying the increase in numbers of satellites has been an increase in size and complexity of the solar arrays. While early satellites generally had less than 100 watts requirement, this has grown to the point where current requirements are between 1 KW and 1.5 KW, and still increasing. Selected satellites have, of course, been launched with higher power arrays. The largest U.S. solar array flown was on Skylab I, launched on May 14, 1973, into near earth orbit. Skylab carried two separate solar array systems, one for the orbital workshop consisting of two deployable wings together carrying approximately 148,000 of 2 x 4 cm n-p silicon solar cells for more than 6 KW of power in orbit (one wing was lost in flight however so this power was halved). The second array for the Apollo Telescope mount consisted of four wings with 123,000 2 x 2 cm cells and 41,000 2 x 6 cm cells for a total power in orbit in excess of 10 kilowatts.

The array power in Skylab can be considered modest in light of plans for further spacecraft. As an example [2], the NASA-sponsored Power Extension Package (PEN) to be used in conjunction with the space shuttle for extended missions will require an array generating 25 KW of power at beginning of life. The Solar Electric Propulsion System (SEPS) will require 38 KW beginning of life power. These would themselves pale into insignificance should the Solar Power Satellite (SPS) as proposed by Peter E. Glaser [3] become a reality. Such a satellite would generate 5 GW of electricity to be beamed to earth via microwave.

Accompanying the growth in power requirements has been the need for improvements in solar cell conversion efficiency. This improvement in conversion efficiency directly impacts on such parameters as weight, cell area, and stowed volume. Equally important is the requirement for the cells to have a good tolerance to high energy proton and electron irradiation in near earth orbits. (Required end of life power/efficiency directly affects the weight, area and stowed volume of cells which must be placed on the satellite).

The above factors have over the years driven the development of space solar cells. In the early days of space application, a selection of technologies was available. In 1954, Bell Telephone Laboratories produced the first practical single crystal silicon solar cell with 6% efficiency [4]. In the same year, 6% efficiency cadmium sulphide solar cells were reported

[5]. This was also the year in which the photovoltaic effect was reported in gallium arsenide [6]; one year later efficiencies of 1 to 4% for small polycrystalline devices and 6.5% for cadmium diffused GaAs wafers were reported. The silicon cell advanced more rapidly in terms of efficiency and cost, and from 1958 onwards dominated the space cell market. Cadmium sulphide solar cells could not compete in terms of efficiency stability and reliability, so never have become a force in either terrestrial or space applications. GaAs cells continued to advance, and by 1962 2 cm^2 p on n diffused cells had been achieved with typical 8.5% efficiency, and a maximum as high as 13-14%. By 1963, silicon cells were typically being prepared at a mean AMO efficiency of 11%, with peak efficiencies of 13% and good radiation resistance for n on p structures. GaAs cells were of the same order of efficiency, but found to degrade more with low energy proton irradiation, particularly in the blue part of the spectrum, and were much more expensive. Consequently in 1964 work on GaAs cells in the U.S. virtually ceased.

Little progress in cell development was made until 1972, when after a detailed study of the factors determining efficiency was conducted, the silicon "violet" cell was introduced [7], with shallow junctions, low series resistance and better radiation resistance. The advances have continued until at present, the prospects for further increases in efficiency and improvements in radiation tolerance are negligible. Hence as satellites increase in their power requirements, new space solar cell technologies are necessary. Accordingly emphasis has once again shifted to the GaAs cell because of its superior bandgap match to the solar spectrum - hence higher efficiency, hence the prospect for higher power per unit weight/volume/area. The GaAs cell has not remained static at 1964 levels, but has advanced to the point where 16-18% efficiencies can be readily produced based on the AlGaAs/GaAs structure first reported by Russian workers in 1971 [8]. The AlGaAs layer provides a window which significantly reduces surface losses.

The present assessment is that silicon solar cells have approached their limit in terms of power/weight or power/area ratio. Further advances in space cell technology must be achieved through other materials, in particular GaAs. Consequently, the GaAs cell is the major focus of this study.

1.2 Objectives of Work

Canada has been active in the satellite field since the launching of Alouette I on September 29, 1962. In the 21 years since, Canada has built up a world-class space industry with plans to continue in the development of communications satellites. It is precisely in this area of communications that Canada has, and must maintain, a technological lead. The necessity to participate in all aspects of satellite development, production and launching requires that facilities are in place in Canada to handle each of these areas. SPAR Aerospace represents the cornerstone of a space industry in Canada - their ability to bid successfully for the manufacture of solar blankets is a recent indication of the progress being made. However, for Canadian satellites as well as any other satellites in which

Canada participates, the solar cells are made by a few suppliers in the USA, Europe or Japan. The questions which must be asked are:

1. Would Canada be in a more competitive position to win satellite contracts with a Canadian space cell manufacturer available? and
2. If a Canadian space cell manufacturer were to emerge, what should be the cell technology offered?

This study was commissioned to answer these questions. The former was to be answered by means of a market study to ascertain the total space cell market for the 10 year period 1982-1992, and to estimate that market which Canada has a chance to capture. The latter question was to be answered by means of a thorough survey of present and future space cell technologies. Both tasks were carried out through a detailed literature survey and consultations with a range of individuals and organizations. (A partial list of those consulted is given in Appendix A.)

From the beginning it became clear that it would be difficult to enter the space cell market with a "me too" silicon cell technology. Consequently it was specified that GaAs technology would be studied in detail. As noted in section 1.1, this technology offers the greatest prospect for future development to keep pace with the expanding power requirements of the satellites yet to be launched. The studies reported here show that this area is rapidly evolving, but is not yet dominated by any companies. Accordingly if Canada is to develop a competitive domestic production of space solar cells it must be in this area.

1.3 Outline of Report

With the development of the space cell placed in a historical context in this chapter, the rest of the report is devoted to a variety of tasks. Chapter 2 presents a detailed survey of the current status of silicon space solar cells. This serves as the basis against which to measure progress in GaAs solar cells. The present state-of-the-art GaAs solar cell technology is also presented in Chapter 2, as well as a preliminary look at the directions of the technology. A comparison is made between GaAs and Si cells to show the benefits offered by GaAs.

Future directions for GaAs space cells are explored in Chapter 3, and the leading technology presented. This technology, viz., MOCVD, is shown to be the one which must be exploited if Canada is to enter the space cell market. A detailed development scenario, including preliminary cost estimates, is presented in Chapter 4 to show how space qualified GaAs cells might be achieved in time for flight on MSAT to be launched in 1988.

No cell development can be properly considered without serious attention being paid to deployment in arrays. Accordingly Chapter 5 considers use of the GaAs cell in arrays, with respect to wraparound contacts, coverglass interconnects, shadowing effects, modification needed for blanketing, etc. It is evident from this consideration that close co-operation will be necessary between the potential cell manufacturer and the constructor of the array.

Chapter 6 presents the results of the market study directed at determining whether the market is sufficient to justify Canada becoming a space solar cell manufacturer. Included is an assessment of the impact such a capability would have on Canada's ability to capture a larger share of world satellite markets.

Finally conclusions and recommendations are presented in Chapter 7. Included in the recommendations is that

(a) Canada fund a company to develop GaAs solar cells prepared by the MOCVD technique, and

(b) that a timetable be selected to allow arrays of these cells to be flown on MSAT in 1988.

2.0 CURRENT STATUS OF SPACE SOLAR CELLS

2.1 Introduction

This chapter reviews the current status of space solar cells. It begins (section 2.2) with a review of silicon space cells, which dominate the space market at this time. The state-of-the-art is defined, as well as the reality of cells actually employed vs those waiting in the wings. This assessment is based on a literature search as well as discussions with selected individuals/groups. Future directions for silicon technology are briefly discussed.

Section 2.3 discusses the current state-of-the-art for GaAs space solar cells, and shows future goals for this technology. Section 2.4 then compares GaAs and Si technologies with respect to radiation resistance, cost, weight, area and power. It is shown that GaAs cells offer the most prospects for future development.

2.2 Status of Silicon Space Solar Cells

Considerable progress has been made in recent years in developing silicon solar cells for space use [9]. This includes improved performance in terms of radiation resistivity and higher power/weight ratio (by means of improved efficiency, improved anti-reflection properties and by ultra-thin cells). However, despite these improvements, the cells actually used in space are still of the conventional types which are relatively thick and use standard add-on anti-reflection coatings [10]. This is attributable to the very conservative nature of the space industry, which will institute changes only if the risks are minimal. Development continues, however, and silicon cells are not being pushed towards the limits achievable with this material. The following sub-sections discuss some of these developments to indicate the current status and future directions for silicon space cells.

2.2.1 Conventional Silicon Cells

A number of suppliers of space-qualified silicon solar cells exist. These include Spectrolab, COMSAT, OCLI and Applied Solar Electric Corporation (ASEC) in the U.S., AEG Telefunken in Europe and Sharp in Japan. An examination of their cells indicates that they all supply a similar product. Typical parameters are as tabulated in Table 2.1. Variations exist from manufacturer to manufacturer, but generally the product is essentially the same, providing a reliable source of energy in current satellites. Texturizing of the front surface to improve anti-reflection properties is noted as being optional. In general, few texturized cells are actually used in space, since the extra energy absorbed by the cell means it operates at a higher temperature (up to 15°C higher [10]). The resulting reduction in voltage output at the higher temperature offsets the increased current obtained from the texturized cell. An optional wraparound contact is available from some suppliers, but the extra cost (see Chapter 5) means that is is not used to any extent.

State-of-the-art silicon cells exhibit considerably better performance, but to date are still not employed in

Table 2.1: Typical Conventional Silicon Space Cell

PARAMETER	TYPICAL VALUE
Substrate Resistively	2 ohm-cm for LEO 10 ohm-cm for GEO (up to 20 ohm-cm)
Substrate Type	P
Crystallinity	Single Crystal
Orientation	(100)
Thickness	200μm Typical, up to 300μm
Junction Depth	0.15 to 0.3μm
Front Contact	Ti-Pd-Ag
Back Contact	Al-Ti-Pd-Ag or Cr-Pd-Ag
Back Surface Field	on Majority
Back Surface Reflector	on Some Cells (Al layer)
Typical Size	2 x 2cm, 2 x 4cm and 2 x 6cm (some 5 x 5cm and 6 x 6cm)
Anti Reflective Coating	$Ta_2 O_5$ Texturizing Optional
Typical Efficiency (AMO)	12-13%

satellites. Some of the advances over the conventional cell are detailed in the next sub-sections.

2.2.2 The State-of-the-Art in Si Space Cells

NASA, one of the largest users of space solar cells has set out four goals for future space cells: higher efficiency, longer life (improved radiation resistance), improved specific power (watts per kg of array weight) up to 300 W/kg and lower costs (from over $500/W at present to $30/W if possible [9, 11]. In an attempt to improve their product to meet these goals, silicon space cell manufacturers have focussed their efforts in the following areas:

- larger area cells
- thin and ultra-thin substrates
- improved back surface fields (BSF)
- texturized front surface
- back surface reflecting (BSR) contacts
- reduced contact grid area
- improved AR coating

The result of these efforts has been improvements in cell performance. The structure and performance of the "state-of-the-art" cells available from the different manufacturers are remarkably similar [12, 13, 14, 15]. A typical fabrication process for these thin cells is outlined in Table 2.2. The performance of the cells varies somewhat depending on the actual substrate thickness and whether or not texturizing is used. Typical AM0 cell parameters are open circuit voltage around 590 mV, short circuit current about 38 mA/cm^2, fill factor around

Table 2.2: Simplified processing for a representative 'state of the art' Si solar cell.

- starting substrate p-type 10 Ω-cm
- thin wafers to 50-100 μm by chemical etch
- front surface texturizing etch (optional)
- high temperature phosphorous diffusion (junction depth about 0.15 μm)
- p+ back surface field diffusion from Al paste
- evaporate back contact (Al-Ti-Pd-Ag)
- laser scribe into final size (2 x 2cm)
- evaporated front metal (Ti-Pd-Ag)
- define and etch grid pattern (photolithography)
- evaporate antireflection coating ($Ta_2 O_5$)
- test cells

77%, giving an AMO efficiency of approximately 13% [12]. The average efficiency for production cells varies from 12.5-13.5% for 50 μm thick cells without texturizing [13, 14], to 14.5% for texturized cells. There is considerable spread in the efficiency with many cells going over 15% [14].

Using these cells, the 300 W/kg goal can be met and possibly exceeded [9]. The thin cells also exhibit improved resistance to ionizing radiation so that their useful life in space will be somewhat longer. The main problem with the thin cells is a low yield; usually less than 50%. The primary cause is cracking of the fragile wafers during handling. This becomes worse as the cells are made larger. Thus, only 2 x 2 cm and some 2 x 4 cm cells are made regularly. Because of this size limitation, the more complex processing and the low yield, the cost goals are not being met.

2.2.3 The Future of Silicon Space Cells

There are still a few improvements that can be made in silicon space cells [16, 17, 18]. One factor that needs improving is the open circuit voltage. With the 10 Ω.cm substrates currently being used to achieve good radiation resistance, V_{oc} is limited to about 600 mV. Values up to 700 mV may be possible through the use of low resistivity material and the reduction of surface recombination losses [18]. It is widely claimed that an ultimate goal of 18% AMO efficiency is achievable for silicon cells [18]. Whether the process required to attain this will be cost-effective and whether the high efficiency can be maintained in production are two questions which will have to be answered.

Considerable effort is being spent on improving the thermal performance of silicon cells by adjusting their overall absorption of the incident sunlight [16, 17]. If the cells can be made to operate a few degrees cooler in the vacuum of space, then their output power will be greater. This can be achieved by either reducing the amount of light absorbed or by increasing the emissivity of the array for long wavelength radiation. In both cases, the cell and its coverglass must be considered together [17]. Reducing the absorption must be done carefully lest the cell efficiency be reduced at the same time [16]. The best solution is to reflect those wavelengths which cannot be used by the cell; i.e. photons with energies less than the bandgap of silicon (1.1 eV). This can be done either with a selection reflecting coating on the coverglass or with a reflecting contact on the back surface (BSR) [16, 17].

Two innovations in silicon solar cell designs deserve mention. One is the gridded back contact in which the back contact metal is put on in a grid pattern like the front contact rather than covering the entire back surface [19]. This has been found to reduce the back surface recombination losses and improve the absorption of photons with energies close to 1.1 eV. The result is a 5-8% increase in short circuit current for some types of thin cells [19].

The second innovative cell design is the vertical multijunction cell (VMJ) [20, 21]. In the VMJ cell, the junction is perpendicular to the cell surface rather than parallel to it.

This is usually achieved by selectively etching narrow slots deep into the substrate before making the junction diffusion. The junction then follows the reentrant surface of the slots [80]. The purpose is to reduce the distance that photogenerated minority carriers have to diffuse in order to reach the junction and be collected. The deep grooves also act like a texturized surface to reduce reflection losses. The result is an improved short circuit current and better radiation resistance [22]. Although it has been six years since the VMJ cell was demonstrated, it has not been brought out of the laboratory. The reason is probably that the process is viewed as being too involved or the structure too fragile for large scale production and use in space.

Rather than try to further improve the efficiency of silicon space cells at even higher fabrication costs, there have been some attempts to greatly reduce the cost of the cells, usually by sacrificing efficiency. Such devices would only be cost effective for very high power satellites where the solar cell cost is a major component of the mission cost. ASEC has approached this problem by producing large area (25-40 cm^2) solar cells [23]. The cells use 200 μm 2 Ω.cm substrates and low cost processing. Typical efficiencies are 12.5-13% (AMO 28^{o}C) and ASEC expects them to cost $30-45/watt in large numbers. The cells are space qualified and could be improved by adding BSF and BSR contacts. To further reduce space cell costs, it has been suggested that modified terrestrial cells be used [24]. The specific power of the array (W/kg) could of course suffer since terrestrial cells have low AM0 efficiencies.

In summary, silicon space solar cells are now a mature product, making use of advanced techniques to achieve improved performance. As these techniques are adopted, however, it becomes increasingly harder to continue raising the efficiency. It is generally agreed therefore, that silicon cells are approaching their limit and that no further major improvements in efficiency can be expected. Thus, cell manufacturers are now concentrating on decreasing the weight, increasing the radiation resistance and reducing the cost of their product. In any case, silicon cells will doubtless continue to be the prime source of power in space for many years to come.

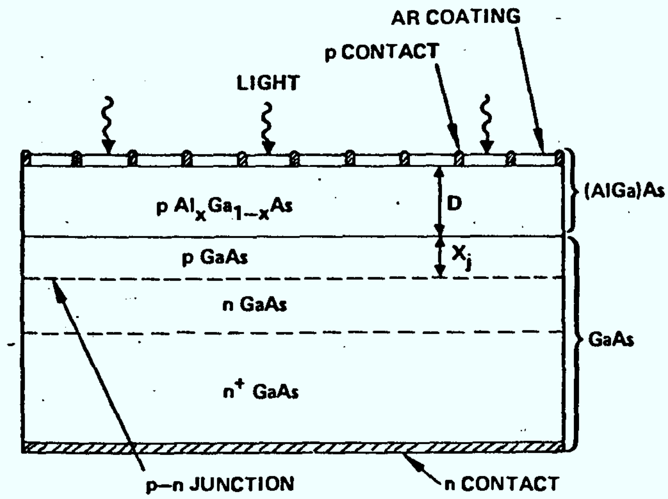
2.3 GaAs Space Cells

Gallium arsenide has always been recognized as a good material for solar cells. Its direct bandgap matches the solar spectrum well and only very thin layers are needed to achieve a high efficiency [25]. Until recently, however, its high cost, poor availability, and difficulty with doping and ohmic contacts prevented GaAs from being exploited [26]. Many of these problems have been overcome in the past decade, however, so that there is now renewed interest in the material and its potential is being realized. Progress has been so rapid that space qualified cells are now being manufactured. Some cells have even been flown on the Navy NTS-2 satellite [27] and more are being flown on the Italian San Marcos and other satellites [4]. The two most developed cell designs will be described.

2.3.1 AlGaAs/GaAs Heteroface Solar Cell

The "state of the art" in GaAs solar cells is represented by the heteroface structure in production at Hughes Research Labs [28]. The cell structure is shown in figure 2.1 [29]. The starting substrate is a Bridgeman-grown, n^+-type, single-crystal GaAs wafer, Te doped to 10^{18} cm^{-3}. A 10 μm thick buffer layer, Sn doped to 10^{17} cm^{-3} is first grown to separate any surface defects from the active region of the cell. A p-type $Al_{0.85}Ga_{0.15}As$, Be-doped to 10^{18} cm^{-3} is then grown on top to a thickness of 0.5 μm. During this growth, beryllium diffuses into the n layer to form a pn homojunction about 0.5 μm deep. The keys to high efficiency in this structure are the doping level in the buffer layer which controls Voc, the thin AlGaAs "window" layer which lets most of the sunlight into the cell and the shallow junction which improves the radiation hardness of the device. The front and back metallizations are designed for good adherences and low resistance. The AR coat and grid pattern are the same as those used by Spectrolab for their Si space cells.

The fabrication process for the heteroface cell is outlined in figure 2.2 [29]. The key process is the "infinite solution" liquid phase epitaxy (LPE) technique used to grow the two layers [30]. In this process, the substrates are cut to rectangular shape for maximum area utilization and loaded into a graphite holder. The holder is held vertically in an H_2 ambient and dipped into a high-purity solution of GaAs in a melt of Ga and Al, doped with Be and held at a temperature of 700-750°C. The Ga:Al ratio is adjusted to control the composition x in the



p CONTACT: Au–Zn–Ag

n CONTACT: Au–Ge–Ni–Ag

AR COATING: Ta_2O_x

p $Al_xGa_{1-x}As$: $x > 0.85$

$D + X_j < 1.0 \mu m$

Figure 2.1: Hughes Research Labs AlGaAs/GaAs heteroface solar cell structure [29].

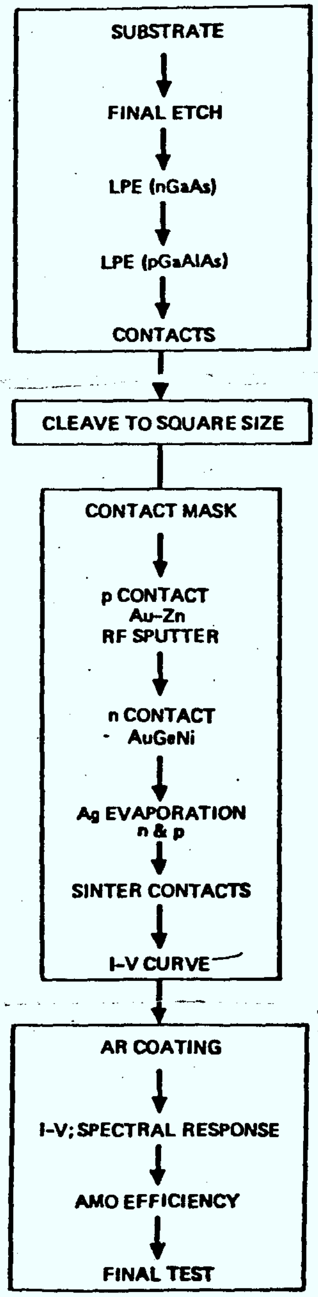


Figure 2.2: Hughes heteroface space solar cell fabrication process [29].

growing $Al_xGa_{x-1}As$ layer. Extreme care is taken to avoid contamination of the melt. Growth of the two layers takes about three hours and with the proper controls, reproducible, uniform results are achieved. The "infinite solution" process represents the most advanced of LPE techniques. It is being scaled up to handle 80 2 x 2 cm wafers at a time [29]. As shown in Figure 2.2, the rest of the fabrication process is conventional.

The production cells made in this way have AMO efficiencies of 16-18% with the best cells around 19%. Typical characteristics are V_{oc} = 1 volt, I_{sc} over 30 mA/cm^2 and fill factor over 75% [29]. It is hoped that the process and cell structure can be optimized to reach 20% AMO efficiency which is about the limit for this device. These cells have been fully characterized, subjected to proton and electron irradiations [31] and are now space qualified, having passed all the mechanical and thermal tests. An earlier version of the same cell performed well on the NTS-2 satellite experiment [27].

These cells are currently in production at a rate of 5000/year [28]. The 2 x 2 cm cells cost about $200 each. Hughes plans to scale up in one year to 100,000 cells per year with a cost below $60 each. Eventually, the hope to produce 500,000 2 x 4 cm cells per year at a cost of about $50 apiece. The major concern now is the substrate cost; $5-8/cm^2 [2]. This is expected to drop in one or two years to $1-3/cm^2 as the supply increases and larger substrates become available.

2.3.2 Shallow-Homojunction GaAs Cell

The other cell structure which has demonstrated high efficiency is the n^+p homojunction developed at the MIT Lincoln Laboratory [32, 33]. Though it has not been developed to the same extent as the heteroface structure, it may have some advantages which give it the potential for higher efficiency.

The cell structure is shown in figure 2.3 [33]. The p^+ substrate is doped with Zn to 10^{18} cm^{-3}. A 2 μm p^+ buffer layer is grown, followed by the 2 μm thick p layer (10^{17} cm^{-3}). The very thin n^+ (5×10^{18} cm^{-3} s-doped) is the key to high efficiency [32]. Most of the light passes through it and is absorbed in the p region where the high electron mobility ensures good collection efficiency. The shallow junction also makes the device more resistant to radiation damage [33]. The cell performance has been modelled and found to match the experimental results [34]. The model predicts that AM1 efficiencies up to 22% may be possible.

The simplified fabrication requires no vacuum processing [32]. The GaAs layers are deposited in an atmospheric-pressure vapour phase epitaxy (VPE) reactor. In this process, $AsCl_3$ is carried by a steady H_2 flow over a melt of Ga. The Ga vapour reacts with the reduced As to deposit GaAs on the substrate which is heated to about 700°C. The layer quality and deposition rate are controlled by the $AsCl_3$ flow. Dopant species (dimethylzinc for p-type and hydrogen sulphide for n) are added to the carrier gas. A byproduct of the reaction, HCl may act to clean the substrate.

The n^+ layer is initially grown 100 nm thick. After deposition, the surface is anodized [35] to provide the AR coating, to thin the n^+ region to 50 nm and to partially passivate the surface of the cell. Following photolithography to etch windows in the oxide, gold is electroplated on the front and back surfaces and sintered to make ohmic contacts [32].

The homojunction cells have received only limited testing and most of this was under AM1 illumination. Efficiencies up to 21% (AM1) were measured, with V_{oc} = 0.97 volts, I_{sc} = 25 mA/cm^2 and a fill factor over 80% [34]. The few AM0 measurements indicated an efficiency close to 17% [33]. Thus, this structure works as well as the heteroface. Initial irradiation work indicated that the MIT structure degraded less under irradiation than did the heteroface structure [33, 36]. Moreover, the homojunction recovered more of its initial output after annealing.

As far as is known, there are no immediate plans to further develop the shallow-homojunction cell. However, studies indicate that the VPE process can be cheaper than LPE in production [37]. Cost predictions vary from about $400/watt now to $80/watt in the future (compared to $1000 and $300 respectively for the LPE cells).

2.3.3 Other GaAs Cell Structures and Processes

Several other groups are active in GaAs cell development. The closest to Hughes is Applied Solar Energy Corp. (ASEC) which has a contract to produce 5500 2 x 2 cm cells with efficiencies over 16% by the end of 1984 for the U.S. Air Force [2]. They are using a heteroface structure similar to Hughes, but are using the MOCVD process (see Chapter 3). No cells have been made yet but they plan to make 1000 cells/week at a cost of less than $50 each. The cells will be qualified and flown when ready.

Researchers at the Jet Propulsion Laboratory (JPL) have worked with a variety of structures [38, 39]. For several years the AMOS device (an advanced Schottky barrier structure similar to a silicon MIS solar cell) was developed [40]. Efficiencies around 14% (AM0) were achieved but the device was plagued with instabilities. JPL also studied polycrystalline GaAs cells but were unable to achieve high efficiencies [38]. They obtained their best results using the n^+p homojunction. Unlike MIT however, they use MOCVD processing, grow the 50 nm n^+ layer directly and then evaporate an Sb_2O_3 AR coat. AM1 efficiencies up to 19% have been demonstrated [38].

Varian Associates has used both MOCVD and LPE to fabricate AlGaAs/GaAs heteroface cells designed for terrestrial concentrator applications [41]. Like ASEC, they grow the pn homojunction directly rather than relying on diffusion from the p^+ AlGaAs window. To avoid problems contacting the AlGaAs layer, they grow p^+ GaAs over it and then etch this away after the contact grid has been deposited. The Varian cells use a Si_3N_4 AR coat. The efficiency at 400 x AM2 varies from cell-to-cell but many values over 20% were reported [41].

In Japan, Mitsubishi has developed a GaAs cell and process similar to that used by Hughes [42, 43]. The main difference is that no buffer layer is used. A single Zn-doped AlGaAs deposition (by LPE) acts as a diffusion source for a deep junction (1-3 μm) in the n-type (10^{17} cm^{-3}) substrate. A Ga soak is used to improve the substrate surface prior to deposition. The cell uses a Si_3N_4 AR coat. They can fabricate many 2 x 2 cm wafers at a time and claim AM0 efficiencies over 18% [43]. Some radiation testing has been done and the cells are being qualified for space.

One group at the Rensselaer Polytechnic Institute in New York has made p^+n homojunction cells by Zn diffusion from a spin-on source at temperatures below 600°C in an open tube furnace [44]. Electroplated contacts and an Sb_2O_3 AR coat completed the structure which achieved an AM0 efficiency over 12%. This structure could readily be improved. MIT also tried this diffusion approach and measured efficiencies up to 14% AM1 [45]. The results were not reproducible however, and they are continuing to use VPE. Other companies interested in GaAs cells are COMSAT Laboratories and Rockwell International.

2.3.4 Discussion

As shown above, two structures predominate the GaAs cell developments: the AlGaAs/GaAs heteroface and the shallow homojunction. Both of these have advantages and disadvantages. The primary advantage of the heteroface device is the use of a p^+-AlGaAs window. This provides a low resistance current path for collected holes to the metal contact grid and helps to passivate the GaAs surface [29]. There are, however, several problems with the AlGaAs layer. Firstly, it is not perfectly transparent, but absorbs some short wavelength photons with energies greater than the bandgap (about 2 eV). This can be minimized by making the layer very thin [29]. Making good ohmic contacts to AlGaAs is difficult because of the aluminum oxide which forms on the surface [41]. Hughes solved this problem with a proprietary metallization process [29]. Lastly, there is a slight lattice mismatch between AlGaAs and GaAs which may cause surface defects and recombination losses.

In the heteroface structure, most of the photons are absorbed near the surface of the p-diffused region. The minority electrons must then diffuse to the junction, about 1/2 m away (see Figure 2.1). Normally, the electron diffusion length is long enough (on the order of 10 μm) that there is little recombination. In a compensated region or after ionizing irradiation however, the diffusion length will be substantially reduced and p-region recombination will increase. To avoid this effect, Hughes has made the junction shallower [31]. Now however, more photons are absorbed in the n-type buffer layer where the minority hole mobility is typically very low (about 1/20 of the electron mobility). Therefore, optimizing the structure means trading off these two deleterious effects.

In contrast, the n^+p homojunction has several advantages. There is no AlGaAs layer and thus no absorption loss and no contact problem. Even though the n^+ layer is very thin, its electrons have a much higher mobility than the holes in a p-type AlGaAs layer so that the sheet resistivity is about the same [33]. With a thin n^+ layer, most of the optical absorption occurs in the p-layer, close to the junction. The p-layer is not compensated so the electron collection efficiency should be high and will be aided by the p^+ BSF region (see Figure 2.3) [33]. Moreover, better radiation hardness is obtained with the very shallow junction.

Notwithstanding these advantages of the homojunction structure, the heteroface seems to be the choice of most groups. It may be that the heteroface structure is better developed, but there are also some problems with the homojunction structure. Because of the n^+ layer is very thin, surface recombination may limit the open circuit voltage. The anodized oxide provides some passivation but not as much as an epitaxial AlGaAs layer would. Furthermore, the anodization process may not be suitable for production and does not always give good results [38]. Finally, the front contact grid is only 50 nm or so from the junction so that the sintering step is critical and may lead to long-term shunting problems. With further development, these problems could likely be overcome.

2.4 Comparing Si and GaAs Space Cells

The criteria for selecting space cells are quite different from those for terrestrial photovoltaics. In space applications, the two overriding considerations are the stowed volume and/or weight of the array and the reliability or useful life of the solar cells. The cost of the cells is usually secondary. Translated into solar cell parameters, high efficiency (i.e. high watts/m^2 or W/kg ratio) and good resistance to ionizing radiation are the most important factors. The latter determined the useful life of the array and thus the satellite as well. Ultimately, the cost is most important - the cost of the

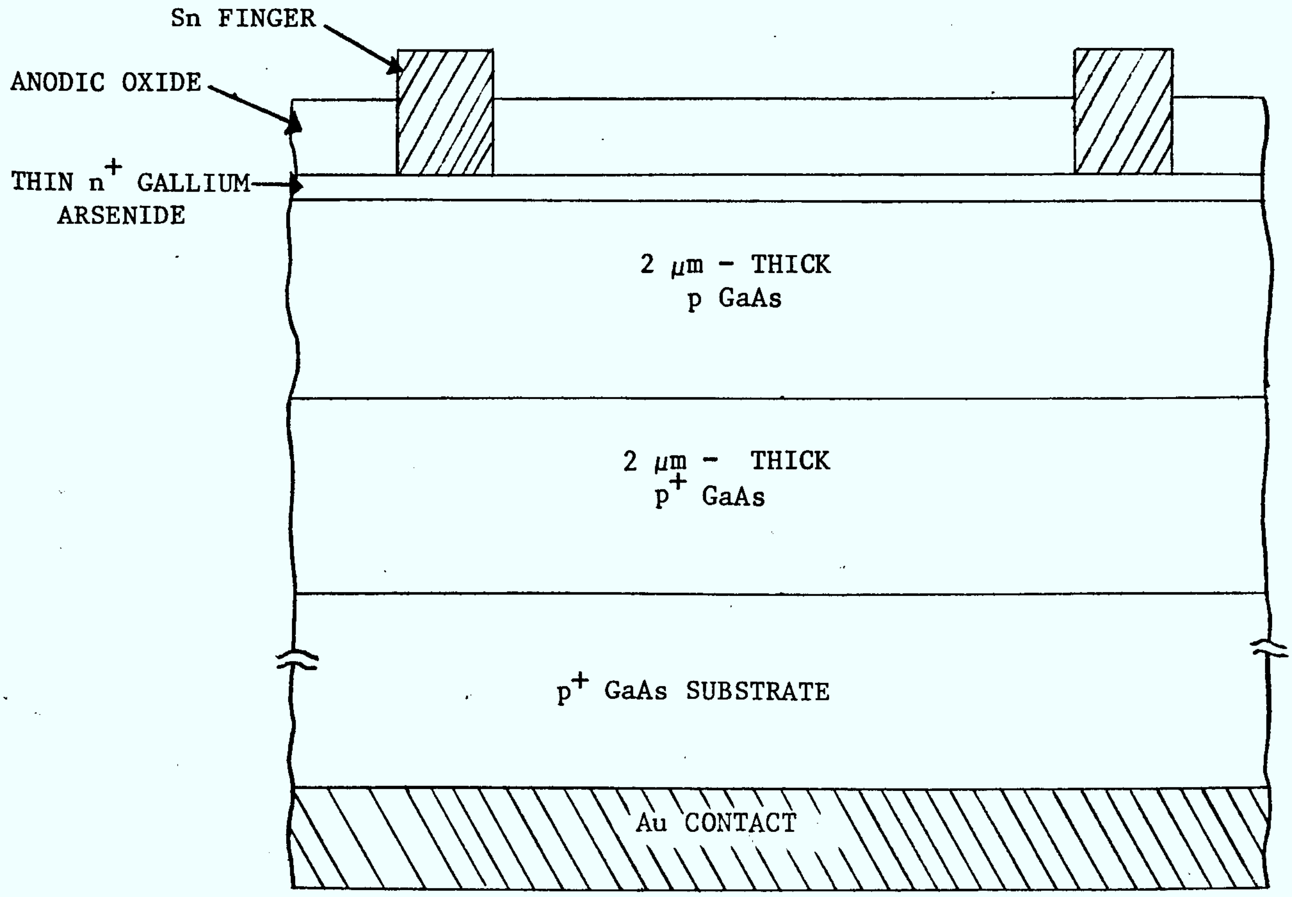


Figure 2.3: MIT Lincoln Laboratory n^+ p shallow homojunction GaAs solar cell structure [33].

entire spacecraft over its useful life. In most satellites, the solar array is a small fraction of the total cost, thus a high cell cost is acceptable if it provides better performance and/or longer life. Many authors have compared Si and GaAs for space applications [2, 29, 37, 46, 47, 18]. This section summarizes their findings and conclusions.

2.4.1 Radiation Effects

The major operating environment concern for space cells is the flux of ionizing radiation found in space. This consists of protons, electrons and other particles with a wide spread of energies. The energy spectrum and particle flux varies considerably around the earth due to the earth's magnetic field. The radiation field has been fairly accurately mapped so that the yearly dose in any orbit can be estimated [48, 49]. For solar cells, the most important particles are electrons and protons.

In silicon, the effect of ionizing radiation is fairly straightforward. The energetic particles knock atoms out of the crystal lattice, leaving a track of point defects [50]. These act as recombination centres, reducing the minority carrier lifetime and hence the collection efficiency, current and voltage of the solar cell. The effects are cumulative so that over the life of the cell, its efficiency slowly decays. The "end-of-life" (EOL) is nominally determined as the time in orbit (or total flux) at which the array power drops to some percentage of its "beginning-of-life" (BOL) value. Typical EOL/BOL ratios are 55-80% depending on the satellite design and its orbit.

In silicon, all energetic particles have similar effects and the degradation coefficients for all energies of interest have been determined experimentally and explained theoretically. Therefore, a 1 MeV electron equivalence flux is now used to simulate the space environment so that the EOL efficiency can be determined in the laboratory [51].

This simplified analysis cannot be applied to GaAs cells. Since GaAs is a binary compound, the damage mechanisms are more complex [52]. Since GaAs has a direct bandgap, the effects of radiation damage are also different [2, 29]. Furthermore, there has been less work done on GaAs than Si so that these effects are not fully understood or characterized. What is known is that there is no damage equivalence between different energetic particles [53]. Electrons, protons and neutrons all act differently. Moreover, the radiation effects have been found to vary non-linearly with cumulative dose and dose rate.

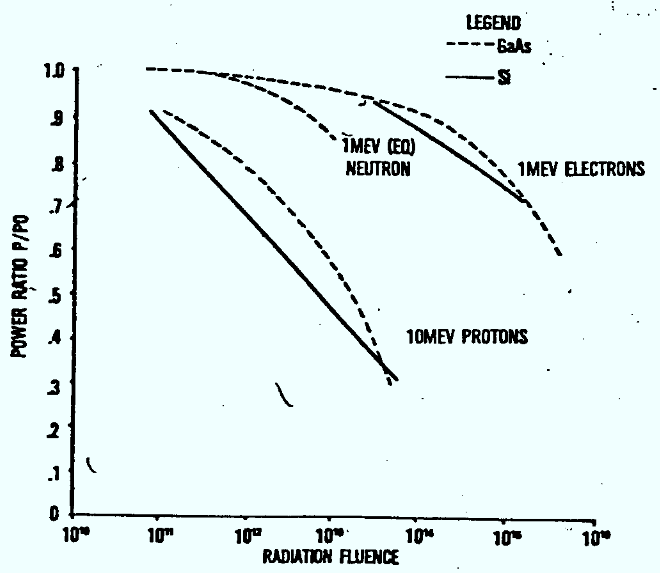
Low energy particles generally cause more damage in solar cells because they are stopped in the active junction area. Higher energy particles pass through the cell or are stopped deeper in the substrate and cause little damage near the surface. Space cells are always provided with coverglasses (see Chapter 5) to absorb the low-energy particles and thus extend the cell life. However, the coverglass also slows down the relatively fewer higher energy particles so that by the time they enter the cell, they are low-energy particles. Thus, it has been found experimentally that 200-300 KeV protons produce the most damage in GaAs cells with attached coverglasses [31, 54, 55].

It is now generally recognized that GaAs cells are superior to Si cells in terms of radiation resistance [2, 28, 37, 46]. The most extensive testing has been done using the Hughes heteroface cell [31, 54]. The results, compared with similar data for silicon cells are summarized in Figure 2.4 [37, 46]. The graphs show the effect of 1 MeV electron fluence on the cell output power. The comparison of Si and GaAs in this way is not entirely fair since the electron equivalence does not apply to GaAs. The results however are backed up by the NTS-2 flight experiments [27]. For silicon cells, a fluence of 4 x 10^{14} e/cm^2 corresponds roughly to 10 years in geosynchronous earth orbit (GEO) [37]. A low earth orbit (LEO) has a higher radiation flux.

From these figures, it can be seen that GaAs cells maintain higher efficiencies than silicon cells out to very high flux levels. The EOL/BOL power ratios at 10^{14} to 10^{16} e/cm^2 are slightly higher for GaAs. Note that the figure compares advanced Si cells with the relatively undeveloped GaAs structures. As the GaAs designs improve, the radiation hardness can be expected to get better as well. At high flux levels (10^{15} 1 MeV electrons/cm^2), recent work demonstrates the superiority of GaAs [56]. EOL/BOL ratios of 60-63% were measured for heteroface cells compared to 50-55% for silicon cells. Moreover, modelled results for a graded-bandgap structure predicted a ratio of 78% for the same fluence level [56]. It was already noted above that a shallower junction in the heteroface structure improves the hardness [31]. Also, the n^+p homojunction structure appears to be even more resistant in initial tests [33].

There is the potential in future satellites to extend

(a)



(b)

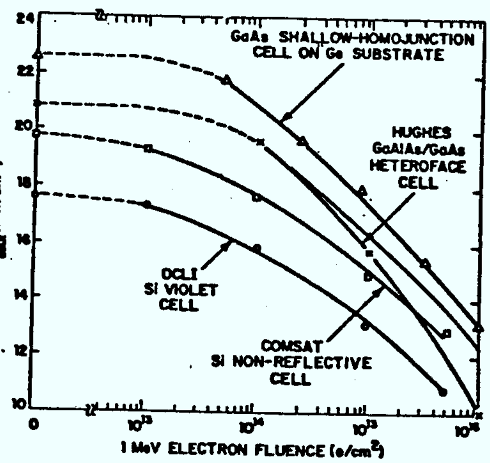


Figure 2.4: Effects of radiation on the output power of Si and GaAs space cells [37, 46].

the useful life of the array by annealing out radiation damage. Thermal annealing repairs some of the lattice damage and partially recovers the lost efficiency of the cell. Annealing is also done in the laboratory to characterize the radiation damage. Considerable annealing work has been performed in both Si and GaAs space cells [31, 52, 55, 57, 58, 59]. This work has shown that more annealing is possible in GaAs than in Si and at lower temperatures. Significant annealing occurs at 200°C which raises the possibility of periodic [37] or continuous [18, 57] annealing in space to extend the array lifetime almost indefinitely.

2.4.2 Weight/Size and Power/Cost Comparison

Traditionally, GaAs was considered handicapped for space applications by its high density (about 2.2 times that of silicon). Weight was the overriding factor in satellite design. Leaving aside the fact that only a few μm of GaAs are required compared to about 100 μm for silicon, several factors act together to change this viewpoint. First, the solar cell is only one part of the array. The coverglass, adhesive, interconnects and support structure also add weight, reducing the effect of the cells' own weight. Secondly, GaAs has a higher efficiency than silicon so that a smaller (and lighter) array can give the same power. The better EOL/BOL power ratios for GaAs further reduce the array size.

In all, for the same EOL power and 300 μm thick substrates, a GaAs cell array weighs only 5-25% more than a Si cell array [47]. As for silicon, thinner GaAs substrates are possible, reducing the effect of the cell weight in favour of GaAs [37, 46]. Space cells are often compared in terms of specific power or watts per kilogram of array weight. Present day Si cells produce 40-80 W/kg. New Si cell designs are expected to reach 200 W/kg. With very thin GaAs cells (see Chapter 3) however, values over 1000 W/kg are feasible [37]. Finally, as satellites and arrays become larger, the stowed volume becomes more important than weight as the primary limitation of the launch vehicle. With its higher efficiencies, GaAs has the clear advantage in this respect.

The other traditional problem with GaAs was cost. GaAs wafers are many times more expensive than Si wafers. The processing is also more costly at present. By the time the cells have been tested and arrayed however, the costs are much more comparable. GaAs is also becoming less expensive and this can be expected to continue as new technology is implemented and scaled up. In conclusion, then, the original problems with the weight and cost of GaAs are still present but are now less important and will be overcome in the future.

2.4.3 Other Considerations

One important factor which has not yet been mentioned is the operating temperature and its effect on cell output. In the lab, cells are tested at 25-28°C. In earth orbit, however, they typically operate at 50-70°C [46]. It is well known that GaAs cells operate better at elevated temperatures than do Si cells [25, 37]. Thus, the room temperature advantages of GaAs become more important under actual operating conditions.

Moreover, since GaAs has a higher bandgap than Si, it absorbs a smaller fraction of the AM0 spectrum. Hence there is less waste heat to dissipate and the cells should operate cooler than Si cells.

Another factor sometimes used against GaAs is its strength. GaAs is weaker and easier to break than silicon [26]. This would seem to be a severe problem during a high-acceleration launch, especially for the fragile, deployable arrays now being designed. If care is taken, however, this is not a real problem. Some changes in handling and arraying techniques are required (see Chapter 5), but once the arrays are made, the cells can withstand the acceleration and vibration [28]. The cell contacts have also been shown to survive 30,000 thermal cycles, representing about 5 years in LEO. As cells are made thinner (50 μm), the coverglass becomes the dominant structural element and the difference between Si and GaAs again becomes less important.

One final concern is user acceptance. Even if the cells are proven, satellite manufacturers are understandably conservative and may shy away from GaAs as they have thus far shied away from the new generation of Si cells. Any uncertainty (however small) is not welcome in this critical part of the satellite. Most of this wariness should dissipate after larger GaAs arrays have been flown. In any case, array manufacturers are likely to stay with Si cells until they are forced to use more advanced devices. With the trend toward larger and higher vehicles, this will happen sooner or later.

2.4.4 Conclusions

Silicon solar cells are now an advanced, mature product. While some improvements can be made, the AMO efficiency, currently at the 14-15% level is not expected to increase further. In comparison, GaAs cells are relatively young and there is much room for their improvement. Efficiencies of 18% have been achieved and 20% appears to be an attainable goal. The weight, cost and radiation resistance can likewise be improved. By and large, the old processing and reliability problems have been overcome as the technology has advanced and the traditional concerns about weight and cost are not so important now. In conclusion, GaAs is clearly seen as being important for the future.

GaAs cells will be used initially in small, experimental arrays. As advances are made and operating experience gained, GaAs will gain acceptance and will begin to be applied in applications where high temperature, high radiation or long life are important. Eventually, GaAs will supplant Si cells in many applications, especially for high-power systems where array area and stowed volume are the primary constraints.

3.0 THE FUTURE OF GaAs SPACE CELLS

In terms of material control and processing technology, GaAs is widely perceived as being 5-10 years behind silicon. This can be turned around to imply that major improvements in GaAs material and processing can be expected in the next 5-10 years. These will doubtless result in advances in devices, including solar cells. Present day GaAs cells have AMO efficiencies of 16-18%. The theoretical limit (without concentration) is about 23-24%. Thus, a practical limit around 20% is probable. This will be achieved by higher-quality substrates, better-controlled depositions and optimization of the cell structure; just as Si solar cells were improved over the past 20 years.

3.1 Advanced Cell Structures

Unlike Si, GaAs is a binary, III-V semiconductor. The possibility of replacing part of the Ga and/or As with other elements in the third and fifth columns of the period table opens up a whole new dimension of potential solar cell devices. This has already been introduced in the use of GaAlAs in the heteroface structure described in Chapter 2. By taking suitable combinations of Al, Ga and In mixed with P, As and Sb, the bandgap, lattice constant and other properties of the resultant semiconductor can be tailored to meet specific requirements. The most promising application of these mixed semiconductors to photovoltaics is in the design of tandem or cascade solar cells.

The structure of a simplified tandem solar cell is illustrated in Figure 3.1 (a) [60]. It consists of a cascade of two pn junction solar cells made of semiconductors with different bandgaps. The top solar cell has the higher bandgap and efficiently absorbs short wavelength photons. It also acts as a window for longer wavelengths, letting them pass through to the second cell with the lower bandgap where they too are absorbed. The purpose is to better match the solar spectrum by absorbing more photons and using more of the absorbed photons' energy than is possible with a single bandgap material. In theory, efficiencies up to 30% can be achieved if the tandem cells are properly designed and matched [60, 61].

There are several ways to use the electrical power from the two cells [62]. They can be physically separate (4 terminal device), they may have one common connection between them (3 terminal device) or they may be integrated and internally connected in series (2 terminal device). These three options are illustrated in Figure 3.1 (b) [62]. In terms of fabricating the cascade cell, a monolithic stack of n and p doped layers of the two semiconductors is the most practical approach [61] and the one likely to be most cost effective in the long run.

The use of a series-connected monolithic stack places severe constraints on the choice of semiconductors and the cell structure [61]. To make use of all the power available in both cells, they must be designed to operate at the same current. Thus, the bandgaps must be carefully chosen for the solar spectrum (AM0) and/or the thickness of the top cell must be carefully adjusted to control its absorption. Theoretical calculations have shown that for maximum overall efficiency, the

(a)

(b)

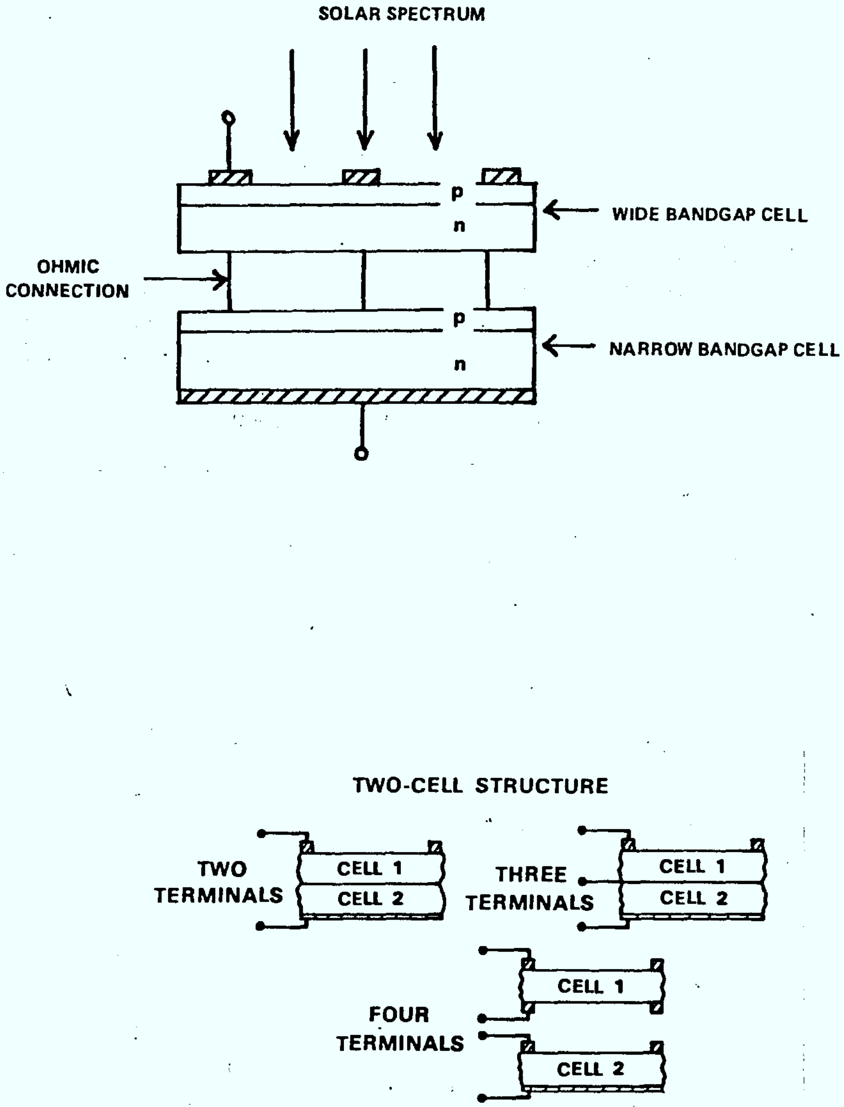


Figure 3.1: Two-cell tandem solar cell:

(a) tandem cell concept [60],
(b) three different interconnect modes for the two cells [62].

bandgaps of the two semiconductors should be 1.0-1.2 eV and 1.6-1.8 eV depending on the operating conditions [60, 62]. Furthermore, the lattice constants of the two semiconductors should be close enough to allow the top cell to be grown epitaxially on the bottom cell* [61].

These constraints severely limit the choice of semiconductor materials. Figure 3.2 shows the energy bandgaps and lattice constants for various III-V semiconductors [60]. For binary compounds (circles), the only possibilities are AlAs/GaAs and AlSb/GaSb, neither of which fits very well. Similarly, no ternary semiconductor (solid lines as for example AlGaAs) fit the criteria well either. Efficient AlGaAs/GaAs cells have been made, but the bandgaps are not ideally suited. To satisfy all the criteria, the quarternary semiconductor GaAlAsSb (hatched area in the middle of Figure 3.2) is the only real choice. Most work on monolithic cascades has thus focused on this system.

In a monolithic cascade cell there remains the problem of electrically connecting the two junctions in series [60]. If the device is simply made with four semiconducting layers in series, an additional pn heterojunction results at the interface between the two cells. To avoid this problem, two techniques have been developed. The simplest in principle is to short out this parasitic junction with a metallic connection after the stack has been fabricated [64]. The more usual approach is to add two highly doped layers between the two cells so that the

* Ways of avoiding this last constraint have been developed but they are quite complicated [62, 63].

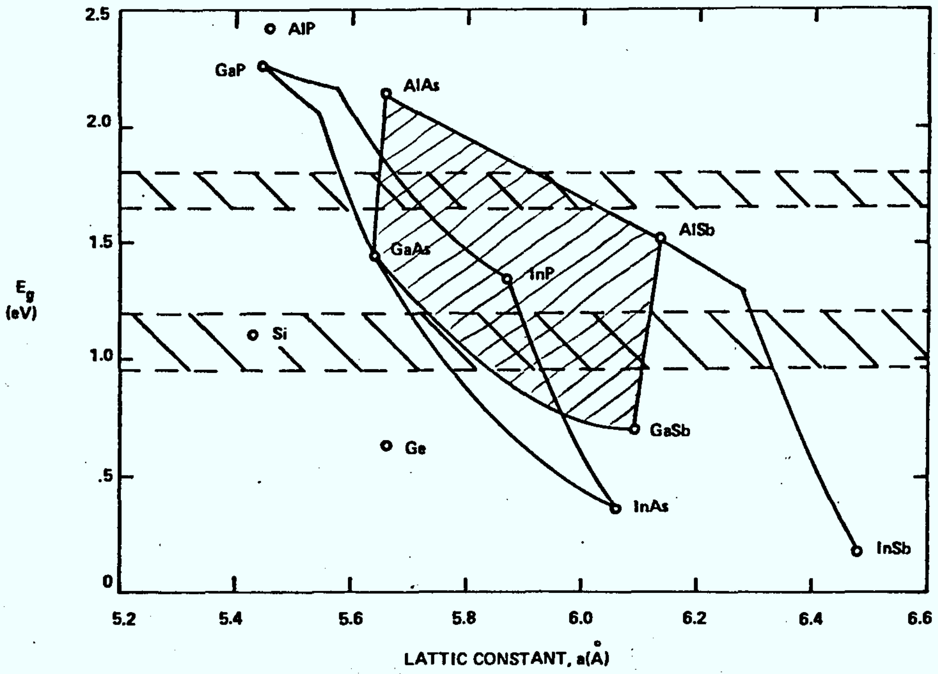


Figure 3.2: Bandgap and lattice constant values for the III-V semiconductors [60].

parasitic junction becomes an n^+-p^+ tunnel junction. With sufficiently high doping, both the n^+ and p^+ regions can be made degenerate and majority carriers can readily pass between them. To reduce optical losses in the cascade cell, these layers are made very thin and with the same bandgap as the upper semiconductor layers [60].

Much of the research on cascade cell structures has been carried out by workers at the Research Triangle Institute [60, 63, 65, 66]. They have extensively investigated the AlGaAs, GaInAs, GaInP, and GaAsSb ternary systems as well as the AlGaAsSb quarternary system using both LPE and MOCVD techniques. In spite of the potential of the AlGaAsSb system, good results have not been achieved due to deposition control problems and excessive lattice defects at the growth interface which cause low open circuit voltages. Best results were obtained for the AlGaAs/GaAs cascade structure [65], probably because AlGaAs and GaAs are very compatible and their processing is the most developed of the III-V compounds. 15% AM0 efficiencies were measured for non-optimized devices without an AR coating [65]. The theoretical efficiency for this system is 24%.

Varian Associates has also developed an AlGaAs/GaAs cascade cell [64, 67]. Their 9-layer monolithic structure is deposited by MOCVD. To avoid the problems associated with an n^+p^+ tunnel junction, they short the parasitic np junction with a metal interconnect deposited in grooves etched through the upper solar cell. The structure is shown in Figure 3.3 [64]. This cell exhibited an AM0 efficiency of 15.7%. It was designed

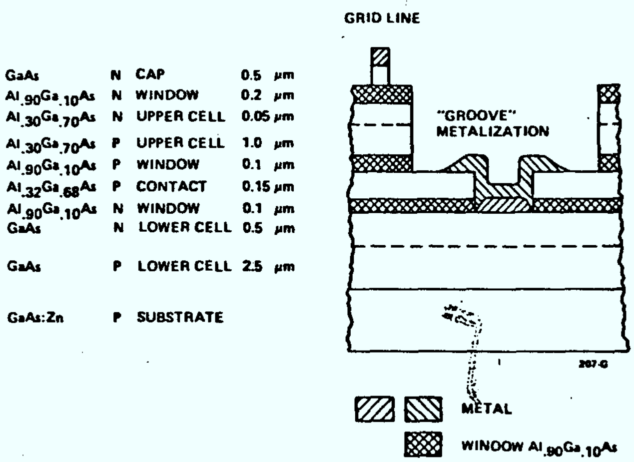


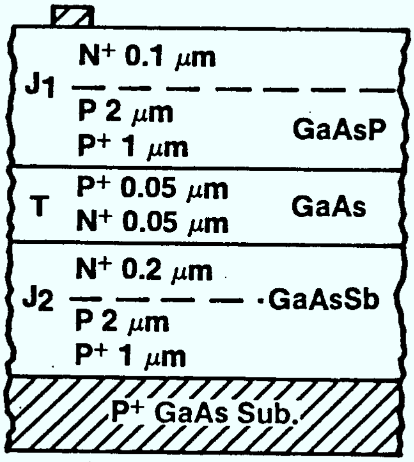
Figure 3.3: Structure of the metal-interconnected cascade cell ($\dot{M}IC^2$) made by VARIAN [64].

however for concentration applications for which values up to 21.5% were measured. Some improvements in the structure can be made [67].

Other researchers are also working with cascade cells. An Italian group has used LPE to make a simplified, three-terminal AlGaAs/GaAs solar cell [68]. Under high concentrations of AM1.5 sunlight, efficiencies of 20.5% were measured. Workers at Chevron Research Co. have developed GaAsP and GaAsSb ternary solar cells with bandgaps of 1.65 and 1.2 eV respectively [69]. For both of these, they have measured efficiencies close to 15%. The two were then fabricated in a 3-terminal monolithic cascade with good results. Two possible structures for this device are shown in Figure 3.4. No quantitative values were reported, but high open circuit voltages were measured. A low pressure MOCVD process was used for all the depositions [69]. These results appear very promising.

Clearly, the development of cascade cells is in its infancy. Reproducible, optimized, practical, large-area devices cannot be expected for several years. Nevertheless, the potential for cells of this type with efficiencies around 25% AM0 exists. They will probably be used mostly as concentrator cells due to their inevitably high cost. The logical extension of the two-cell cascade is a multiple cell cascade. As the number of cells in the stack increases, so does the theoretically possible efficiency [61]. With a four cell stack, the AM0 unconcentrated efficiency can be 40%. This increases to 48% with a 24 cell stack. Under high concentrations, efficiencies over 60% are

(a)



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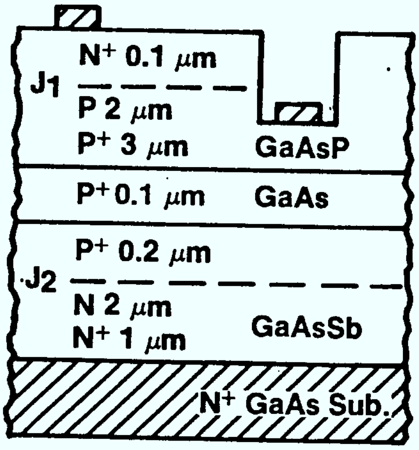


Figure 3.4: Two possible structures for the III-V cascade solar cell developed by Research Triangle Institute [69]:

(a) two terminal cell,
(b) three terminal cell.

theoretically possible [61]. While the realization of such structures is not currently feasible, these results indicate that 30% efficient cells will likely be made in the forseeable future.

3.2 Innovative GaAs Substrates

Even though the higher cost and weight disadvantages of single crystal GaAs substrates are becoming less important, there has been considerable work done to reduce the amount of GaAs used. Since only a few μm of active material are required for efficient cells, most of the 300 μm thickness of a standard GaAs wafer is used only for structural support. Three different techniques have been developed to make ultrathin GaAs solar cells in which only a few μm of GaAs are needed and the structural support is provided by some other material which is lighter, stronger and less expensive.

In the "galicon" approach, a single crystal silicon wafer is used as the carrying substrate for a thin film GaAs solar cell structure [70, 39]. Due to a large lattice mismatch between them, GaAs cannot be grown epitaxially on Si. However, GaAs will grow on Ge substrates as well as on GaAs substrates [32]. Also, by a variety of techniques, single crystal Ge layers can be deposited on Si wafers [70, 39, 71]. The "galicon" structure therefore starts with a p-type Si substrate with a thin, single-crystal p^+ Ge overlayer. The thin-film GaAs solar cell structure is then grown on top of this.

Efficient GaAs/Ge/Si solar cells were first demonstrated by the MIT Lincoln Laboratory researchers in 1981 [70]. AM1 efficiencies up to 12% were reported. They have since improved the process to achieve 14% efficiency [72] using their n^+p homojunction structure [32]. The epitaxial Ge layer is electron-beam evaporated onto the silicon substrate which is heated to about 550°C [71]. The GaAs layers are deposited by VPE [32]. They expect that further improvements will result in 16-17% efficient cells. Other research groups are also working on the same approach. JPL has made GaAs/Ge solar cells and grown Ge layers on Si substrates but have not yet demonstrated a complete GaAs/Ge/Si solar cell [39, 38]. They use a more complicated GeH_4 pyrolysis coupled with laser annealing and polishing to obtain high quality Ge films. Epitaxial Ge layers on Si have also been demonstrated by an Italian group using e-beam evaporation [73] and researchers at the University of Illinois who used sputtering techniques [74]. TPK has also done some work with epitaxial Ge on Si using e-beam evaporation and GaAs solar cell development using MOCVD (TPK subcontract to McGill University) [75].

The second approach, also developed at MIT is the CLEFT technique (cleavage of lateral epitaxial films for transfer) [76]. In this process, VPE GaAs is deposited over a carbonized photoresist layer on a conventional single crystal GaAs substrate. The epitaxial growth begins at openings in the photoresist and is thus seeded by the underlying substrate. As deposition proceeds, the epitaxial layer grows laterally over the photoresist until it covers the entire surface. It is then built up to a thickness of 5-10 μm. The substrate orientation, photoresist pattern and growth conditions are all optimized to obtain the most uniform and highest quality GaAs films. The film quality obtained is better than that of the "galicon" substrates [77].

Once the GaAs layers has sufficient thickness, the solar cell structure is grown. The contact grid and AR coat are deposited and the cell is then bonded to a glass superstrate with a clear epoxy. Only then is the cell separated from the substrate. The substrate and superstrate are separated by cleaving the GaAs at its weakest link: the openings in the photoresist [77]. The substrate can then be reused to grow another film. The solar cell, now permanently attached to the superstrate is finished by applying a back contact. Using the n^+p homojunction structure [32], AM1 efficiencies of 15-17% were measured [77]. While this technique is experimental and appears rather complicated, it does work and is a promising approach to light-weight, ultra-thin GaAs solar cells for space or terrestrial applications.

Varian Associates has very recently demonstrated an ultra-thin GaAs solar cell for concentrating applications [78]. The AlGaAs/GaAs heteroface structure is about 5 m thick and is grown on a conventional, thick GaAs wafer by MOCVD. After making the front contact and adding the AR coat, the cell is bonded to the 150 m thick coverglass superstrate using a silicone resin. The GaAs substrate is then etched off the back. The etch stops at a thin AlGaAs layer just under the active cell structure [78]. The back contact metal is then applied and sintered. Preliminary tests indicated an efficienccy of 13.7% under highly concentrated AM1 sunlight. It should be noted that the GaAs substrate can in principle be recovered since it is dissolved in the etch solution.

Clearly much work remains to be done before these very thin GaAs cells become practical. Large-area, high-efficiency devices have to be made reproducibly. The process has to be shown to be cost-effective; that is, less expensive than using a self-supporting GaAs wafer. Some people doubt if the "galicon" approach will ever be applied to space cells and feel that the CLEFT and VARIAN ultra-thin substrates are too fragile. In addition, the processing cost may be too high for terrestrial applications. These doubts will be answered in the coming years. In any case, these three innovative approaches to GaAs solar cell substrates are very interesting and should be further developed.

3.3 Assessment of GaAs Processing Technology

Most GaAs devices are made by epitaxial deposition of variously doped layers with varying compositions. The conventional open-tube diffusions used with silicon are not possible with GaAs as the compound breaks down at the required temperatures. Diffusion from spin-on sources and ion implantation have been used successfully but by and large have not produced as good results as epitaxial deposition. Even with Si, epitaxy has a degree of impurity profile control not possible by other techniques. For the growth of thin GaAs layers and other III-V semiconducting compounds, there are four epitaxial processes which can be used. Liquid phase epitaxy (LPE) and $AsCl_3$-Ga vapour phase epitaxy (VPE) are the most common and have been described in Chapter 2. The other two are MOCVD and molecular beam epitaxy (MBE). MBE is a very advanced ultra-high vacuum technique for depositing very high quality semiconductor films one monoatomic layer at a time under very controlled conditions. The apparatus tends to be extremely expensive and the growth rate and system throughput extremely low. The MBE technique is thus not seriously considered for solar cell development or production.

Metallo-organic chemical vapour deposition (MOCVD, also referred to as MO-VPE and other variants) is a recently developed variation of VPE. It provides more flexibility and better growth control than $AsCl_3$-based VPE at a much higher throughput and a fraction of the cost of a MBE system. From the work described in Chapter 2 and the previous sections of this chapter, it is clear that many research groups (including JPL, ASEC, RTI, VARIAN and Chevron) are using MOCVD for GaAs cell development. It is now widely accepted that MOCVD is the GaAs deposition process for the future §64, 67, 38, 2, 37].

In the MOCVD process, all the reactants and dopants enter the reactor in gaseous form, carried by hydrogen [75, 79]. Many of the source materials are gaseous or liquid organo-metallic compounds: trimethylgallium (TMGa), trimethylaluminum (TMAl), dimethylzinc (DMZn), etc. Others such as arsine (AsH_3) and H_2S or H_2Se are simple gases. The substrates are held on a graphite susceptor which is heated to 600-650^{o}C. When the arsine and TMGa enter the hot zone around the substrates, they are reduced and react together to deposit GaAs on nearby surfaces, including the substrates. The reaction products (most methane and suspended metallic compounds) then pass out of the reactor.

A simplified schematic of an MOCVD system in shown in Figure 3.5. The system is clearly adaptable to a wide range of materials - anything that can be transported in gaseous form. Remote controlled mass flow meters are used to control the flow of reactants. Thus, the entire process can be put under computer control for precise deposition rate and doping control. The GaAs film quality is controlled by adjusting the As:Ga ratio. The dopant species are added in trace concentrations and are incorporated into the growing layer. By adding TMAl or other organo metallics in controlled ratios, virtually any binary, ternary or quarternary III-V semiconductor compound can be produced.

The susceptor can be made large enough to hold many wafers and can be heated by RF induction, internally or externally by high-power IR lamps. The heating can also be under computer control. The optimal vacuum pump adds another degree of flexibility to the system, allowing operation over a range of pressures from atmospheric pressure down to 1 torr [75] or less [69]. This allows the deposition rate to be revised over a large range and reduces the use of the expensive reactant materials. Typical deposition rates are from less than 1 μm per hour to more than 10 μm/hr. Practical MOCVD systems are discussed in Chapter 4.

MOCVD is more flexible and controllable than the more usual halide-based VPE system [38]. No Ga melt is required as all the reactants are treated similarly. There is no problem with HCl etching. The growth temperature of the substrate can be lower in MOCVD than in VPE. Finally, it should be easier to scale up the MOCVD approach since it has a single high temperature zone and a cold-wall reactor tube [38].

For GaAs solar cells, the main contender to MOCVD is LPE which has been developed to an advanced level at Hughes [28]. Researchers at RTI, who have used both LPE and MOCVD report several problems with LPE [65]. The dopant species have to be chosen to be compatible with the LPE melt, and the dopant concentration is difficult to control. Temperature control of the metallic melt is critical and complex. A separate melt is required for each layer deposited. At the temperature used (700-800^{o}C) dopant diffusion can be a problem.

MOCVD has many advantages over LPE. Most important of these is that MOCVD provides good control over growth rates and doping [64, 2]. Many different layers can be deposited sequentially in the same reactor and the deposition can be completely automated. Very thin layers (less than 50 nm) and layers with doping levels down to $10^{15}cm^{-3}$ can be achieved with MOCVD [56]. Layers deposited by MOCVD have good uniformity over large areas. There are no limitations to scaling up the process to handle many, large wafers at a time [2]. GaAs can be grown at lower temperatures than LPE (600-650^{o}C) minimizing dopant diffusion. There is minimal contamination since only the reactant species contact the growth surface.

Researchers at VARIAN, who have also used both LPE and MOCVD report that the yield of good GaAs solar cells is higher with MOCVD [41]. They also found that layers deposited by MOCVD were smoother and more uniform. Furthermore, cells made by VPE (which is similar to MOCVD) have less degradation to radiation and better recovery when annealed than do similar cells made by LPE [37]. Though workers at Hughes would likely contest some of these statements, it is interesting to note that they too are developing an MOCVD capability [28].

In conclusion then, since MOCVD appears to be superior in several important areas this early in its development, it will surely be the most important process for GaAs cell fabrication in the future. Some MOCVD process development has occured in Canada. A small, low-pressure system has been constructed at McGill University [80] and another system has been developed at NRC in the Division of Chemistry [29]. Other Canadian groups are also interested in this technology.

4.0 A PLAN FOR THE DEVELOPMENT OF GaAs SPACE SOLAR CELLS

4.1 Introduction

In this chapter, a plan is presented which describes how the development of a GaAs space cell production facility in Canada can be undertaken. The immediate goal of this development is to produce GaAs cells to fly on the MSAT spacecraft in 1988. In the long term, however, this development would be the basis for production of solar cells for use on most Canadian and many foreign satellites in the 1990's and beyond.

The primary constraint on this development scenario is time. To fly in 1988, space-qualified cells would have to be ready early in 1987, leaving roughly three years for their development and initial production. This constraint means that a coordinated and well-directed program should be initiated quickly. It also limits the type of cell structure and processing which can be considered; both should be as simple as possible without sacrificing cell performance.

The plan presented here is designed to start from the present circumstances in 1983 and build up the facilities and capabilities to the point where, in late 1986, limited production of efficient GaAs space cells using the MOCVD process can begin. This production would then supply sufficient cells (say 5000 2 x 2 cm cells for instance) for a small array on MSAT or some later satellite. That this plan is feasible and that the goals can be met is being demonstrated by a similar development plan now underway at ASEC where 5500 cells are to be produced in under 3 years.

The plan presented here is divided into three phases: implementation of MOCVD, GaAs cell development and limited space cell production. Other scenarios are of course possible but it is believed that this plan is the most realistic for starting on a small scale and building up to full-scale, pilot-line production in the available time period. In what follows, the three phases are described. The technology requirements of each in terms of equipment and materials are considerd. The manpower needs and costing estimates are then presented based on a time schedule spanning the three phases and the periods 1983 to 1988.

4.2 Phase I: MOCVD Implementation

The first phase of the program involves setting up an MOCVD system and the support facilities required to deposit and characterize GaAs layers on SI GaAs substrates and then depositing undoped and doped layers in a controlled manner. This phase will therefore be comprised primarily of equipment acquisition and technology implementation rather than research.

4.2.1 MOCVD System

The prime consideration, of course is the MOCVD system itself. There are many possibilities for obtaining an appropriate system. They can be divided into two categories: purchase of a complete, installed system, or building up a system from its components. Both approaches have their advantages and disadvantages.

Several companies can supply and install complete MOCVD systems. One such supplier is Cambridge Instruments (Cambridge

England, New York, Montreal) which has two systems. The MR100 is a small, research-oriented system (single wafer, low gas flows) with microprocessor deposition control and numerous options which allow the system to be adapted for varying purposes. The single-substrate susceptor is heated by quartz lamps. The system can be supplied with a vacuum pump for low-pressure operation. The overall, installed cost of a system designed for deposition of doped GaAs layers is about $250,000 (all costs are in Canadian dollars with taxes included).

The Cambridge MR200 is a multiwafer production system with the same capabilities and options as the smaller system. Twenty 3 inch wafers can be processed simultaneously with a wafer-to-wafer film thickness uniformity of ± 28%. The quality of undoped GaAs films is such that mobilities around 40,000 $cm^2V^{-1}S^{-1}$ are measured at 77K. The system is well designed but some improvements could be made. The cost of a complete system is close to $400,000 and the system could be delivered and operating six months after ordering. A scaled-down version of the MR200, designed for research and eventual scale-up to production can be obtained at a lower cost.

Other suppliers of MOCVD systems include Spire Corp. in Bedford, Massachusetts, NAVTEK in Massachusetts and Crystal Specialties in Oregon. Although not strictly speaking a manufacturer of MOCVD systems, Research Triangle Institute in North Carolina could supply and install a complete research system similar to theirs for about $200,000. The RTI system is designed for achieving high-quality GaAs films, care having been taken to eliminate leaks, sources of contamination and dead spaces. The RTI system uses RF heating to heat a single 2 inch wafer. However, they plan to construct future systems with IR heating and room for multiple wafers. High-quality undoped GaAs layers with 77K mobilities up to 80,000 $cm^2/V/s$ have been grown in this computer-controlled system.

Several possibilities exist for building up an MOCVD system. The advantages of a "home built" system are that the hardware costs are lower and the system can be tailored to the research needs. The disadvantages are that the labour costs are higher and, without a good design and/or experience in MOCVD systems, the resulting system will inevitably have problems. Thus, any built-up system should be based on a good design and be guided by an experienced person.

MOCVD has been implemented in the NRC Division of Chemistry. TPK has explored the possibility of transfering this technology to industry. A small, manual, basic MOCVD system could be built up in this way for under $50,000 in materials. Another approach would be to purchase the design of the RTI system for about $60,000, then spend about $90,000 for the required materials and put the system together over a three-month period. The overall cost (labour included) would be somewhat lower than purchasing the entire system outright from RTI.

There are several Canadian companies with interest and/or experience in MOCVD and CVD systems. These include the Ontario Research Foundation in the Toronto area, Process Technology Inc., in Fredericton, N.B., and OMVPE Technologies Inc., in Montreal. A coordinated combination of one or more of these along with NRC assistance could doubtless produce a good MOCVD system.

The decision of which type of system to obtain depends on a number of considerations. There is a tradeoff between system size and cost. While a small, simple system is the least expensive, it would be difficult to use on a regular basis and could not be adapted to any sort of production. On the other hand, a large system which could readily be modified for production would be more expensive, both in capital cost and in materials usage. Another consideration is the type of control. While computer control greatly increases the cost of a MOCVD system, it greatly adds to its utility, provides for more uniform and repeatable results, and reduces the labour required to run the system. Other considerations include the type of substrate heating, with IR preferred over RF, number and size of substrates, control range of growth parameters, safety aspects, adaptability to compounds other than GaAs, etc.

The best approach is probably to obtain a small, but well-designed, computer-controlled MOCVD system for Phases I and II. A larger, production-oriented system could then be obtained for the production scale-up in Phase III. By this time, MOCVD techniques should be better developed, and more advanced systems will be available. The research system could be retained for continued solar cell R & D work.

4.2.2 Support Facilities

An MOCVD system cannot be used by itself. For the preparation of substrates, evaluation of the depositions and fabrication of devices on the films, back-up equipment, consumable materials and support facilities are required. While some of these facilities could be remote from the MOCVD location, for highest efficiency and maximum experimental turn-around time, most of the equipment should be at the same location.

For substrate cleaning, a wet-chemistry bench is required, along with a DI water supply. There may also be a need for some form of wafer polishing, either a simple lapping station or a semi-automatic chemo-mechanical polishing station. An ultrasonic cleaning for evaluation of the as-deposited films, a variety of techniques should be available. A lab balance for weight-gain measurement, an optical microscope and a four-point-probe station would be required. Other evaluation techniques which are more expensive to implement, may be available elsewhere as a paid for service. These would include crystallographic evaluations in the form of transmission electron microscopy, x-ray diffraction for thin films and electron diffraction, and semiconductor tests such as photoluminescence and photoconductivity. A scanning electron microscope would also be useful on an occasional basis for film evaluation.

Other film evaluation techniques require that patterns be defined on the film surface and contacts be made to the film. This will require a vacuum evaporator system and some form of pattern definition such as photolithography. While the requirements for these in Phase I would be minimal, both would be used more extensively and at a higher degree of performance in Phases II and III. For evaporating multi-layered contacts and AR coatings, a multiple crucible e-beam evaporator will be required. Similarly, in Phase I, only simple test patterns will be required. Thus, an air abrasive unit or the simplest of photolithography techniques could be used. In Phase II however, when grid patterns have to be defined precisely, a better pattern definition process will have to be used. In addition, a sintering furnace will be required for annealing the contacts. Finally, a liquid nitrogen temperature Hall-effect measurement station will be needed to evaluate the electronic properties of the films.

One important requirement is for a location; a dedicated place to set-up all the equipment and do the research. Much of the process equipment should be in a "clean room" area with the appropriate facilities (power, water, ventilation). Most of the evaluation/test apparatus could be used in a normal laboratory. Both areas should be large enough to accommodate the expansion into Phases II and III.

The Phase I development work will also require some material expenditures. In addition to the gases and chemicals used for cleaning and other usual semiconductor processing, there will be the materials associated with the MOCVD process itself. Single crystal GaAs wafers will be needed in small quantities. There should be no problem obtaining small SI GaAs wafers as there are several suppliers, Cominco, Crystal Specialists, Materials Research and Sumitomo being a few.

The chemicals for MOCVD will be more of a problem. At present, the organo-metallics (TMGa, TMAl, DMZn, CP2Mg, etc.) are available from only a few suppliers and are quite expensive ($550 to $1100 per 25 g bubbler depending on material and supplier). In addition, there has been a problem with quality, the purity varying considerably from one supplier to the next. Alpha Ventron appears to have the best reputation for supplying the critical TMGa. The reactant gases (primarily Arsine) are similarly priced and must also be carefully selected for purity. Phoenix Research is the best source for arsine. Fortunately, for research work, these materials will last several months or more.

4.2.3 Phase I Methodology

The first task in Phase I is to find an appropriate MOCVD system, purchase it and set it up in the clean room facility prepared for it. At the same time, the support facilities and equipment can be obtained and installed, and the initial material supplies purchased. Once the equipment is together and operating, the next step is deposition of undoped GaAs layers to establish the process. These initial films will be characterized for crystallinity, background impurity level and electronic parameters.

A short set of experimental depositions should follow to characterize the growth parameters and optimize the resulting films. In these experiments, the growth conditions (flow rates, temperature, pressure) would be varied systematically and the films evaluated for thickness and quality. Rapid evaluation will allow the process to be selected and fine-tuned quickly.

The next step is controlled doping and characterization of both p and n- type layers on doped GaAs. The final task in

Phase I is to demonstrate high-quality pn junctions grown by MOCVD; a necessary prerequisite for solar cell development. Concurrent with the Phase I depositions, metal deposition techniques for making ohmic contacts will be developed and then used on the test structures (Van Der Pauw patterns, mesa diodes, etc.).

4.3 Phase II: Solar Cell Development

With the MOCVD system and its backup facilities established and characterized, solar cell development can begin. Due to the tight timing constraints, it would be best to use the simplest cell structure possible. This could be the $n^+ p$ homojunction or the AlGaAs/GaAs heteroface, (see Chapter 2), whichever appears most feasible at the time. A final decision on the cell structure cannot be made at this time since it depends on the capabilities of the MOCVD system and the performance of the two cell types. The actual device structure in terms of layer thicknesses and doping levels can be set initially to the published values and then modified as required. Starting with a proven cell design should minimize the research and development work required so that efficient cells can be quickly obtained.

A solar cell is of course, more than a pn junction. Along with the semiconductor structure, good ohmic contacts and an AR coating will have to be developed. In addition, test techniques for evaluating the solar cells will have to be implemented to provide feedback for optimizing the cell design.

4.3.1 Cell Fabrication Process

The details of the deposition process will depend on the type of cell structure and the type of MOCVD system chosen. Also, the process will doubtless evolve in unpredictable ways as the development proceeds. However, a general outline of a typical process can be given as an indication of the level of complexity. The n^+ p homojunction structure (see figure 2.3) will be used as an example.

The starting material for this structure is p^+ GaAs wafers. These will be polished and/or etched and then cleaned and placed onto the susceptor in the MOCVD system. The first layer is a p^+ buffer layer deposited at a high rate (say 10 m/hr) to a thickness of 3 to 10 m. This buffer is required to separate the active cell area from the substrate surface which may have surface defects or residual contamination.

The deposition rate will then be reduced by adjusting the gas flows or other deposition conditions for better control of the thinner active layers. A lightly doped p layer a few m thick would be followed by a very thin n^+ layer. The change from p to n^+ would be abrupt and controlled by changing the dopant species and its flow rate. It is for this sort of precise and repeatable control that a microcomputer controlled MOCVD system is required. The thickness of the n^+ layer is a critical parameter in the cell structure and one which will have to be carefully optimized.

After growth of the cell structure, the substrates are removed from the MOCVD reactor and the contacts are deposited. This is best done by e-beam evaporation through a shadow mask.

The contact used on the front will be different from that used for the back of the cell. Contacts are discussed in the following section. The contacts would be sintered and the anti-reflective coating added (see section 4.3.3). The total area of the cell will be delineated by mesa etching for small devices or scribing for larger cells. Finally, the cells will be tested to measure their I-V characteristics, efficiency and spectral response.

4.3.2 Solar Cell Contacts

The metallic contacts to a solar cell are a critical component, especially for space applications. They must be good ohmic contacts with low resistance. They must be strongly adherent and stable under space conditions to provide a reliable, long life. They should be weldable for ease of interconnection and finally, should be relatively low cost and easy to fabricate. Making good ohmic contacts to GaAs and AlGaAs was once difficult, however these problems have been overcome. Thus, while some research will be required, the selection should be made easy by referring to the published work done by others.

The best developed GaAs space cell contacts are those developed by Hughes [28, 29] for their AlGaAs/GaAs heteroface structure. For the n GaAs substrate, 300 nm of Au-Ge-Ni is used with a 3 μm Ag overlay. For the p AlGaAs front contact grid, a 300 nm layer of Au-Zn is sputtered and a 3μm Ag overlay added. There was no mention of sintering. The problem of aluminum oxide interfering with contacts to the AlGaAs layer was solved but the technique was not disclosed. It probably involves a sputter cleaning process prior to sputter deposition of the grid metal. These contacts have passed all the space qualification tests (temperature cycling, humidity, pull test) and are weldable.

For the homojunction GaAs cell development work done at MIT, electroplated Au contacts were initially used on both front and back [32]. These were then flash annealed for one second at 300°C so as not to damage the extremely shallow junction. The front contact to the n^+ GaAs layer was later changed to electroplated Sn with good results [77]. Varian has developed a thin GaAs cell which uses the multilayered Au/Ge/Ni/Au metallization with thicknesses 50/15/10/100 nm evaporated by e-beam to contact the n^+-type base layer [78]. The contact is sintered for a few seconds at 300°C. For p-GaAs and n-AlGaAs, they have also developed a sintered Al/Mg/Au contact [64]. RTI uses a five-layer Mg/Ti/Pd/Ag/Al metallization for contacting p^+ AlGaAs and a simple Sn/Ag contact for the n-GaAs back contact of their heteroface structure [65]. Both contacts are sintered at 550°C for 3-4 minutes in hydrogen. NASA has performed some research comparing the thermal stability of a variety of GaAs contact metals [81]. Solar cells were baked at 240 to 400°C for long periods. Cells with Pd/Ag, Pd, Ag or Ti contacts suffered degradation in Voc. Better results were obtained with Au, Cr, Zn, Cr/Au.

While there is clearly a lot of research to be done on GaAs contacts, it should be possible to use one of the proven processes. Most of these are based on Au, either pure or alloyed with Ge or Zn. While gold is expensive, the small amount used in a cell should not significantly affect the cost of space cells. Since the Hughes process [29] seems to be the most advanced, it would be a good starting point for Phase II. The contact deposition and sintering details would have to be developed, based on the published literature.

The grid pattern for the front contact is easy to develop and can be readily modified as required. Numerous pattern definition methods can be used including standard photolithography and liftoff techniques. For evaporated contacts, the simplest approach is probably to use a shadow mask to define the pattern as it is deposited. Wraparound contacts could be developed for GaAs cells as for Si cells. The metallization process would be more complex than for two-sided contacts. Wraparound contacts are discussed more in Chapter 5.

4.3.3 Anti-Reflective Coating

The AR coat is another important part of the cell structure. It is designed to maximize the transmission of light into the cell. As such, it should have minimal absorption, should be compatible with the coverglass and its adhesive, and be stable under irradiation, UV and temperature cycling. In addition, a good AR coat should electronically passivate the surface of the cell to improve its collection efficiency. While this effect is more difficult to control on GaAs than for Si cells, it can nonetheless be significant. In general, the most suitable AR coatings are typically transparent oxides of metallic elements with refractive indice around 2.

As with cell contacts, a lot of work on AR coatings has been published so that no new research need be initiated. Hughes uses the proven vacuum-deposited Ta_2O_x AR coating borrowed from Si space cells [29]. Workers at the Research Triangle Institute also use Ta_2O_5, but cover the 56 nm thick layer with 80 nm of SiO_2 for a two-layer AR coat [81]. The GaAs cell group at MIT uses an anodized native oxide of GaAs [82, 35] for the AR coat in all their work [77, 35]. They claim the native oxide passivates the surface and have achieved high efficiencies using it. Others at JPL have tried the same anodization but found it caused junction shunting [38]. They then tried Sb_2O_3 with better results. Sb_2O_3 has also been used by others [44]. The JPL group has also used Si_3N_4 [39] as has Varian [41] and a Japanese group at Mitsubishi [43].

There is clearly a good selection of AR coating materials as well as deposition techniques. For this project, the selection will be based on the deposition facilities available and compatibility with the cell structure being constructed. For example, anodization reduces the thickness of the top GaAs layer and is thus suited for the $n^+ p$ homojunction structure. Whichever AR coating is used, it will have to fit in with the rest of the fabrication process (e.g. contact deposition, photolithography). In any case, the thickness of the AR coat will be adjusted to obtain the best match between the AM0 spectrum and the GaAs cell.

4.3.4 Backup Equipment and Materials

Since solar cell development involves more than simple junction growth, additional backup equipment or facilities will be required. As mentioned under Phase I, a multiple-crucible e-beam evaporator will be required to deposit the multiple-layer metal contacts discussed above. This evaporator should be under computer control for precise control of evaporation rate and thickness. A simple photolithography process will also be required, either to define the contact grid patterns directly on the cells or to make the shadow masks used during evaporation. This equipment need not be high resolution, but it should be adaptable to a variety of photoresists.

As larger cells are fabricated, a wafer scriber will be needed to cut them out of the larger GaAs substrates. The scriber could be diamond or laser operated, whichever is more suitable and, for eventual use in Phase III, should be semiautomatic. Another useful instrument would be an ellipsometer to measure the AR coatings.

Most of the extra equipment needed in Phase II however, will be used to test the solar cells as they are produced. An AMO solar simulator with a calibrated reference cell is needed if meaningful efficiency measurements are to be made. This will be coupled with an electronic controller to measure I-V characteristics and calculate fill factor and efficiency. To measure spectral response, a monochrometer or spectrometer will be needed. Additional useful equipment would include a C-V plotter for finding impurity profiles and instrumentation to measure minority carrier lifetime or diffusion length in GaAs. This latter equipment would not be required continuously and could likely be borrowed or used elsewhere on an as-needed basis.

The materials requirements will also expand in Phase II. Evaporant source materials (pure metals, AR coatings) will be needed, as will photoresists and other chemicals and gases. Mask making equipment, contact pads, a vacuum chuck, and other miscellaneous hardware will also be needed. Finally, n^+ or p^+ GaAs wafers will have to be supplied in addition to the SI wafers used in Phase I.

4.3.5 Phase II Methodology

The first major task in Phase II is to demonstrate a working solar cell. This will require development work in three areas: deposition of the correct sequence of semiconductor layers, formation of good ohmic contacts for both sides of the cell, and addition of an AR coating. The first devices will by necessity be small, unoptimized and probably with a simplified structure. However, as confidence and understanding of the various processes grows, more cells will be produced, with larger areas and higher efficiencies.

The second task will therefore be optimizing the cell structure and the fabrication process. The approach will be to systematically experiment with variations in each of the process parameters (doping level, layer thickness, contact sinter, etc.) to determine which combination provides for the best results. Each cell made will be tested and the results used to direct the optimization toward maximum cell efficiency.

Once the best structure has been found, the process will be "fine tuned". More cells will be made with larger areas to assess how well the process will scale up. Representative cells will be fully tested to gain an understanding of the limiting factors in the design. There may be some theoretical work involving cell modelling to ensure that all possible means for improving the cell have been considered and, if feasible, adopted. The purpose of Phase II will thus be to demonstrate that cells with high efficiency (say over 16% AM0 with 1 cm^2 area) can be made repeatedly.

4.4 Phase III: Production Scale Up

After efficient GaAs solar cells have been demonstrated, the process must be taken out of the laboratory context and put into small-scale production. The magnitude of this task will depend on the anticipated scale of the production, in terms of both the size and number of cells. For instance, delivering 10,000 2 x 2 cm cells for 800 peak watts at AM0 will require a much larger scale effort than producing 100 of the same cells for a tiny experimental array. At present, the goal is to put two small arrays, each about 1 m^2 on the MSAT. Thus, with the engineering model and the flight model, some 10,000 2 x 2 cm cells will be required in all. Phase III is therefore geared toward this level of production.

Regardless of the scale of production, the tasks in Phase III will remain the same. The process must be scaled up to the designed cell size and implemented in a batch processing mode. The cells must be space qualified by passing rigourous tests and a quality control program must be implemented. The only effect of the scale of production will be on the magnitude and duration of the final production runs.

4.4.1 Process Scale-Up

This basically entails modifying the process developed in Phase II to make large cells in batches (say twenty or more at a time), repeatably with an acceptable throughput and uniformity in cell performance. The degree of effort required for this will depend on the type of facilities and equipment obtained in Phases I and II. If this development work was started in a small clean room/lab with manual-operated, research-oriented equipment, then scale-up will require all new facilities and equipment. If, on the other hand, the original equipment can be readily adapted for production, and/or the lab facilities can accommodate new equipment, then the transition to production will be smoother and quicker.

For the scale of production envisaged, it would be unrealistic to try to use the same MOCVD system for all three phases. Not only would a production system be wasteful and awkward for single-wafer development work, but also the MOCVD art is advancing so rapidly that a system obtained for Phase I would be obsolete after two years unless major modifications could be made to it. Finally, obtaining a second system would allow the first system to be retained for further research. Thus, it is recommended that a second, production MOCVD system be obtained before the scale-up begins to allow it to be installed and characterized.

The same arguments do not necessarily apply to the remaining processing equipment and backup facilities. With foresight in Phases I and II, the equipment can be used directly in production, or modified for that purpose. For example, a large, multi-hearth, microprocessor-controlled, e-beam evaporator could be used in all three phases with minor changes. Other processes such as the wet chemistry and the cell testing could be readily automated if the equipment used in the first two phases was appropriate. Other test equipment would require little modification since the full range of semiconductor and cell tests would only be performed occasionally as a spot-check for quality control.

Production of solar cells will clearly require the use of larger quantities of consumable materials. Process solvents and gases, evaporation sources, MOCVD reactor chemicals and everything else used in the process will have to be supplied on a continuous basis. Obtaining the necessary materials in the required volume when needed, and assuring their quality and uniformity will be a major challenge. For example, at present, it is difficult to find suppliers of low dislocation density, heavily-doped GaAs substrates in large areas and numbers (on the order of square meters per month). Similarly, regular supplies of uniform-quality organo-metallics may be difficult to obtain. Fortunately, such problems should be less severe by the time Phase III begins.

Along with the increased materials usage comes a waste disposal problem. While it may be acceptable to vent the MOCVD reaction products outside the building during the development phases, some form of filtration or scrubbing is needed in production. Similarly the acids and solvents used in the remainder of the process will have to be properly disposed of. Because of the highly toxic nature of many of the chemicals used, strict safety precautions, including periodic health checks of the production workers will have to be enforced. It may be wise to implement these in Phase II or even I.

4.4.2 Space Qualification

Cells destined for use in space must be fully characterized. In addition, they have to pass rigourous tests to prove that they will survive launching and operate reliably in the space environment. The tests which should be performed can be divided into three groups: photovoltaic tests, mechanical tests and radiation tests. As much as possible, these tests should be performed on cells with the coverglass and interconnects attached (see Chapter 5) to best simulate the condition in which they will be used.

The photovoltaic or electrical tests will involve characterizing entire batches of cells to determine the cell-to-cell and batch-to-batch uniformity and performance distribution. I-V curves will be measured and the fill factor and efficiency determined. The effect of operating temperature on efficiency will be measured and the spectral response will be found. The mechanical testing will involve temperature cycling, thermal shock, contact pull tests, vibration, humidity, etc. [83].

Radiation testing will be performed to assess the susceptibility of the cells to electron and proton irradiation at different energies and fluxes characteristic of the radiation environment expected for MSAT. Annealing studies may also be performed although these are not a necessity. The effects of the irradiations on the photovoltaic parameters will be measured, enabling the prediction of end-of-life power or efficiency.

Ideally, the initial testing should be performed on the development cells from Phase II. The test results then would be available before the final process was fixed so that improvements could be made if necessary. Full testing would be carried out only on the early production cells after fixing the final process. The tests should use several representative cells for statistical significance. Also, the tests should be performed by an independent test laboratory to ensure unbiased results.

4.4.3 Quality Control

To qualify a solar cell process for space, stringent requirements must be met. The clean room operation must be well controlled for high yield and uniform performance of the cells. Batch control will be used to monitor the details of the process from incoming wafer inspection to final cell testing. The process will be specified to the final detail of wafer handling and equipment preparation. The cells will be 100% tested for I-V characteristics. Furthermore, spot checks of other tests (spectral response, contact pull, Hall measurements) will be performed to maintain high quality and spot problems as they arise.

Quality assurance will be a full time job. In addition to monitoring the production and testing the product, there will be continuous liaison with the material suppliers and the cell purchaser/user. This will continue through the arraying phase up to the satellite assembly and even after launch. The purpose is to assure that the cells meet the specifications, are uniform in quality and have the highest probability for reliable operation in space.

4.4.4 Phase III Methodology

Scaling up for production will clearly require a large-scale effort and fuller use of the facilities and equipment. The initial work of qualification testing, installation of a production MOCVD system and other adaptations should begin as early as possible so that the development to production transfer can proceed without delay. The early quality control preparations and procurement of materials can also start before Phase II is complete.

The key milestone in Phase III will be the finalization of the production process. Prior to this will be the transfer of the process to the production equipment and the demonstration of initial batches of large cells. There will doubtless be many minor changes as the process is adopted to the new equipment and in response to the test results. This "fine tuning" process could go on forever, but at some time, the process will be fixed and properly documented. At this point, all the preparations will go into effect. The use of the clean room will be tightened up, the quality control program will be implemented and then production will commence.

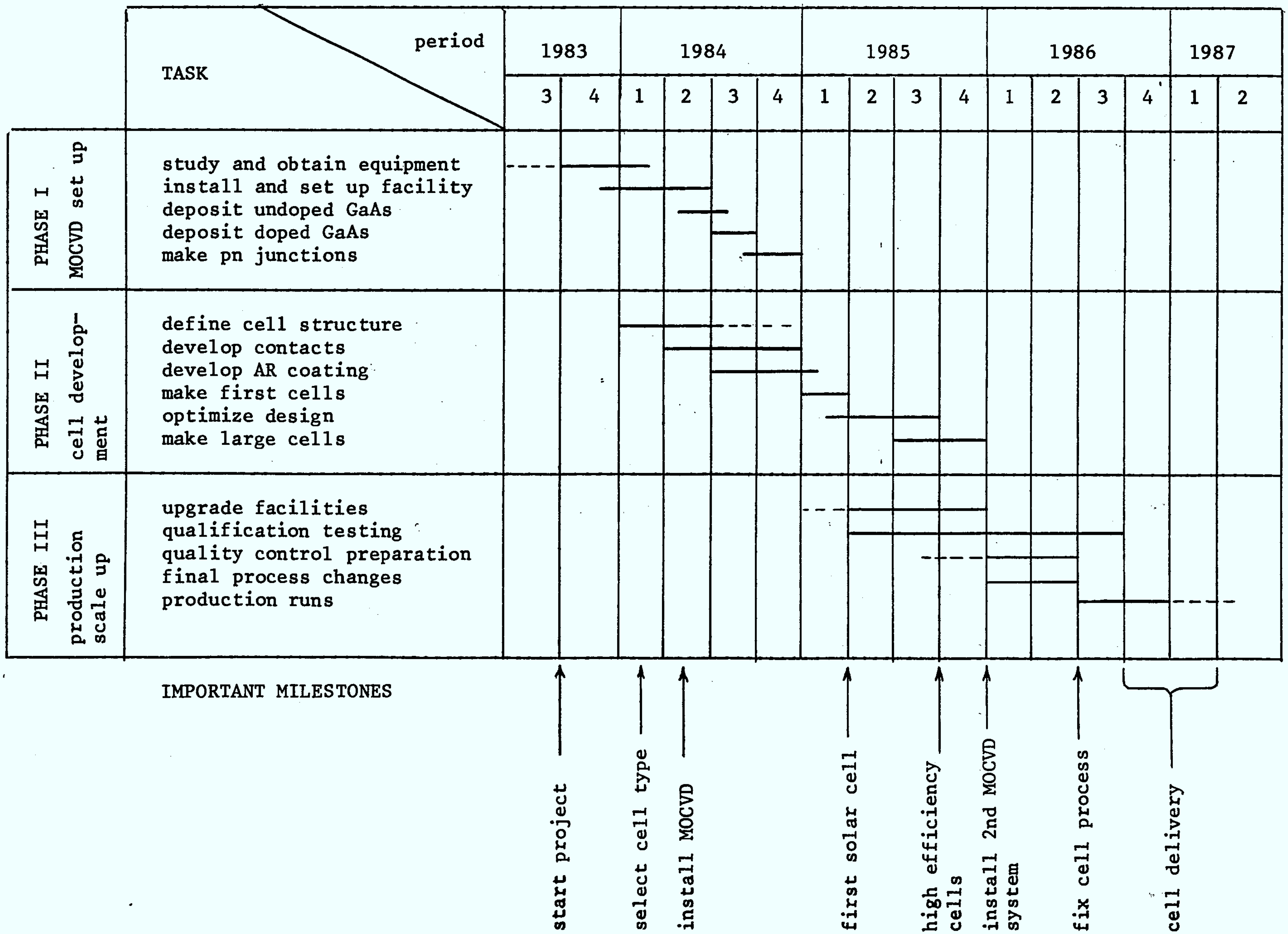
If all goes well, the actual production should be a denoement; short and uneventful. The factor limiting the production rate will likely be the MOCVD system throughput. Though three runs per day (single shift) may be feasible, two is more likely. If the Cambridge MR200 system was used, twenty 3 inch wafers with seven 2 x 2 cm cells per wafer could be processed at a time for a throughput of 280 cells per day. Thus, production of 1000 cells per week appears possible so that the 10,000 cells should require no more than three months. For good batch control and to accommodate maintenance and cleaning, this should probably be relaxed by a factor of two.

4.5 Suggested Development Schedule

To develop the capability of producing space-qualified GaAs cells in three years will require a large-scale, well directed and coordinated effort. The goal of this program is to have a small GaAs solar cell array to fly in 1988, either on MSAT or some later spacecraft. To meet this goal, the solar cells will have to be delivered at least a year in advance to the array manufacturer so that the satellite arrays for the engineering and flight models can be delivered on time. This leaves approximately three years for the entire project. Therefore, the three phases of the development have to be tightly scheduled to make best use of the available time.

A suggested development schedule based on the three phases as described above is given in Table 4.1. This schedule breaks down the phases into major tasks and fits them into the

Table 4.1 GaAs Space Cells: Suggested Development Plan



time from the end of 1983 to the beginning of 1987 by quarterly periods. The schedule applies only to the development and production of the solar cells. The development of suitable arraying techniques is not considered though it obviously must fit into the same time frame. Other possible R&D work, on tandem cells for instance, is not considered either. The three phases as well as the individual tasks have been overlapped as much as possible. Although the time is critical, in actuality, it will depend on the rate of progress and the results obtained. Clearly, there is not much room for settbacks and unforeseen delays. What follows is a brief description of the schedule.

Phase I of the project should start late in 1983 with the selection of equipment for the facility, especially the MOCVD system. This should be done quickly as the delivery and installation could require six months. Setting up the facility should start about the same time with preparation of the clean room and other laboratories. Deposition of GaAs layers can begin as soon as the MOCVD system is ready and will proceed from undoped to doped GaAs films to pn junctions, with the appropriate testing and characterization. Experience indicates that it is possible to achieve these results in the 6-8 months following installation of the MOCVD system [75].

Phase II represents an increase in the level of effort as the work shifts to the more diverse area of cell development. This work can begin very early with the selection of the type of cell to be developed: homojunction or heteroface. This decision should be made early as it may have a bearing on the MOCVD system (e.g. is AlGaAs needed?). Further studies would then define the initial solar cell structure in terms of layer thicknesses and doping levels. This work would continue as cell optimization once the first cells were made. The initial work on metal contacts and AR coatings can also proceed in parallel with Phase I.

Fabrication of the first solar cells will follow directly after the demonstration of pn junctions, using the results of the initial work in Phase II. After this, with a concerted effort, the cell structure and process can be optimized and applied to larger cells over a period of about nine months. Solar cell testing will also be started at this time, the needed test equipment having been obtained earlier in Phase II.

Phase III should also start as soon as practicable; in this case, about the time that working solar cells are first demonstrated. The facilities can be gradually upgraded as required in preparation for eventual production, culminating in the installation of a production MOCVD system. Qualification testing should also begin at this time, using early cells from Phase II and providing some feedback for the optimization work. This testing should continue until delivery of the first production cells.

Preparation of the quality control methods begin well before they are needed. After the production MOCVD system is installed, the process will be transferred to it and any final changes made. Quality control will be implemented and the production process finalized. The remaining six months (or more) can then be devoted to production.

Table 4.1 also shows the expected occurrence of the most important milestones in the project. It is unlikely that the GaAs solar cell work will end when the project finishes. Both the R&D work and cell production could continue at this time depending on the market for the cells and the need for further research work.

4.6 Manpower Requirements

The key to success of any project is the people working on it. The development of a new technology within a tight schedule requires experienced and qualified personnel. It is expected that Phase I could start with about five people and that by the time production begins in Phase III some thirteen people would be working full time. In addition, there would be a need for consultants and/or part time people to help out in many of the tasks. The key personnel requirements are as follows:

a) Project Director: This person will direct and coordinate the project and administer the facilities. He (or she) will be in charge of planning, keeping the project on schedule, hiring staff, reporting on progress and ensuring that all the work proceeds without snags. In addition, he will provide liaison with crown agencies, suppliers, the arraying subcontractor, independent test labs and the ultimate users of the cells. One important job function will be arranging continued funding for the project. The person for this position need not be technically oriented but should be familiar with the operation of high technology.

b) Technical Professionals: In Phase I, two engineering or scientific people will be needed. Between them, they should have expertise in GaAs processing, chemistry and physics, semiconductor test techniques and MOCVD technology. In Phase II a third engineer will be needed, with expertise in photovoltaics, especially space cells and testing. In Phase III a total of six technical professionals will be required. One of these will likely become production manager. In addition to the three in Phase II, a quality control officer, an engineer in charge of qualification testing and a production engineer should be added.

c) Technologists: One technologist is required in Phase I to look after operation of the clean room as well as installation and operation of the process equipment. He should be familiar with CVD and vacuum systems and be able to perform the initial depositions and to some degree, the film evaluation. A second technologist should be added in Phase II to take care of equipment maintenance and the wider range of processing and testing. Both of these will continue through Phase III.

d) Technicians: Process technicians will be required throughout the project to do the day-to-day process work. In Phase I, one good technician should be enough but in Phase III, it is expected that four technicians will be neded for solar cell production.

Table 4.2 shows a breakdown of manpower needs for the above categories and for the three phases. Clearly, these numbers are estimates only and the actual manpower requirements may be slightly different depending on the type of equipment and

LABOUR CATEGORY	PHASE I	PHASE II	PHASE III
Director/Manager ($55k/yr.)	(1) 1.25	(1) 1.0	(1) 2.5
Engineer/Scientific ($40k/yr.)	(2) 2.1	(3) 4.2	(5) 7.1
Technologist ($25k/yr.)	(1) 1.1	(2) 1.5	(2) 3.5
Technician ($20k/yr.)	(1) 1.0	(2) 2.5	(4) 4.75
Part Time ($45k/yr.)	(several) - 1	(several) - 1	(many) - 2

Table 4.2 Manpower requirements for the suggested GaAs space cell development; (people), total man years.

the scale of production opted for.

4.7 Project Cost Estimate

Having examined the equipment, materials and manpower needs and looked at the timetable for the three phases, an estimate of the overall cost of the project can now be made. Since the project starts on a relatively small scale and then expands, the budget too will start small and grow. This estimate is necessarily just that; an estimate. Because of the uncertainty of the equipment, the process and the schedule, the estimate is only an approximation. Furthermore, the estimate is arrived at using 1983 dollars; that is, ignoring inflation, salary increases and other economic variables.

a) Labour Costs: based on the manpower estimates in section 4.6, the unloaded labour cost estimates for the three phases are as follows:

	Phase I	Phase II	Phase III
	\$245K	\$400K	\$695K
b) Operating Costs:			
i) overhead 80% of direct labour (building maintenance & operation, secretarial staff, travel, etc.)	\$196K	\$320K	\$556K
ii) clean room operation and maintenance (\$30K/yr)	\$ 30K	\$ 30K	\$ 30K
iii) Materials (organo metallics, solvents, chemicals and substrates*)	\$ 20K	\$ 50K	\$600K

* Based on a cost of $\$8/cm^2$ for Bridgman GaAs wafers; about 70,000 cm^2 being required for 10,000 solar cells. Price may vary considerably with wafer quality and is expected to drop in the future.

c) Capital Costs:*

i) MOCVD system	$250K	-	$400K
ii) e-beam evaporator	$100K	-	-
iii) other processing equip.	$100K	$ 50K	$100K
iv) test equipment	$100K	$100K	$ 50K
d) Other Direct Costs This includes subcontractor fees, the cost of external services (e.g. qualification testing), and consultants.	$ 20K	$ 20K	$ 50K
e) Total Cost Per Phase	$1060K	$970K	$2490K

f) Total cost of project:

- direct labour	$1340K
- overhead	$1072K
- clean room	$ 98K
- materials	$ 670K
- capital equipment	$1250K
- other costs	$ 90K
TOTAL	$4520K

To put this grand total of $4.5M in perspective, consider the similar program now in progress at Applied Solar Energy Corp. Their program is expected to last 2 2/3 years at a cost of some $2.5M (U.S.) plus about $400K (U.S.) in initial capital outlay. Adjusting this to Canadian dollars, for the longer duration of the suggested development and for inflation produces the overall project cost of some $4.8M. Thus, the $4.5M figure is quite reasonable. Clearly this funding will have to come from a variety of sources in Canada. The overall sum could probably also be reduced slightly by careful cost cutting measures in procurement and in overhead expenses.

* These costs may vary considerably depending on the type of equipment and the supplier.

5.0 ARRAY CONSIDERATIONS

5.1 Introduction

Coupled with the selection of a space qualified solar cell must be a consideration of the type of array to be used, and the operations which must be carried out to realize that array. Whether the array is body-mounted or of the paddle-wheel type; whether it is flexible or rigid; whether it is of the fold-out or roll-out type; in each case the task of making the array will be different. The type of array will also impact on the type of solar cell. For example, an ultra-light flexible array implies that the solar cells should also be ultra-light and flexible. The thin silicon solar cell is one example of such a cell.

It is not enough to develop a solar cell, as outlined in Chapter 4, without giving due consideration as to how the resultant solar cell will be deployed in a suitable array. It can not normally be used without a suitable coverglass - in particular, the GaAs solar cell would be particularly susceptible to low energy proton irradiation without such a cover. Thus some attention must be given to the question of a suitable coverglass during the cell development. Other factors which must be considered are the interconnection procedure (hence the type of contacts to be placed on the cells), the susceptibility of the cells to shadowing when used in an array, ability to withstand large temperature variation both during arraying, and when operating in space. In addition with the movement towards concentrators in space, consideration must be given to this during the actual cell development. Some of these considerations are treated briefly in this chapter, for purposes of ensuring that should a GaAs solar cell development begin, they will be incorporated into the development at an early stage. The cell development should proceed in conjunction with the development of the capability to incorporate the cells into arrays.

5.2 Blanketing Techniques and Trends

Space arrays may be classified in a number of ways. In relation to their deployment relative to the satellite body, they may be classified as body-mounted or deployable types. The latter are often referred to as wings or paddle-wheels. The body-mounted arrays are clearly easier to handle, and tend to be more reliable since they have a rigid substrate on which they are mounted, and which provides both physical strength and extra cooling capability. However, such arrays are restricted in their power capabilities, being limited by the size of the spacecraft body. In terms of the solar cells which can be utilized, there would appear to be no restriction. The future in terms of extending their power capabilities resides in either increasing the physical size of the satellite (new launching vehicles would be needed) or of using higher efficiency solar cells. The tandem cell concept could find application here.

Deployable arrays may be classified as rigid, semi-rigid, or flexible arrays. In the rigid array, solar cells are mounted on a rigid structure, and a number of these rigid panels are hinged together, stored in folded form until the spacecraft has reached its final orbit, then opened out into wings. In the U.S. all deployable arrays are currently of the rigid type, while

Europe is more willing to exploit the flexible array [84]. Even in the rigid array, the concern is for specific power per unit weight as the trend goes to higher power satellites. Thus, light structures have evolved. Most of the rigid panels flown have been constructed in honeycomb form, with metal or reinforced plastic cores and face sheets [1]. Earlier versions used aluminum for both core and facesheet; later versions used aluminum core with glass/epoxy facesheets; still later versions used graphite/plastic facesheets. In the interests of weight reduction, the trend is towards rigid perforated honeycomb substrates combined with flexible facesheets. The TDRSS solar array substrate is a leading example of this trend [85]. Figure 5.1 illustrates this concept, where Kapton is used for both the front and rear facesheets. The substrate is rated at a weight factor of $0.75 kg/m^2$. Note that the substrate is just over 10mm thick which allows the complete array to occupy a relatively small volume when stowed. With this use of Kapton, fixing of cells to the substrate would be similar to the methods used for flexible substrates. This consideration will be left to Section 5.6.

From the standpoint of specific power per unit weight, the flexible substrate array is an attractive option, particularly for high power arrays. The flexible array, sometimes known as a solar cell blanket, is used in space as a membrane stretched between rigid support frames or as a non-supported sheet. The supported sheets imply a fold-out deployment, while the non-supported sheets could either be folded up into a flat-pack or

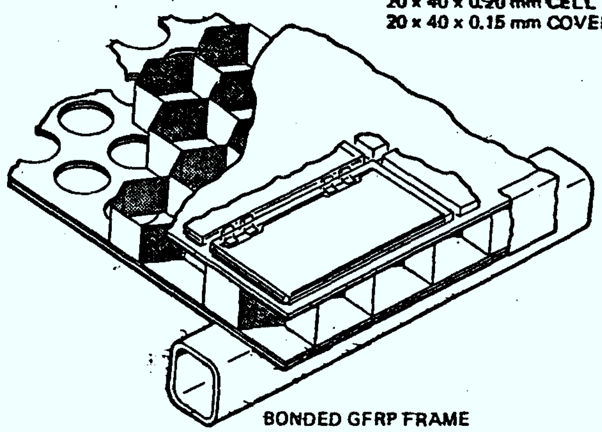


Figure 5.1: Honeycomb substrate and solar cell stack configuration for TDRSS. [85].

rolled onto a drum for storage. In either case, a deployable element is required to draw the blanket outwards from the stowage unit. Clearly with a flexible substrate, attention must be given to the mechanical strength/handling properties of the solar cells. Without a rigid substrate, the question of reliability arises, and it is this question which has delayed the acceptance of the flexible array by the U.S. space industry. Since the purpose of going to flexible substrate is to reduce both weight and stowage volume, then it is logical that thin cells should also be used in the arrays. Thus 50-100 micron thick silicon solar cells are one candidate for such arrays, as would be GaAs cells if they can be developed to be thin enough. In such cases most of the mechanical strength for the cells would be provided by the cover glass or superstrate, rather than the substrate. In addition, since the flexible substrate provides little protection against radiation damage from particles entering via the back of the cell, attention must be paid to ensuring that the cells used have high radiation tolerance. Fortunately this is the case for both thin silicon cells, and for GaAs cells. In the latter case, the absorption of low energy protons at the back side of the cell would not affect the operation of the cell. A further factor which has to be considered is the temperature of operation of the solar cells, since flexible substrates are less capable of dissipating heat than rigid arrays, hence the cells would operate at higher temperatures. Materials considerations must account for this; as well, an advantage is to be expected for the GaAs cell.

While the above considerations are those which relate directly to the solar cells to be used with flexible arrays, for completeness the status of flexible arrays will be briefly reviewed. Bogus [86] has recently presented an update of the solar array activities in Europe, where the flexible array has found much greater acceptance than in the U.S. Using silicon solar cells the double roll-out concept has been tested to 9kW power levels, and with ultra-thin cells is predicted to have the capacity to go to 20kW. The flexible fold-out array of the type to be used in L-SAT has been tested to 4.2kW, and is predicted to be extendable to 11kW. For very large arrays the SOLA program, which concentrates on developing a planar flexible blanket array, is under way. In 1980, AEG-Telefunken had demonstrated the capability to fabricate arrays using 80-100 micron silicon solar cells with minimal loss due to breakage during handling [15]. The panels realized withstood the various qualifying tests as well as panels with the thicker conventional cells. This included rolling the panels around a 20cm diameter drum (thinner cells could be expected to survive this test better than the thicker cells). The development is aimed at using 50 micron thick cells in this type of array. Designs were advanced in the U.S. in 1978 [87] for ultra-low-mass flexible arrays using 50 micron silicon cells, and partially tested out. The concepts suggested that specific powers of 200W/kg could be achieved using either roll-out or fold-out concepts for a 10kW beginning of life array.

The question of blanketing must concern any firm developing a solar cell for space applications. In realizing the blanket, once a cell has been realized, it must be tabbed for interconnecting to other cells, a coverglass must be added, interconnection carried out, and bonded to the substrate. Thus the cell design must be such that the highest possible yields are attained during each of these steps. The rest of this chapter will pay attention to these steps with emphasis on the GaAs cell in this context.

A special space array, not yet mentioned but becoming of increasing interest as power requirements grow, is the concentrator array. This approach would be particularly important for the GaAs solar cell, so merits special consideration. This is treated in Section 5.8.

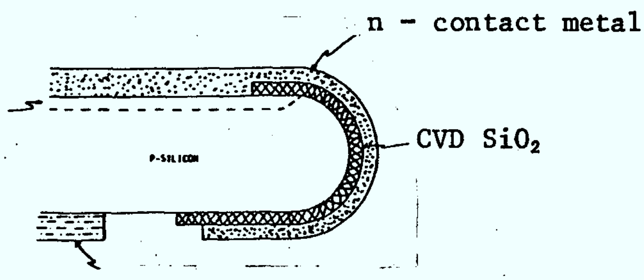
5.3 Solar Cell Contacts

The primary requirement for solar cell contacts are (a) that they make a low resistance electrical (ohmic) connection to the cell, (b) they have sufficient bond strength that they do not pull off during cell interconnection, acceleration during launch, deployment or as a consequence of thermal stressing during operation and (c) they are easily soldered or welded to. The contacts in general use on silicon space cells are vacuum deposited Ti-Pd-Ag layered structures. Titanium provides a good ohmic contact; palladium provides a humidity seal, passivating the contacts and grid lines. A thin soft solder coating dipped or pressed may be used to allow for ease of soldering cells together, however this is not necessary when a welded interconnecting scheme is done, leading to saving one processing step, and making the contact thickness more compatible with thin solar cells. For the back of the cell, a thin Aluminum layer may be used, which in the case of the silicon cell contributes to forming a back surface field, as well as aiding in back surface reflection.

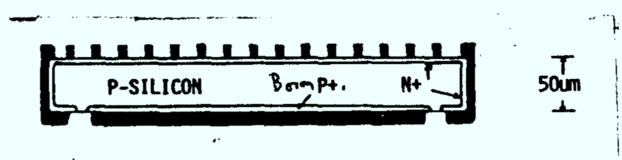
The Ti-Pd-Ag contacting technique has also been tested for GaAs cells [29], and found to work well. Consequently the same considerations apply as for silicon cells with respect to solderability or weldability.

The contact pattern on a solar cell bears substantial consideration during cell development. The front contact should occupy as small a total area as possible. For standard top/bottom cells, the top contact pad will remove some of the potential active area of the cell from the production of power. This loss can be reduced by using wraparound contacts. In this concept, the front contact is wrapped around the edge of the cell to the back. This offers potential advantages for array formation since interconnection can be done using only the back side of the cell. This also impacts on the coverglass technology as well as potential spacing of the cells.

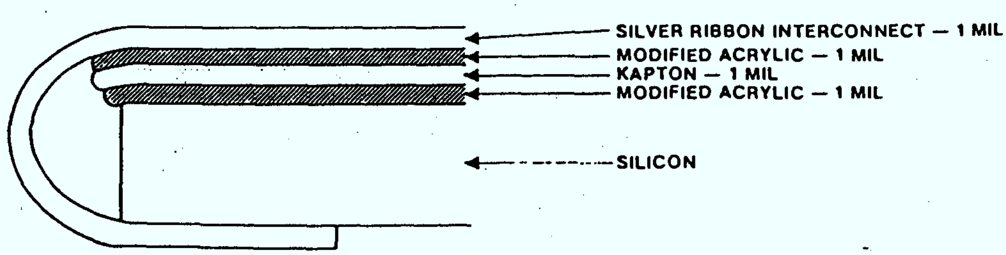
Three approaches to coplanar contacts are given in Figure 5.2 [23, 16, 88]. The three approaches, represented by the wraparound contact [23], the wraparound junction [16] and mechanical wraparound [88] have been demonstrated to work for silicon solar cells. The first approach uses a deposited insulator (e.g. SiO_2, Si_3N_4) which is patterned on both top and bottom surfaces. The silver layer then wraps around the cell edge on this insulator. The wraparound junction implies the top



(a) X - section of wraparound contact cell edge



(b) X - section of wraparound junction cell



(c) Mechanical wraparound contact configuration

Figure 5.2: Three types of wraparound contact cells.

diffusion extends around the cell edge to the back. It is probably the easiest to make for thin cells. The mechanical approach has been demonstrated using a laminated acrylic/kapton/acrylic/silver ribbon bonded to the cell back, with the silver ribbon then wrapped around to the front and welded into place. In this case no contact area saving is achieved on the front surface. However, no "give-away" losses are encountered on the back surface as is the case for the first two approaches. All three approaches result in additional costs for the cells themselves - between 40 and 50% for the first two while the mechanical wraparound added more than 20% to the cost. This must be considered in light of savings when creating the actual solar arrays in order to justify the extra expenses.

While no wraparound contacts have been reported for GaAs solar cells, there is no reason why either of the wraparound contacts should not work. (The wraparound junction would not apply for deposited layer cells.) Both should be considered when a decision is being made regarding contacts for the cells being developed.

5.4 Solar Cell Coverglasses

Before interconnecting cells together, the front surface must be protected by a coverglass. This may, in the case of cells with coplanar (wraparound) contacts be added once the cell is completed. In the case of Top/Bottom cells, the interconnecting material may be attached to the front contacts prior to adding the coverglass, however, in some cases the coverglass does not cover the edge contact pad to allow interconnect welding at a later time. For thin cells it is particularly important to add the coverglass as early as possible, since once added the fracture rate caused by mishandling is negligible after coverglass bonding [15].

Initially coverglasses were used for temperature control only, however, with better understanding of space radiation effects, addition of the cover was also aimed at protecting the cell from some of the effects of irradiation - most notably low energy proton irradiation. Current coverglasses are discrete, being bonded to the solar cell with a suitable adhesive, which must have the property that it does not darken under ultraviolet radiation. Little success in integrating the cover glass to the cell has been reported, although electrostatic bonding has been attempted, but unsuccessfully to date since the greater than 400°C temperatures needed cause damage to the cell [89].

The two types of covers most frequently used are fused silica (Corning) and ceria-doped microsheet (Pilkington Perkin-Elmer). The former, in industrial grade, is nearly free of impurities that result in colour centers during ultraviolet or charged particle radiation. If present, these reduce transmission. The prime example used is Corning Glass 7940. Thicknesses range from .75 microns to 500 microns - the incidence of colour centers increases with increasing thickness [10]. Often with fused silica an ultraviolet reflective coating is used to reduce the darkening in the cement. This ultraviolet inhibition is already present in ceria-doped microsheet which for

0.1 mm thickness exhibits a natural sharp cut on wavelength at approximately 0.35 microns. The cerium oxide prevents formation of colour centers during UV and particle radiation. It is worth noting that the operating temperature of the solar cell can be adjusted by proper coating when fused silica is used; ceria-doped glass does not have the flexibility [10].

In bonding the coverglass to the solar cell consideration must be given to the physical properties of the solar cell and the interface between the adhesive and the antireflective coating of the cell. In general it is desirable to have the coverglass as thin as possible (for lightweight arrays), without sacrificing the radiation protective properties. To this end experiments are underway with a denser form of ceria-doped glass [90] which may be used in 0.05 mm thickness. To prevent breaking of cells due to mismatch between expansion/contraction coefficients of the glass and the cell, the bonding adhesive must be flexible. To this end silicones are typically used. The coverglass may cover all the cell, overhang on all sides, or leave the metal contact pad bare to facilitate interconnection. The configuration to be used depends on the contact pattern on the solar cell, and on whether front interconnect bonding is to be done prior to adding the coverglass. This should be considered during design of the solar cell.

The same coverglasses and adhesives as currently used for silicon cells should also be applicable to GaAs cells. Consequently, the only major consideration during the cell development will be in the handling techniques while adding the coverglass, with perhaps some adjustment in the AR coating to ensure optimum optical matching when the coverglass is in place.

5.5 Cell Interconnection

While a soldering interconnect approach may be used, welding is emerging as the technique for fastening the interconnect material to the cells, particularly for lightweight arrays. This approach obviates the need for a solder coating step. Advances are continually being made in welding techniques, e.g. ultrasonic [91] and resistance [92], which has found greater acceptance in Europe than in the U.S.

The interconnection of cells is an important consideration since stresses are placed on the contacts as the array encounters large temperature differences between dark and light zones during orbit of the earth. Two cells bonded side by side on a flexible substrate may exhibit motion as illustrated in Figure 5.3. A rigid interconnect would either break under the stresses generated or tear away the contacts from the cells. Thus the interconnect material must be flexible and allow for stress relief. For conventional thick cells, the interconnects may have out of plane stress relief loops as illustrated in Figure 5.4 (a). However, as cells decrease in thickness, the loops extend too far above the coverglass, so in-plane stress relief is necessary (see Figure 5.4 (b)). This may be accomplished using a mesh interconnect material, or a serpentine pattern (Figure 5.5), such as employed by AEG-Telefunken [15]. This in-plane stress relief is particularly necessary for cells

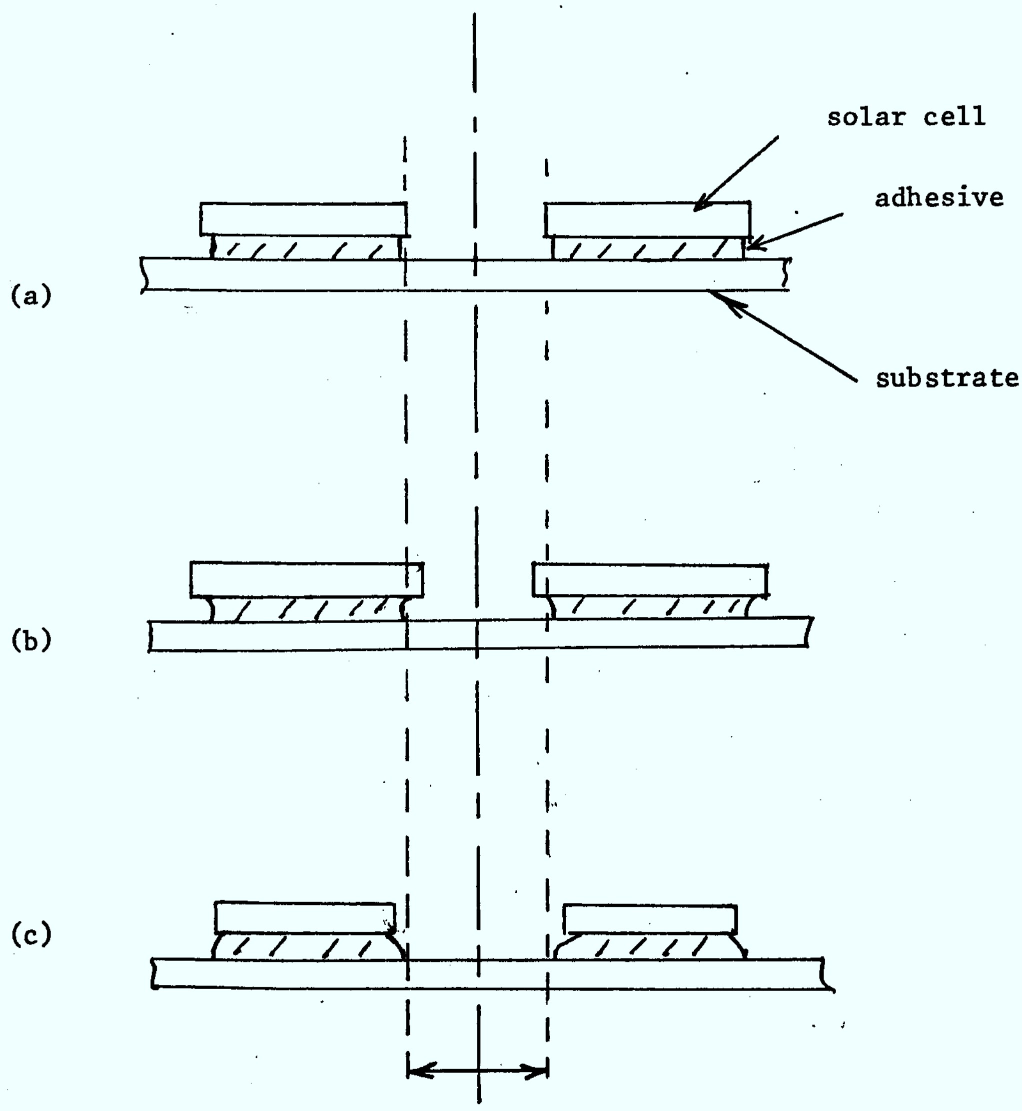
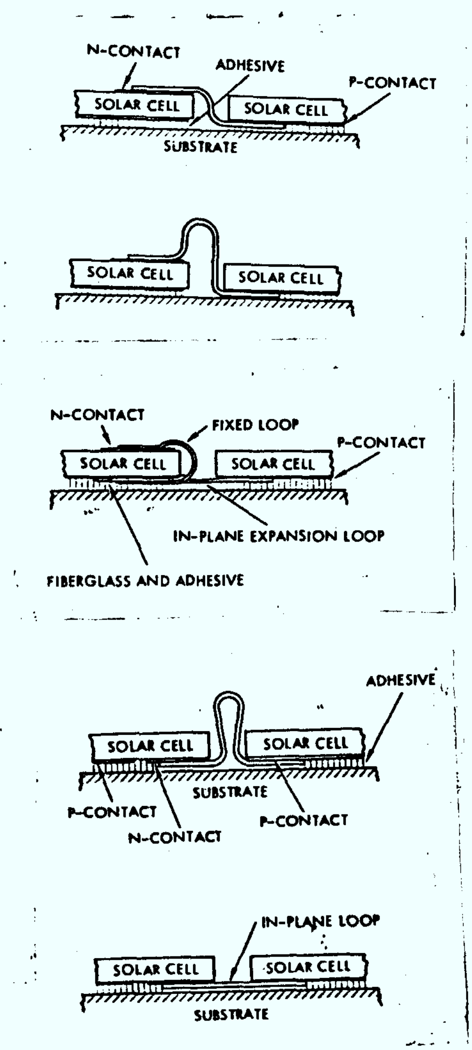


Figure 5.3: Changes in cell spacings due to temperature change.

(a) Equilibrium temperature
(b) Elevated temperature
(c) Low temperature



(a)

Z - Interconnect for top-bottom cells

out of plane interconnect loop for top-bottom cells

in plane expension loop interconnect for mechanical wraparound contact cell

(b)

out of plane loop interconnect for wraparound contact cell

in plane expansion loop interconnect for wraparound contact cell

Figure 5.4: Sample interconnects for solar cells showing out of plane and in plane interconnects [1].

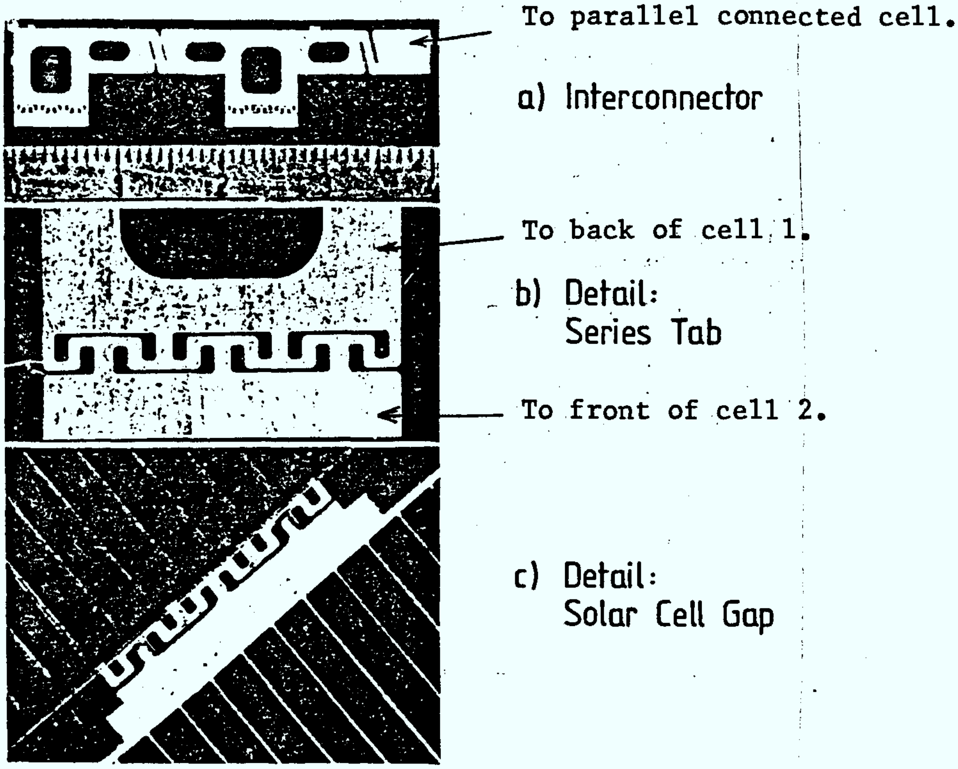


Figure 5.5: Serpentine pattern for in-plane cell interconnection [15].

with wraparound contacts.

The choice of interconnect material is also important, since it must be compatible with the contact material on the cells themselves and be flexible. Since silver is currently used as the outer layer of space cell contacts, by implication, silver should be used on the interconnect. Koch and Snakker [15] used a patterned silver interconnect which welds readily to the cell contacts. Others use silver plated materials such as Invar [87].

The sequence of operations, methods of holding cells, pressure of weld head, temperature, will all influence the strength of the bonds and overall process yield. These considerations must be built into the design of the GaAs solar cell proposed in Chapter 4. There is no reason to suspect, however, that procedures cannot be adopted to give good reliable interconnect with high yields during the arraying process.

5.6 Substrate Bonding

Substrate bonding is not perceived to be a problem for thin silicon or GaAs cells. Here it is assumed that the worst case will be flexible substrate such as bare Kapton, fibreglass reinforced Kapton, or carbon fibre reinforced Kapton. The question is one of use of a suitable adhesive, such as RTV S-691, which is flexible to allow ready expansion and contraction of the solar cells as temperature conditions vary. Koch and Snakker [15] reported no problems in handling for 100 micron thick silicon cells.

5.7 Diode Protection

Solar cell arrays can be destroyed by a number of irregularities during space flight. These include shading of parts of the array during operation, so that they act as power drains, shorting or opening of individual cells, non-uniform illumination. Hot spots can develop, destroying part of the array. In series connection most of the generated power can be dissipated in a partially shaded section where a reverse bias develops. In parallel connection, a whole row of devices containing shaded cells may become reverse biased as the rest of the array attempts to force the full photocurrent through that row.

To alleviate such a problem, shunt diodes can be placed across the parallel rows, and blocking diodes in each row of a series configuration. One approach is to use discrete diodes which could be mounted in the satellite proper. However, since many such diodes would be required in a large array, they must be incorporated into the array itself. Ideally, the diode should be configured to the same geometry as the solar cell, be bonded to the same substrate and use the same coverglass. If GaAs cells are to be used, the protective diodes ideally should be made of GaAs for compatibility, however silicon diodes such as that reported by Rasch and Roy could be used [93]. Such a diode development must be considered along with the actual cell development.

5.8 Concentrator Arrays

As higher power levels are envisaged for space arrays, the concentrator approach becomes more attractive, having the potential to reduce costs of very large arrays ($\geq$100kW) for low earth orbits. Further the use of concentration could extend the operating range of photovoltaics out to 6 AU, much further than is currently possible. A number of concentrator design concepts have been developed, ranging from simple troughs to very elaborate configurations.

Space concentrators are generally of the mirror or reflective type, since acrylics such as used in fresnel lens concentrators are too heavy for space. Designs may use spectrally sensitive reflector coatings on lightweight transparent membranes such as Kapton to prevent excessive heating of the solar cells [94]. The material could then be used in a collapsible trough concentrator which opens up during deployment. One such design for a collapsible concentrator is a truncated pentahedral pyramid concentrator configuration [95] which deploys by some means such as shown in Figure 5.6. This would have a concentration ratio of 6 for GaAs. A simple V-trough concentrator would have a concentration ratio of 2 for silicon cells.

Perhaps the most attractive concentrator for space is the miniaturized Cassegrainian concentrator module. A nine-element demonstration module has been developed [96] with the structure shown in Figure 5.7. Each optical element consists of three electroformed reflectors: a primary parabolic, a secondary hyperbolic, and a tertiary light catcher cone to improve off-

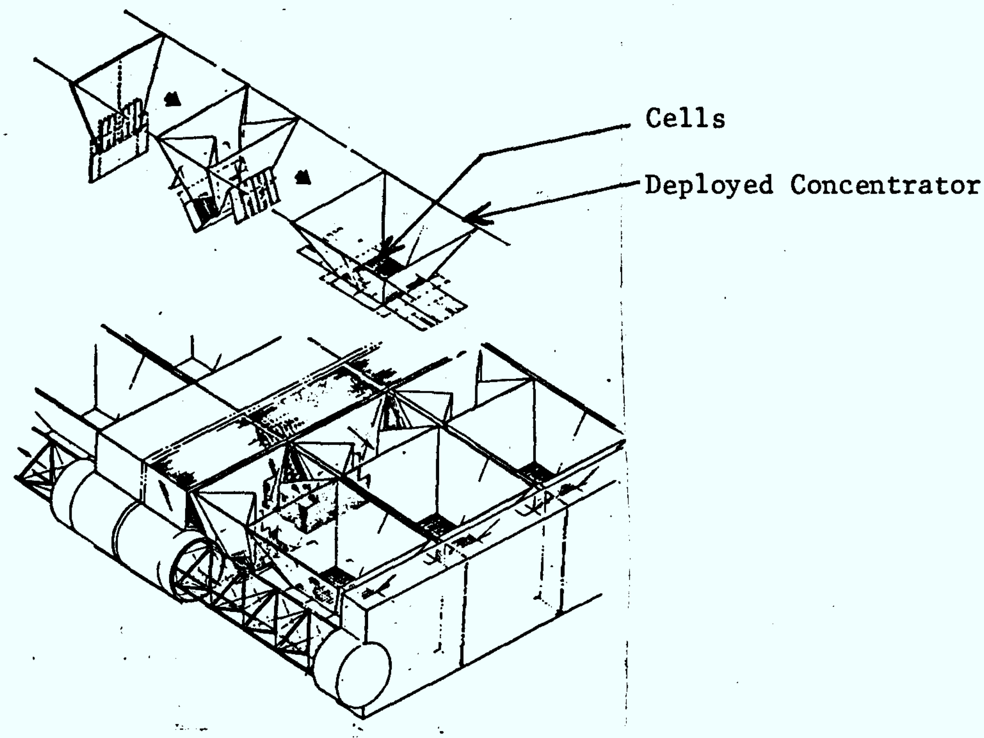


Figure 5.6. Representation of pentahedral pyramidal concentrator design and its deployment [95].

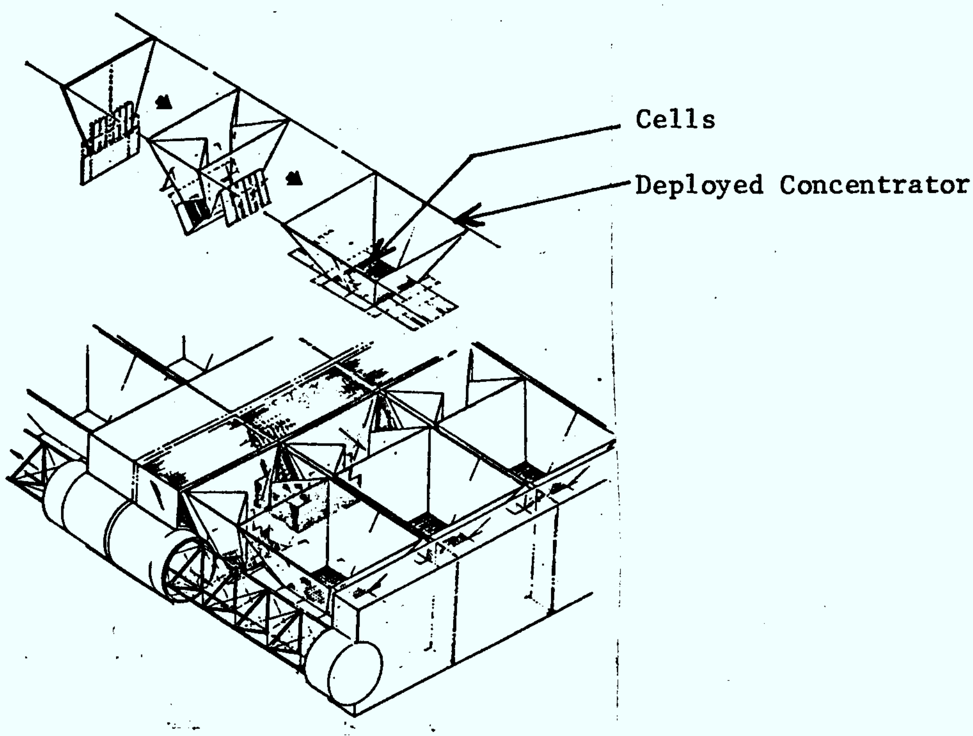
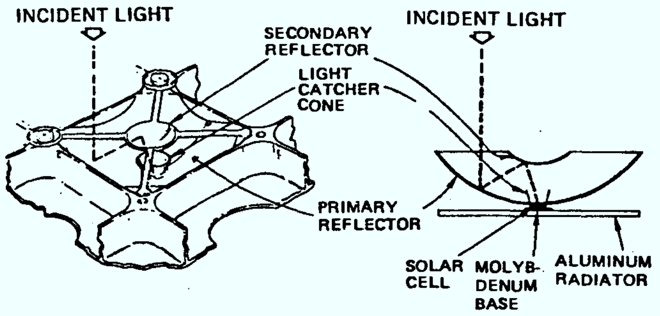
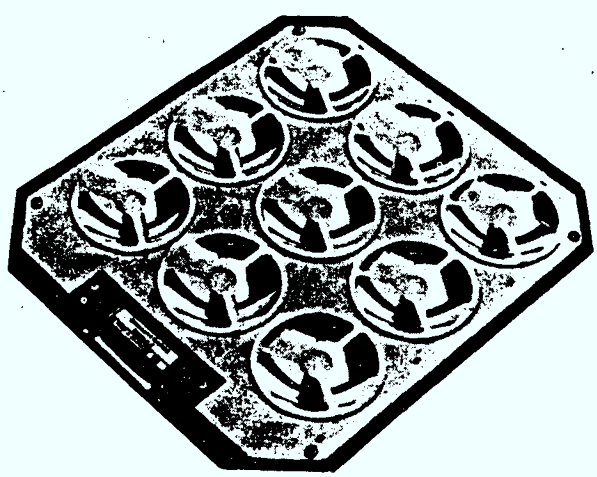


Figure 5.6. Representation of pentahedral pyramidal concentrator design and its deployment [95].



(a) Cassegrainian Concentrator Element Concept.



(b) Nine-element Cassegrainian Concentrator Demonstration Module.

Figure 5.7: Miniaturized Cassegrainian Concentrator for space [95].

pointing tolerance. The primary reflector is approximately 52 mm in diameter. Solar cells 5 x 5 mm in size with a 4 mm diameter active area are used, soldered to a molybdenum base, which in turn is soldered to a 0.25 mm thick aluminum radiator fin. This unit gives a concentration ratio of 100 suns. However, the most striking feature is that the unit appears virtually as a flat plate-like structure about 13 mm thick. This should be compared to the approximately 10 mm thickness referred to in Section 5.2 for rigid arrays with no concentration. Consequently the units could be hinged, stowed and deployed in the same manner as the honeycomb rigid solar panels.

For concentration the GaAs solar cell must be considered to be very attractive due to its larger energy bandgap, hence lower susceptibility to temperature changes than silicon. The Cassegrainian structure would result in 88°C at 235 nautical miles and approximately 64°C in geosynchronous orbit [95]. The GaAs cell could be deliberately operated at higher temperatures (say 200°C), thereby allowing self annealing of radiation damage to occur [35]. A higher end of life power could thus be expected than for a silicon cell operated on the same mode. An additional attractive future of the concentration approach in light of possible problems with the supply of good GaAs substrates, is that the cells are small (for high concentrations), hence more cells can be yielded from a single GaAs wafer. The major factor to be considered in adapting the GaAs cell to concentrator applications is the design of the front grid which must be considerably finer than for cells operating at one sun.

5.9 Conclusion

From the arraying considerations given in this Chapter, it should be clear that much thought must be given right from the outset of cell development as to how the cell will be used. This implies a close linkup between the agency charged with blanketing and the cell developer. (Both operations could, of course, reside in the same company.) Handling techniques would have to be developed to account for the physical strengths of the material used in the cells to ensure adequate yields at all stages of the process, and compatible materials would need to be used for interconnects, bonding, etc. Proper attention to details such as this should help to ensure a successful development program.

6.0 MARKET SURVEY

6.1 Introduction

Included in the major objectives of the project were the estimation of the total space solar cell market over the next ten years, prediction of the proportion which would be accessible to the GaAs solar cell technology, and assessment of the fraction of the market which would be open to capture by a Canadian manufacturer should one emerge. This information, together with the technical information on future technological directions for space cells, would provide a basis for a decision as to whether Canada should develop a space solar cell capability, and if so, what technology should be selected.

The methodology employed in meeting the above objectives was a two-phase one. The initial approach (Phase I) was to attempt to predict the total number of satellites to be launched in the period in question, and estimate the total power requirements. This was done through a mixture of literature search and consultations with various individuals and organizations. The literature survey involved (a) a reference search at NRC's CISTI library from which were selected and evaluated a list of publications which predicted future directions for space cell and satellite development, and (b) study of published reports which forecast total satellite launchings, hence the total predicted space cell market. Among the individuals and organizations consulted in Phase I were: (i) Canadian planners - to confirm the results gleaned from the literature survey and evaluate their perception of the marketplace for Canada, (ii) users of space solar cells - to further estimate cell requirements, and to assess their willingness to introduce new cells into their satellites, and (iii) companies in Canada active in assembling solar blankets - to establish whether they would accept and be willing to work with a Canadian space cell manufacturer.

Upon completion of Phase I, it became clear that political as well as technological considerations would play crucial roles in determining future space cell markets. Thus in Phase II much of the assessment of technology directions reported in Chapters 2 and 3 is relevant. A detailed study of up-to-date published literature on technology directions was supplemented through consultations with companies and individuals by telephone, letter, and, in some cases, personal visits. The personal visits were to play a key role. These visits were to: (a) selected manufacturers of space cells to determine their impression of technology directions and their market experience - particularly with reference to customer acceptance of new products such as GaAs cells; and (b) individuals with experience and expertise in space cells and a strong feel as to the future directions space cell technology would follow - primarily to help in assessing which types of cells would dominate future markets, and why.

Results from both phases are summarized in this chapter. It has clearly emerged that high efficiency GaAs cells will in the future capture a significant portion of the space cell market - particularly as satellite power requirements increase. A Canadian manufacturer of such cells could expect, so long as both performance and price competitiveness are demonstrated, to be able to capture a significant proportion of the North American market in commercial satellites, and in particular should be able to dominate the Canadian satellite market.

6.2 Satellite Launchings

In estimating the total space cell market, it is necessary to know the number of satellite launchings expected, and the power requirements for those satellites. However, before wasting time estimating the satellites to be launched by the communist block countries, it should be noted that these are not available as a market to a NATO country. Consequently the study was restricted to non-communist satellites to be launched over the next ten years.

In establishing the total number of non-communist satellites to be launched, a number of sources were consulted [97 - 100]. Different pictures of total launchings emerged from these sources, with some of the sources (e.g.[99] and [100]) being of little actual value in predicting future markets for space cells. The most useful and complete studies were those conducted by Battelle Columbus Laboratories [97] as commissioned by NASA.

In the Battelle studies done in 1981 and 1982, both a high and a low model were adopted in predicting the number of payloads over a 16 year period starting in the year of prediction. Table 6.1, a comparison of the two models for the 1981 and 1982 predictions, points out the difficulty in

Table 6.1: Comparison of Satellite Launch Predictions By Batelle's Columbus Laboratories for 1981 and 1982.

Mission Category	High Model No. of Payloads		Low Model No. of Payloads	
	1981	1982	1981	1982
International Communications	29	44	22	37
U.S. Domestic Communications	83	148	65	103
Foreign Regional Communications	141	176	84	110
U.S. Geostationary Earth Observations	8	10	8	9
Foreign Geostationary Earth Observations	26	23	14	14
U.S. Low Earth Observations	36	32	20	16
Foreign Low Earth Observations	47	77	22	34
Navigation Aids	12	8	7	6
Foreign Planetary	9	15	7	12
Scientific/Technical Development	50	60	28	33
Materials Processing	8	57	1	26
Multiservice Spacecraft/Vehicles	10	14	12	13
TOTAL	459	664 145%	290	413 142%

predicting the total market for satellites. By shifting the time base by one year, and assuming a growing activity, the 1982 models predict over a 40% increase in the total number of launchings for either the high or low models. Table 6.2 shows the projected breakdown by year, using the 1982 predictions. From this table, extracting data for the period 1982-1992 inclusive, gives an estimated 407 payloads by the high model and 263 by the low model, a considerable spread.

Of particular interest to this study are communications satellites, since this is the area in which Canada participates, and the major potential market area for Canadian-made space solar cells. The categories requiring special consideration then, from Table 6.2, are International Communications, U.S. domestic communications, and Foreign Regional communications. International communications are represented in the study by INTELSAT launchings, and are given in Table 6.3(a) and 6.3(b). Over the 10 year period 1982-1992, this represents between 27 and 31 satellites. U.S. Domestic Communications satellites in the same period should account for between 54 and 78 launchings. Total Foreign Regional Communications satellites as shown in Table 6.2 range from 72 to 110 launchings. Of these the Canadian component as given in Table 6.4 is 10-13 satellites. The only other distinctly Canadian satellite mentioned in the Battelle study is RADARSAT which represents one (1) launching in the 1982-92 time frame by either model.

In the September 20, 1982 issue of Satellite Week [98], a summary is presented of U.S. Domestic Satellites, both

TABLE 6-2: PAYLOAD DATA BY MISSION CATEGORY

CATEGORY	MODEL	LAUNCH SCHEDULE 82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	TOTAL
INTERNATIONAL COMMUNICATIONS	H	2	5	3	2	2	3	2	3	5	4	0	3	2	2	3	3	44
	L	2	3	3	2	2	2	3	3	3	2	2	2	1	2	3	2	37
U.S. DOMESTIC COMMUNICATIONS	H	6	5	14	5	8	7	11	7	7	8	11	12	19	11	10	7	148
	L	5	4	8	4	10	4	9	4	3	3	5	8	7	15	7	7	103
FOREIGN REGIONAL COMMUNICATIONS	H	3	11	6	11	12	10	15	13	9	10	10	12	12	12	16	14	176
	L	3	4	4	7	6	7	11	5	9	8	8	7	10	8	6	7	110
U.S. GEOSTATIONARY EARTH OBSERVATIONS	H	0	1	0	0	2	0	0	2	0	0	2	0	0	2	0	1	10
	L	0	1	0	0	0	2	0	0	2	0	0	0	2	0	0	2	9
FOREIGN GEOSTATIONARY EARTH OBSERVATIONS	H	0	0	1	2	2	1	1	0	3	1	1	1	5	1	3	1	23
	L	0	0	0	1	1	1	0	1	1	1	0	1	1	2	1	3	14
U.S. LOW EARTH ORBIT OBSERVATIONS	H	0	1	2	2	2	2	0	2	3	2	3	3	3	2	2	3	32
	L	0	1	1	1	1	1	1	1	1	1	1	2	0	2	0	2	16
FOREIGN LOW EARTH ORBIT OBSERVATIONS	H	1	0	4	4	4	7	5	5	6	5	5	10	4	7	4	6	77
	L	0	1	2	3	3	0	6	6	0	1	3	0	3	1	3	2	34
NAVIGATION AIDS	H	1	2	2	0	2	1	0	0	0	0	0	0	0	0	0	0	8
	L	1	0	2	1	0	2	0	0	0	0	0	0	0	0	0	0	6
FOREIGN PLANETARY	H	0	0	1	3	1	0	2	1	0	2	1	1	1	0	2	0	15
	L	0	0	1	2	1	0	0	1	1	1	1	2	0	0	2	0	12
SCIENTIFIC/TECHNICAL DEVELOPMENT	H	9	3	3	1	9	5	3	4	3	1	3	4	1	3	3	5	60
	L	7	0	5	0	1	3	4	2	2	0	2	2	1	1	2	1	33
MATERIALS TEST/ PROCESSING	H	0	0	0	1	2	1	3	3	3	3	4	7	7	7	7	9	57
	L	0	0	0	1	1	0	2	0	2	1	3	2	4	2	4	4	26
MULTISERVICE SPACECRAFT/VEHICLES	H	1	2	0	1	0	1	0	2	1	2	0	1	1	0	1	1	14
	L	1	2	0	0	0	1	1	1	0	2	1	0	2	0	2	0	13
GRAND TOTAL	H	23	30	36	32	46	38	42	42	40	38	40	54	55	47	51	50	664
	L	19	16	26	22	26	23	37	24	24	20	26	26	31	33	30	30	413

H = high model
L = low model

Table 6.3 (a)

BATTELLE'S COLUMBUS LABORATORIES

SATELLITES BY LAUNCH DATE - HIGH MODEL

	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	Total
Intelsat	2	5	3	2	2	3	2	3	5	4	0	3	2	2	3	3	44
US DOMESTIC COMMUNICATION SATELLITES																	
Telstar	–	1	1	–	1	1	1	–	1	–	–	1	1	1	–	1	10
Westar	2	–	1	–	–	–	–	–	–	–	–	2	2	–	–	–	7
TDRS	–	2	2	–	–	–	1	1	–	–	–	1	3	–	1	1	12
Satcom	3	–	2	1	–	–	–	–	1	2	2	–	–	–	–	–	11
SBS	1	–	1	–	1	–	1	1	–	1	–	–	1	1	1	1	10
Galaxy	–	2	1	–	–	–	–	–	–	–	2	1	–	1	–	1	8
Syncom	–	–	2	2	1	–	–	–	–	–	–	–	2	2	–	–	9
G Star	–	–	2	–	–	–	–	–	–	–	–	–	2	–	1	1	6
SPC	–	–	2	1	–	–	–	–	–	2	2	–	1	–	1	–	9
FLT Satcom	–	–	–	1	1	1	–	–	–	–	–	–	–	–	–	–	3
STC	–	–	–	–	4	2	–	–	–	–	–	4	2	–	–	–	12
DBS	–	–	–	–	–	3	6	3	3	3	3	3	3	6	3	–	36
Data Trans.	–	–	–	–	–	–	1	1	–	–	1	–	1	–	1	1	6
Bankers	–	–	–	–	–	–	–	–	1	–	1	–	1	–	–	–	3
Mail	–	–	–	–	–	–	1	1	1	–	–	–	–	–	2	1	6
Total US Domestic	6	5	14	5	8	7	11	7	7	8	11	12	19	11	10	7	148

Table 6.3 (b)

BATTELLE'S COLUMBUS LABORATORIES

SATELLITES BY LAUNCH DATE - LOW MODEL

	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	Total
Intelsat	2	3	3	2	2	2	3	3	3	2	2	2	1	2	3	2	37
US DOMESTIC COMMUNICATION SATELLITES																	
Telstar	-	1	1	-	-	-	2	1	-	-	-	-	1	-	-	-	6
Westar	2	-	1	-	-	-	-	-	-	-	2	1	-	-	-	-	6
TDRS	-	1	1	1	1	-	-	-	-	1	-	1	1	1	1	-	9
Satcom	2	1	-	-	1	-	1	-	-	-	1	1	1	1	-	-	9
SBS	1	-	1	-	-	1	1	1	-	1	-	-	1	1	1	-	9
Galaxy	-	1	1	-	1	-	-	-	-	-	1	1	-	1	-	-	6
Syncom	-	-	2	1	2	-	-	-	-	-	-	-	-	2	1	2	10
G Star	-	-	-	1	1	-	-	-	-	-	-	-	-	1	1	1	5
SPC	-	-	1	1	1	-	-	-	-	-	-	-	1	1	1	1	7
FLT Satcom	-	-	-	-	1	1	1	-	-	-	-	-	-	-	-	-	3
STC	-	-	-	-	2	2	2	-	-	-	-	2	2	2	-	-	12
DBS	-	-	-	-	-	-	2	2	2	-	-	-	-	2	2	2	12
Data Trans.	-	-	-	-	-	-	-	-	1	-	-	1	-	1	-	1	4
Banking	-	-	-	-	-	-	-	-	-	-	1	-	-	1	-	-	2
Mail	-	-	-	-	-	-	-	-	-	1	-	1	-	1	-	-	3
Total US Domestic	5	4	8	4	10	4	9	4	3	3	5	8	7	15	7	7	103

Table 6.4

SATELLITE BY LAUNCH DATE

CANADA

		82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	TOTAL
Telesat	H	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2
Anik C-1, C-2	L	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2
Anik C-3	H	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	1
	L	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	1
Anik F	H	–	–	–	–	–	1	1	–	1	–	–	–	–	–	–	–	3
	L	–	–	–	–	–	–	1	–	1	–	1	–	–	–	–	–	3
Anik D-1, D-2	H	1	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	2
	L	1	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	2
F/O	H	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	1	2
	L	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	1
MSAT	H	–	–	–	–	–	1	–	–	–	–	–	1	–	1	–	–	3
	L	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0
Dir. Broad.	H	–	–	–	–	–	–	2	1	1	–	–	–	–	2	1	1	8
	L	–	–	–	–	–	–	–	–	1	–	1	–	–	–	–	1	3
TOTAL	H	2	1	1	1	0	2	3	2	2	1	0	1	0	3	2	2	23
	L	2	1	0	1	1	0	1	0	2	0	3	0	1	0	0	2	14
OTHER																		
Low earth	H	–	–	–	–	–	–	–	–	1	–	–	1	–	–	1	0	3
observation	L	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	1
(RADARSAT)																		

approved and applied for, till the end of 1987. The relevant section is included as Appendix B, while a summary is presented in Table 6.5. This suggests a total of 52 satellites to the end of 1987. Allowing an average of 6-8 satellites per year thereafter to 1992, would suggest the US Domestic satellite market to be in the range of 82-92 launchings in the 1982-92 period. This is substantially higher than that projected by Battelle Columbus Laboratories.

The reports prepared by Frost and Sullivan [99, 100] while expensive, cast little light on the satellite market. They address only the communications satellite market, but not in any significant depth, and their forecasts lack backup in terms of who will be launching what satellite and when. The value of these reports lies primarily in their assessment of the actual players in the satellite business.

In the discussions with Canadian planners, a picture also emerged of the expected numbers of satellites to be launched. In particular discussions with Gray McCullagh and Don Buchanan of the Department of Communications (see Appendix C for notes on discussions), resulted in a prediction of the order of 92 domestic satellites plus or minus 9-10 in the period 1982-1992 (excluding INTELSAT). This would compare with 70 in the period between 1972 and 1982. If we add to that the 27-31 predicted for INTELSAT by Battelle, we arrive at a total of 109-133 satellites. In addition there will be military satellites. This is predicted to be only 5-10% of the total satellites; which assuming 10% would be 11-13 satellites. In any case this latter number is not important to a Canadian manufacturer; security is all-important,

Table 6.5

US DOMESTIC SATELLITES 1974 to 1987

Satellite Week, Sept. 20, 1982

OPERATOR	SATELLITE	LAUNCH
Western Union	Westar 1	1974
Western Union	Westar 2	1974
RCA	Satcom 1	1975
RCA	Satcom 2	1976
Western Union	Westar 3	1979
SBS	SBS 1	1980
SBS	SBS 2	1981
RCA	Satcom 3R.	1981
RCA	Satcom 4	1982
Western Union	Westar 4	1982
Western Union	Westar 5	1982
RCA	Satcom 5	1982
SBS	SBS 3	1982
RCA	Satcom 1R.	1983
Hughes	Galaxy 1	1983
AT&T	Telstar 301	1983
RCA	Satcom 2R.	1983
Western Union	Westar 6	1983
Hughes	Galaxy 2	1983
Southern Pacific	Spacenet 1	1984
SBS	SBS 4	1984
AT&T	Telstar 302	1984
GTE Satellite	G Star 1	1984
GTE Satellite	G Star 2	1984
Western Union	Westar 7	1984
Southern Pacific	Spacenet 2	1984
RCA	Satcom 6	1985
RCA	Satcom KU-1	1985
RCA	Satcom KU-2	1985
Western Union	Westar 8	1985
Western Union	Westar 9(KU)	1985
Western Union	Westar 10(KU)	1985

Table 6.5 (cont'd).

OPERATOR	SATELLITE	LAUNCH
AT&T	Telstar 303	1985
GTE Satellite	G Star 3	1985
Southern Pacific	Spacenet 3	1985
American Satellite	ASC 1	1985
United States Satellite	USSI 1	1985
United States Satellite	USSI 2	1985
Rainbow Satellite	Rainbow 1	1985
Cablesat General	Cablesat 1	1985
Cablesat General	Cablesat 2	1985
Western Union	Westar 11L(KU)	1986
SBS	SBS 5	1986
American Satellite	ASC 2	1986
Advanced Business Comm.	ABC 1	1986
Advanced Business Comm.	ABC 2	1986
Rainbow Satellite	Rainbow 2	1986
RCA	Satcom KU 3	1987
RCA	Satcom KU Spare	1988
AT&T	Comstar D-4	?
GTE Satellite	G Star 4	?
Hughes	Galaxy 3	?
Southern Pacific	Spacenet 4	?
Space Communications	TDRS/AW	?
Space Communications	TDRS/AW	?
American Satellite	ASC 3	?
United States Satellite	USSI 3	?
Advanced Business Comm.	ABC 3	?
Rainbow Satellite	Rainbow 3	?
Cablesat General	Cablesat 3	?

so components would be supplied from the USA.

6.3 Power Level Predictions

Power requirements for satellites have since Vanguard increased considerably. At the same time, the beginning-of-life specific power of solar arrays has increased from the value of about 2 W/kg to the 66 W/kg of the planned Solar Electric Propulsion System. Future arrays will be required to provide 300 or more W/kg. This will apply to very large arrays which are quite some distance off, in time, and thus are not considered in this market study. It should be pointed out, however that high efficiency GaAs solar cells can be expected to capture a very significant portion of the large array market, so that the power level predictions given here may be very low concerning space solar arrays in the 1990's. The total power requirements of arrays will be such that considerably more production capacity will be needed than is currently available or in the planning stages.

In arriving at power level predictions, certain very gross assumptions must be made. First of all, some model must be selected from among the various predictions given in Section 6.2 for the total numbers of satellites to be launched. Then assumptions must be made as to the percentage of satellites which will be in the body mounted array type and wing (blanket) arrays type. Finally, some prediction of the power level for each type must be made.

For purposes of prediction, the Battelle results are assumed to be the best estimates available. These are summarized in Table 6.6 according to three periods. The first is for 1982-1992 encompassing the period for which this survey was originally intended to be carried out. The second period is 1988-1992, the latter half of the survey period. This is included since, if the first Canadian GaAs solar cells were to fly in MSAT, and were accepted for use in satellites, then this would define the potential market available in the survey period. The third period, 1988-1997, represents the potential market for a 10 year period after the possible first flight of Canadian-built GaAs solar cells. An estimate is made in Table 6.6 of the satellites open to capture, insofar as supplying solar cells, to a Canadian manufacturer. A conservative approach has been adopted. It is assumed that virtually all Canadian satellites are accessible once space-qualified cells are available. For all other satellites the estimate is 10-20% of the total satellites. (It is recognized that U.S. communication satellites are more open to capture than European ones as discussed in Section 6.4.) Using this model then, of the 165 satellites predicted between 1988 and 1992, 25 are open to capture by a Canadian manufacturer, while in the 1988-1997 period, 52 of the 364 satellites are open to capture.

The next task is to determine the power levels required for these satellites. In doing this, consideration must be given to the type of application, trends in efficiency of cells per unit area (as efficiency increases, making more power per unit area available, there will be a tendency to add more equipment to each satellite, hence requiring more power). The launch vehicle

Table 6.6: Estimate of Satellites (Batelle) and Numbers which could be supplied by Canadian Manufacturers.

	TYPE OF SATELLITE	Range 1982-1992	Avg. 1982-1992	Range 1988-1992	Avg. 1988-1992	Open to Capture	Range 1988-1997	Avg. 1988-1997	Open to Capture
1.	International Communication	27-31	29	13-14	13	2	23-27	25	4
2.	U.S. Domestic Communication	58-89	75	24-44	34	6	68-103	85	13
3.	Foreign Regional Communication (Canada)	72-110 (10-13)	90 (11)	41-57 (6-8)	49 (7)	10	79-123 (9-16)	100 (12)	18
4.	U.S. Geostationary	5-7	6	2-4	3	0	6-7	6	1
5.	Foreign Geostationary	6-12	8	3-6	4	0	11-17	14	2
6.	U.S. Low Earth Orbit	10-19	14	5-10	7	1	11-23	17	2
7.	Foreign Low Earth Orbit (Canada)	25-46 (1-3)	35 (2)	16-26 (0-1)	21	2	25-57 (1-3)	40 (2)	4 (2)
8.	Navigation Aids (Canada)	6-8 (0-1)	7	0 (0-1)	0	0	0 (1)	0	0
9.	Foreign Planetary	8-11	9	4-6	5	1	(8-10)	9	1
10.	Sci./Tech. Development	26-44	35	10-14	12	1	17-30	23	2
11.	Material Test/Processing	10-20	15	8-16	12	1	24-53	36	3
12.	Multiservice Spacecraft/ Vehicle	9-10	9	5	5	1	9	9	2
	TOTALS	263-407	332	131-202	165	25	281-459	364	52

must also be considered. In this case it is assumed that the primary launch vehicle will be the space shuttle, which has a cargo bay capable of holding a load roughly 12 meters long and 4.27 meters in diameter, allowing at least 0.152 meters on all sides for dynamic clearance. Slifer [101] has analysed the power capabilities which could be carried by the space shuttle for two types of arrays, viz. a telescoping drum (extension of the spinning satellite concept where cells are body mounted), and a wing (blanket) type of array. In his analysis he restricted the size of the telescoping drum array to occupy one half of the shuttle bay during transport to orbit. On this basis, the shuttle could handle drum arrays with 8.98 kW of solar cells for Low Earth Orbits, and 6.66 kW for Geosynchronous orbits. For the wing array, the comparable figures are 12.5 kW and 9.29 kW respectively. (The shuttle is capable of launching several tens of kW if only a wing is incorporated and no significant spacecraft body. This is not, however, considered in this study.)

Without access to the detailed spacecraft designs corresponding to all types of satellites listed in Table 6.6, it is necessary to make certain assumptions in arriving at power requirements. Currently a significant proportion of satellites require roughly 1 kW end of life (EOL) power. This can be expected to continue in the period after 1988. To arrive at the beginning-of-life (BOL) power, the following models are assumed. Firstly, a radiation-associated degradation of 25% is assumed between BOL and EOL. For the body mounted cells a factor of 2.3

is applied to account for the fact that only a fraction of the cells face the sun at any time. For the wing mounted cells, or body-stabilized blankets, an extra safety margin of 30% is assumed. Applying these factors for the 1 kW EOL arrays gives 2.9 kW BOL cell power for the body mounted array, and 1.6 kW for the wing mounted array.

Recognizing that power requirements are increasing, one could select a number of power level categories. However, with the uncertainties involved, it was decided to select only one additional category for each of the two types of arrays. For the body mounted array an EOL power of 2.2 kW was selected, which by the model discussed above would give a BOL power of 6.66 kW. This corresponds to the maximum power indicated by Slifer [101] for a telescoping drum array to be launched to Geosynchronous orbit. For the wing mounted array, an EOL power of 6 kW was selected, for a BOL power of 9.75 kW. These results, summarized in Table 6.7 should lead to reasonably conservative estimates of the total solar cell market after 1988.

Since the two types of arrays are seen in Table 6.7 to have different beginning of life power levels, then to estimate total power requirements for all satellites, it is necessary to predict the numbers of satellites which are likely to be of the spinning type and the winged type. Buchanan [102] estimates that for the 1 kW EOL satellites roughly 60% will be of the spinner type with body mounted arrays and 40% of the wing (blanket) type. This model is assumed here. For higher power satellites it is likely that the largest numbers will have deployable wing arrays. For the purposes of this study, it is assumed that 80% of the

Table 6.7: Power Capacity Model for Sattelite Arrays
(Large Power Satellites Ignored)

TYPE OF ARRAY	LOW POWER CATEGORY		MEDIUM POWER CATEGORY	
	Est. EOL Power (kw)	Est.BOL Power (kw)	Est. EOL Power (kw)	Est. BOL Power (kw)
BODY MOUNTED (Drum)	1.0	2.9	2.2	6.66
WING MOUNTED (Blanket)	1.0	1.6	6.0	9.75

Source of Figures Discussed in Text.

higher power satellites will be of the deployable wing type, and 20% of the spinner type. Finally, some prediction must be made as to the proportion of satellites in the lower power (1 kW EOL) range and in the higher power range. A reasonable assumption, based on discussions with various individuals, is that 80% will be of the low power type, with the balance being in the higher power category.

Using the above assumptions gives the predicted powers shown in Table 6.8. This analysis results in a market open to a Canadian space cell supplier of 94 kW between 1988 and 1992, and of 207 kW in the 10 year period from 1988 to 1997.

6.4 Market Accessible to Canadian Manufacturer

From Section 6.3, the solar cell power requirements were estimated for three periods, and a scenario given for the market which could potentially be captured by a Canadian solar cell manufacturer. This amounts to 94 kW in the 1988-1992 time period, and 207 kW for the ten year period from 1988 to 1997. This market must now be expressed in dollars to determine if it is sufficient to justify a GaAs solar cell development program as outlined in Chapter 4. Before this is done however, it is worthwhile commenting on the factors that were considered in arriving at the market accessible to a Canadian manufacturer.

In general, one can conclude that the North American market is open to a manufacturer if it has a proven product and the price is right or if it can do something that hasn't been done before, but which is needed. For other markets, political

Table 6.8: Predictions of Solar Cell Power Requirements

PERIOD	TOTAL SATELLITES	LOW POWER RANGE						HIGHER POWER RANGE						TOTAL BOL CELL POWER, kw
		Total No.	BODY		WING		Total Power kw	Total No.	BODY		WING		Total Power kw	
			No.	Power kw	No.	Power kw			No.	Power kw	No.	Power kw		
1982-1992	332	265	159	461	106	170	631	67	13	87	54	526	613	1,244
1988-1992	165	132	79	229	53	85	314	33	7	47	26	254	301	615
1988-1997	364	291	175	508	116	186	694	73	15	100	58	566	666	1,360
Accessible to Canadian Manufacturers 1988-1997	25	20	12	35	8	13	48	5	1	6.66	4	39	45.7	94
Accessible to Canadian Manufacturers 1988-1997	52	40	24	70	16	26	96	12	2	13.3	10	97.5	111	207

and security considerations come into play in defining (limiting) the size of the market for a Canadian manufacturer. These include:

1. NATO Membership - this would prevent Canada's making this technology available to the USSR and other East Block countries.
2. Protectionism - Markets such as Japan and Western Europe are very difficult to penetrate because of their desire to protect and assist their domestic space industries. Japan has a long record of protectionism in most industries. They have been working on GaAs cells for some time, hence would exclude off-shore companies from supplying the Japanese market. In Western Europe, ESA is dedicated to the establishment of an European community, it would be particularly difficult to sell to France and progressively less difficult to sell to Britain and Italy.
3. Security - Military satellites now account for 5% to 10% of the space market with most of the non-Soviet satellites being American. The American military satellites appear to be completely off limits for non-American suppliers because of their high security and strategic importance.

The above factors limit the scope for a Canadian company to dealing mainly in the North American satellite market which builds the satellites for Canada, U.S. and most of the third world countries.

To arrive at a dollar value for the market potential, it is necessary to make some assumptions as to the trend in solar cell prices, in particular, for GaAs solar cells. Perhaps the best estimate of cost trends for GaAs cells is that provided by Brandhorst et al [37]. Their predictions are represented in Figure 6.1, showing the presently available GaAs cells (approximately 16% efficient) made by Liquid Phase Epitaxy (LPE) to cost of the order of $850/watt (1980 US dollars). With future reductions in substrate cost, improvements in substrate quality to give efficiencies greater than 18%, and development of a volume capability, this price could be expected to drop to about $350 per watt (1980 US dollars) for either the LPE approach of Vapour Phase Epitaxy (VPE) as represented by MOCVD.

Finally, as ultra-thin GaAs cells are made at 18% efficiency, this could drop to $60-$70/watt (1980 US dollars). No real time scale is given in this reference however, so some speculation is necessary in predicting the total market value.

Kamath [28], who is directly involved in the LPE GaAs solar cell development at Hughes Research Laboratories, has also projected the costs of GaAs solar cells. For a 2 x 2 cm solar cell after two years experience at a production rate of 100,000 cells/year, he estimates the cost to be less than $50.00 US. Assuming a 16% efficiency for the cells this would amount to a power output of 21.65 mW/cm^2 or 86.6 mW per cell. Thus roughly 11.5 cells would be needed for one watt of power. This would result in a cost of less than $575 per watt (production rate less than 19 kW/year). For a production rate of 500,000 cells per year (43.5 kW/year), this would be reduced to $30/cell or

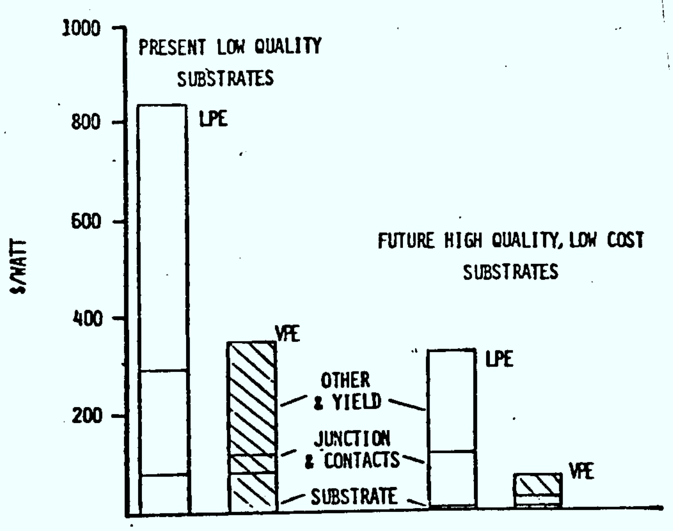


Figure 6.1: Projected cost of Trends for Liquid Phase Epitaxy (LPE) and Vapour Phase Epitaxy (VPE) GaAs Space Solar Cells. [37].

$345/watt which agrees with the projection of Brandhorst et al [37]. For a 2 cm x 4 cm cell, the costs would be reduced, since less handling would be necessary. Thus a price of $70/cell is seen at the lower production level, amounting to $400/watt, or $40 per cell at the higher production level, or $230/watt. Using Kamath's results as background, and a linear interpolation between production levels, Table 6.9 was constructed. Note that technology changes raising the efficiencies result in cost savings, so the trend will be downward during the period of the present study.

The market which can be captured by GaAs solar cells is not predicted by cost alone. Since GaAs cells offer performance advantages over silicon, especially for long life missions, a $300 GaAs cell can be cost competitive with a $100/watt silicon solar cell, and even with zero costs assumed for silicon cells and $60/watt for GaAs, the latter competes effectively [37].

In predicting the actual market which could be captured by a new GaAs space cell, it must be recognized that the space industry is very conservative. The risks are too great to rapidly adopt a new product until adequate confidence can be built up that it will perform reliably. Consequently, even if a Canadian solar cell flew in MSAT, it would be some time before it was accepted by agencies in the U.S. and other countries for use in their satellites. All Canadian satellites could, of course, be artificially forced to use these cells.

If all the market indicated in Table 6.8 as being accessible to a Canadian GaAs solar cell manufacturer, were to be captured, the average yearly production between 1988 and 1992 would be 18.8 kW. Assuming the cells were 2 x 4 cm size, and 17% efficiency, then extrapolation in Table 6.9 would predict a cost of the order of $375/watt (1980 US dollars). Thus the total potential market in this period for the Canadian manufacturer would be $35.25M (1980 US dollars). While this may look very attractive, and would result in development costs being recovered very rapidly, it is not realistic in view of the lag which would inevitably be involved between first flight and utilization. A more realistic projection might be that 20% of this potential market is captured by a Canadian GaAs solar cell. The cost per watt would be higher since the production level would be only about 4 kW/year. Thus the cost would be of the order of $650/watt, so the sales in 1988-1992 period would be about $12M (1980 US dollars).

The following five years to 1997 should see a greater acceptance of the GaAs cell as more experience is gained, and as higher power satellites are flown - there may then be no option but to use GaAs cells. The price of the cells could fall to about $300/watt, leading to a total market which Canada might capture of $34M (1980 US dollars). Assuming a 40% capture rate for this period, and a price of $400/watt, the market would be $18M (1980 US dollars) for the Canadian firm. Thus over the 10 year period from 1988 to 1997, a Canadian firm might realistically expect to sell $30M (US 1980) of GaAs space solar cells, with a potential upper limit of $69.25M (US 1980).

The advent of very large power satellites could, of course, change the scenario considerably, opening up markets for

Table 6.9: Cost projections for GaAs Solar Cells (1980 $ U.S.) Production from Kämath [28]

PRODUCTION LEVEL	16% Cell			18% Cell			20% Cell		
	kw/yr.	cost/cell $	cost/watt $	kw/yr.	cost/cell $	cost/watt $	kw/yr.	cost/cell $	cost/watt $
100,000 2 x 2 cm cells	8.7	< 50	< 575	9.8	< 44	< 511	10.9	< 40	< 460
250,000 2 x 2 cm cells	21.7	40	460	24.4	35.6	409	27.1	32	368
500,000 2 x 2 cm cells	43.5	30	345	48.9	26.7	307	54.4	24	276
100,000 2 x 4 cm cells	17.4	70	400	19.6	62	355	21.8	56	320
250,000 2 x 4 cm cells	43.4	55	316	48.8	48.9	280	54.2	44	253
500,000 2 x 4 cm cells	87.0	40	230	97.9	35.5	204	109	32	184

GaAs cells which are at least an order of magnitude higher. This would not only step up volume, but dramatically reduce costs. Such a study is, however, beyond the scope of this report.

6.5 Impact on Canadian Aerospace Industry

The availability of Canadian solar cells as described in Section 6.4 has a much greater potential impact on the Canadian Aerospace industry than would be implied by the actual value of the solar cell market. The cost of assembling the array adds to the value. In the development of a multi-100 kW low cost solar array, Pack and Mann [103] ranked the cost elements for preparing the solar blanket (flexible blanket). On this basis the cells came out at 25% of the blanket costs. If these same numbers applied to the arrays on the satellites discussed in this study, the value of this market, assuming the same capture rates would be 4 times the value of the solar cells used. Presumably then there will be the addition of the array deployment means which could double this figure. Thus it is possible that the total market accessible to the Canadian industry in terms of solar arrays alone is 10 times the cell value. Finally, the array cost may be of the order of 5% of the satellite cost.

On the basis of the above, if one assumes that the complete arrays corresponding to the solar cells sold are prepared in Canada, then the total value to the Canadian Aeronautics industry would be $300 Million (US 1980 $). If the total satellites could be supplied then the value is $6.0 Billion (US 1980 $). Clearly it is important to do as much as possible in Canada. If the presence of a solar cell manufacturing capability enhances this, then its value is well beyond the market predicted in Section 6.4, both in terms of dollars and in spin-off jobs created.

6.6 Summary

In summary, it is indicated in this Chapter that a total potential market for Canadian-made GaAs solar cells is of the order of $35.25 Million (1980 US dollars) in the 1988-1992 time period and $69.25 Million (1980 US dollars) in the 1988-1997 period. A reasonably conservative assessment for actual capture value as $12 Million (1980 US dollars) and $30 Million (1980 US dollars) respectively for the two periods. No attention is paid to very large satellites, concentrator arrays, nor concentrator cells for terrestrial application.

The spin-off potential for the Canadian Aeronautical industry is perceived to be 10 times the value of the cell market, if arrays only are produced, and a further 20 times if complete satellites are built in Canada.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In carrying out this study, it was concluded that Gallium Arsenide solar cells offer the most promise for the future in space applications. Silicon is currently approaching the limits insofar as power is concerned. In the short term, GaAs based cells would be homojunction or heteroface (AlGaAs/GaAs) structures with efficiencies in the 16-18% AMO range. In the medium term, extensions can be seen to give efficiencies above 20% AMO, while in the long term structures were considered to give efficiencies up to 30% in thin light-weight versions. Coupled with arraying techniques considered very large power light-weight arrays can be envisaged in the 1990's.

It was concluded that any new company entering the space solar cell market should only consider GaAs based solar cells. The most promising technology for such a cell development is concluded to be Metallo Organic Chemical Vapour Deposition (MOCVD). This technology would have significant spin-offs to other devices (e.g. laser diodes). A development scenario was presented which could supply up to 5000 GaAs solar cells in time for flight in MSAT in early 1988 should this scenario be adopted. The cost of this development is concluded to be of the order of $4.8 Million Canadian starting from scratch. Savings can be expected if access to equipment at establishments such as the Communications Research Centre is provided.

A survey of the market revealed that there is considerable uncertainty in the number of satellites to be launched in the 1982-1997 period. The estimates were selected, and the market accessible to a Canadian manufacturer predicted. This was concluded to be 94 kW in the period from 1988 to 1992, and 207 kW from 1988 to 1997 for satellites not exceeding 10 kW in power. The year 1988 was selected as the starting date, since sales that would begin only after first flight. With reasonable estimates of the cost of GaAs solar cells, this market was concluded to have a potential value of $35.25 Million US (1980) in the first period and $69.25 Million US (1980) over the ten year time frame. Applying a reducing factor to account for the slowness of market penetration for GaAs cells, led to the conclusion that a Canadian cell manufacturer could reasonably expect to capture a market of $12 Million US (1980) in the first five years and $30 Million US (1980) over the ten year period. This would have a much greater importance for the Canadian Aerospace industry, since it would allow Canada to bid on complete solar arrays (a factor of 10 higher value) and complete satellites (a further factor of 20 in value).

7.2 Recommendations

Based on the findings in this study, it is recommended:

1. that the Canadian government fund the development of GaAs solar cells for space applications, based on the MOCVD technology;
2. that the development be targeted to allow first flight in early 1988;

3. that with a decision on recommendation 1, steps be taken to reserve space for GaAs cells on MSAT and RADARSAT;
4. assuming a go-ahead decision on cell development, that a deliberate policy be adopted to use the developed cells in all Canadian controlled satellites after 1988;
5. that a rapid and positive decision be made on funding the project so that development can be completed within the very tight time frame.

It is important to act now, since other companies are already in the developmental stage.

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APPENDIX A

PARTIAL LIST OF PERSONS/ORGANIZATIONS CONSULTED

Dr. P. Iles, J.G. Kukulka, and Dr. M. Yeh, Applied Solar Electric Corporation, City of Industry, California (telephone and visit).

Dr. Robert Loo, Hughes Research Labs., Malibu, California (telephone and visit).

Dr. James Hutchby, Dr. J.E. Andrews, Robert Markunas, Research Triangle Institute, Research Triangle Park, North Carolina (telephone and visit).

Dr. Graham Rife, K. Karra, G. Arthur and G. Norgate, SPAR Aerospace, Weston, Ontario (telephone and 2 visits).

Harvey Goldman, Director, Subcontracts on Procurement, Satellite and Aerospace Systems Division, SPAR Aerospace, Ste-Anne de Bellevue, Quebec (visit).

Terry King, SPAR Aerospace.

R.G. McCullagh, Director Marketing Support, Space Programs, Department of Communications.

Don Buchanan, Department of Communications.

H.B. MacRitchie, Sales Manager, Fleet Industries, Fort Erie, Ontario.

Dr. H.L. Macomber, V.P., Mongeon Ltd. (correspondence re markets).

Dr. Denis Flood, Space Photovoltaic Branch, NASA, Cleveland (correspondence).

APPENDIX B

EXTRACT FROM SATELLITE WEEK,

Vol. 4, No. 37, September 20, 1982

—Approved plan whereby Intelsat itself will be able to compete more aggressively in business satellite services. Intelsat will in Dec. consider adding more Ku-band payload to later models of Intelsat V-A, and to Intelsat VI series. Intelsat also will move toward permitting access to its space segment by lower-cost earth stations, particularly customer-premise-type equipment.

We understand that these actions together amount to giving Intelsat "a chance to catch up" but that coordination controversies are far from over.

Rough Governors meeting can be seen as preparation for Oct. 6 Assembly of Parties in Washington when further issues of coordination are likely to dominate discussion. Among other tasks, Assembly must deal with coordination requests for 6 broadcast satellite systems.

With British touting transatlantic capabilities of their forthcoming Unisats (with beam coverage to Chicago), French equipping their Telecom domsats to provide both regional European & transatlantic services, and with U.S. approving its own version of non-Intelsat international satellite services, writing is on wall that Intelsat status quo can't be maintained. While there seems to be general international agreement that Intelsat is useful and should be continued, desire of Europeans and others to participate more directly in international markets is certain to mean that Intelsat's tasks & functions will continue to change. Even those Americans with greatest personal commitment to original Intelsat ideals now accept that Intelsat must adapt to new realities.

Slot Conservation?

SHORTER SPACING SEEMS ONLY WAY TO ACCOMMODATE SATELLITE APPLICATIONS; SATELLITE BRANCH PREPARING FOR FALL ACTION ON 34 CP & SLOT REQUESTS

FCC intends to act before end of year on 2 important & related satellite issues: (1) Pile of more than 30 pending applications for launch authorities, construction permits & orbital slots. If all who have requests actually build & launch their satellites, it will effectively saturate C & Ku slots currently thought feasible for U.S. use. (2) Broader question of future orbital separations.

It's reasonable to draw conclusion that if everyone is really serious in believing that market exists for constellation of 50 U.S. domsats, only way FCC will accommodate all who build & launch will be to gradually move birds closer together. There isn't likely to be overnight shift to 2-degree separations, but given demand, 3-degree C-band spacing (vs. current 4-degree regime) will be necessary by mid-decade, with narrower separation in 1986 and beyond, according to our calculations. At Ku band, where current plan calls for 3-degree spacing, there will also be mounting pressure to move to 2 degrees.

How many slots are available? Theoretically useful North American arc appears to be between 55-143 degrees, which provides earth stations with 5-degree elevation angle and satellites with contiguous U.S. (CONUS) coverage. Available 88 degrees in arc can, at 2-degree spacing, in theory support 44 C-band & 44 Ku-band slots — but calculation isn't that simple. Canadians still have major slice of arc (116-109) reserved to themselves; further, most operators don't want to be much farther out than 66 east or 135 west.

So, at 2-degree spacing, there are really about 30 reasonably good U.S. slots. These slots can accommodate 30 C-band and 30 Ku-band, or 30 hybrid C & Ku-band birds, or some combination. At 3-degree spacing, orbit can accommodate around 20 slots. At 4-degree spacing now benchmark in C-band, orbit can provide only around 15 good slots.

That's supply. Now for demand: We count currently in service, or pending requests, totaling 22 C-band satellites, 21 Ku-band birds, and 8 hybrids — total of 51 spacecraft. Note one particularly sensitive issue raised by slot crunch: How it appears to other nations. With ITU-sponsored conferences on orbital resources coming up, there's sensitivity in U.S. govt. to need to demonstrate that U.S. is conserving orbit. This, too, implies that FCC must start to move birds much closer together. U.S. constellation, if everyone is authorized, and everyone launches, would eventually look like this:

U.S. Domsats—1987 (Approved & Applications)+

Operator	C-band	Ku-band	Hybrid	Total
RCA Americom	6	3		9
Western Union	6	3		9
AT&T	4			4
SBS		5		5
GTE Satellite		4		4
Hughes	3			3
Southern Pacific			3	3
American Satellite			3	3
Spacecom (Advanced Westar)			2	2
ABC		3		3
Rainbow		3		3
Cablesat General	3			3
Totals	22	21	8	51

+ Including ground spares.

Who Wants What

Files at FCC's Satellite Radio Branch show 34 pending requests to build and/or launch new domestic satellites. Applications break down this way: From Western Union, for 3 Ku birds plus Westars 6, 7 & 8; from RCA for 3 Ku's (which FCCers call "queues") plus Satcoms 5 & 6; from American Satellite, for 3 hybrids; from SBS, for SBS 4 & 5; from GTE Satellite Corp., for GSTARS 3 & 4; from Southern Pacific Satellite, for Spacenets 3 & 4; from U.S. Satellite Systems (backed by Manufacturer's Hanover Bank) for 3 Ku's; from AT&T to launch 3rd Telstar; from Hughes for 3rd Galaxy; from Matt Nilson's Advanced Business Communication (backed by Robert Wold) for 3 Ku's; from Rainbow Satellite (backed by Michael Pascucci's Trexar Corp. & Timothy Flynn's Inter Vivos Trust) for 3 Ku's; from new Cablesat General venture of National Christian Network, for 3 C's. We present herewith an update on status of U.S. domsats. Note that * signifies pending application at FCC:

RCA Americom

Satellite	Launch	Slot	Principal Use & Status
Satcom 1	12/75	136	Preemptible.
Satcom 2	3/76	119	Alaska, commercial, govt.
Satcom 3R	11/81	131	Cable TV, serving approx. 6,000 cable heads.
Satcom 4	1/82	83	Cable TV, serving fewer than 1,000 cable heads.
Satcom 5*	10/82	143	Alascom service on 20 transponders.
Satcom 1R*	3/83	139	Commercial & govt.
Satcom 2R*	8/83	66	Preemptible video.
Satcom 6*	1/85		Request prime arc not adjacent to other Satcoms.
Satcom Ku-1*	5/85		Requested slots between 77-88 degrees.
Satcom Ku-2*	10/85		
Satcom Ku-3*	5/87		

Satcom Ku-spare to be built by Jan. 1988.

Note: C-band Satcoms are all 24-transponder configured.

Western Union

Satellite	Launch	Slot	Principal Use & Status
Westar 1	1974	79	Co-located with Westar 2. Lightly loaded.
Westar 2	1974	79	See above. Lightly loaded.
Westar 3	8/79	91	TV & message.
Westar 4	2/82	99	TV & message.
Westar 5	6/82	123	Cable TV.
Westar 6*	9/83		Best available slot requested.
Westar 7*	1984		Best available slot requested. Possible new design.#
Westar 8*	1985		Best available slot requested. Possible new design.
Westar 9*(Ku)	1985		Best available slot with 50-state coverage requested.
Westar 10*(Ku)	1985		Best available slot with CONUS coverage.
Westar 11*(Ku)	1986		Best available slot with CONUS coverage.

Western Union has told FCC that Westars 7 onwards may be based on new body-stabilized platform with solid state amplifiers. Ku-band satellites will have 16x54-MHz transponders with frequency reuse and spot beam capability. Maximum EIRP of 46 dBw.

AT&T

Satellite	Launch	Slot	Principal Use & Status
Telstar 301	7/83	95	Replacing co-located Comstars D-1 & D-2
Telstar 302	8/84	87	Replacing Comstar D-3
Telstar 303*	5/85		4th CONUS slot requested
Comstar D-4		127.25	In service through 1986 or longer.

AT&T is replacing Comstar capacity leased from Comsat General.

SBS

Satellite	Launch	Slot	Principal Use & Status
SBS 1	11/80	100	Lightly loaded at this time.
SBS 2	9/81	97#	Lightly loaded at this time.
SBS 3	11/82	94	
SBS 4*	mid-84	92	
SBS 5*	early-86	96	

SBS requests that it be assigned 2-degree separations and that SBS 2 move to 98 degrees upon launch of SBS 5. SBS further told FCC that it depends on "substantial savings" of exercising option for 5th Hughes satellite at $30 million vs. "outside" price of $45 million.

GTE Satellite Corp.

Satellite	Launch	Slot	Principal Use & Status
GSTAR 1	5/84	106	Video.
GSTAR 2	8/84	103#	
GSTAR 3*	1985	102	
GSTAR 4*		100 or 98	

GTE has pending application to modify launch authority for GSTAR 2 to place it at 104 west, to put GSTAR 3 at 102 west and to reserve 100 west or 98 west for ultimate placement of GSTAR 4. Note that launch request for GSTAR 3 and application for GSTAR 4 CP were filed after May 18 cutoff.

Hughes

Satellite	Launch	Slot	Principal Use & Status
Galaxy 1	6/83√	74	18 transponders sold to cable networks.
Galaxy 2	9/83 √	135	Plans not announced.
Galaxy 3*	√		Requests 50-state coverage.

Hughes informs FCC of "backlog" of 140 requests for video & non-video transponder service.

Southern Pacific Satellite Co.

Satellite	Launch	Slot	Principal Use & Status
Spacenet 1	2/84√	119	Ariane launch. Mainly cable.
Spacenet 2	8/84√	70	Ariane launch. Cable & general purpose.
Spacenet 3*	2/85√	66	Was ground spare.
Spacenet 4*	√		Future ground spare.

Spacenet birds are C/Ku-band hybrids.

Space Communications Co.

Satellite	Launch	Slot	Principal Use & Status
TDRS/AW	√	91	Dedicated Advanced Westar
TDRS/AW	√	79	Shared spare.

This system is jointly owned by Western Union, Fairchild & Continental. Two other satellites will be launched for govt. tracking & data relay. Dedicated Advanced Westar will be purely civil; shared spare will include civil C-band service, Ku service shared with NASA. This program has been plagued with difficulties and it's unclear when system will be available.

American Satellite Co.

Satellite	Launch	Slot	Principal Use & Status
ASC 1*	10/85√	122	Digital networks, leased transponders.
ASC 2*	3/86√	88	
ASC 3*	√		Ground spare.

Hybrid C/Ku satellites.

Continued, P. 8

United States Satellite System Inc.

Satellite	Launch	Slot	Principal Use & Status
USSSI 1*	fall-85√	88	Holding NASA reservation, also considering
USSSI 2*	fall-85√	122	Arianespace launch services.
USSSI 3*	√		Ground spare.

Ku-band satellites with 10 full CONUS, 10 regional & spot beam transponders.

Advanced Business Communications Inc.

Satellite	Launch	Slot	Principal Use & Status
ABC 1*	late-86√	85	
ABC 2*	late-86√	125	
ABC 3*	√		Ground spare.

Each Ku-band spacecraft would carry 20 transponders with various coverage areas.

Rainbow Satellite

Satellite	Launch	Slot	Principal Use & Status
Rainbow 1*	late-85√	131	Video.
Rainbow 2*	early-86√	85	
Rainbow 3*	√		Ground spare.

Rainbow intends to launch 16-transponder Ku-band spacecraft.

Cablesat General

Satellite	Launch	Slot	Principal Use & Status
Cablesat 1*	late-85√	Extreme eastern slot (60-70) requested. Video.	
Cablesat 2*	late-85√	Extreme western slot (140-150) requested. Video.	
Cablesat 3*	√		Ground spare

Intends C-band system. Pres. is Raymond Kassis, also pres. of National Christian Network, whose first DBS application was rejected by FCC. Application filed after FCC's May 18 cutoff.

Bravo Deal Never Close

DEATH OF CBS CABLE SEEN INJECTING CAUTION INTO PLANS OF WOULD-BE PROGRAMMERS & ADVERTISERS

All executives we contacted lamented death of touted CBS Cable, went on to describe harmful impact this first major programming casualty would have on less-than-5-year-old ad-supported segment of satellite cable industry. CBS Cable lost $30 million from Oct. 1981 to Oct. 1982, CBS Bcst. Group Pres. Gene Jankowski told securities analysts last week. He described "worst case" additional losses as $10-$12 million, but he hoped to bring that figure down to zero by selling off original programming, especially talk show called Signature.

APPENDIX C

NOTES OF MEETINGS WITH

R.G. McCullagh and D. Buchanan

January 13, 1983

Notes of Meeting between R. Gray McCullagh and Glen Case
January 10, 1983, 10:00 am, 300 Slater Room 736

GMCC had prepared for me the attached ''Planned and Proposed Satellites Systems''

Japan: was excluded because of their policy of domestic procurement and Gray felt that it would be close to impossible to penetrate their market because they have been working on GaAs for a long time.

USSR: was excluded, as well as all other East Block countries, because it is against NATO regulations to export product or technology of this nature to them.

China: is a question mark at this stage and it isn't known how they will be treated or viewed vis à vis a technology embargo.

Western Europe: Gray thought that unless there was Canadian participation it would be very difficult to crack this market because Europe, through ESA, is dedicated to the establishment of a Europe space industry independent of the US as much as possible.

Within the Western European community, it would be particularly difficult to sell to France and progressively less difficult to sell to Britain and Italy.

USA: The commercial USA market is pretty open and proven performance and price are generally the determining factors. The military satellites appear to be completely off limits for NON-US companies because of high security and strategic importance.

The military satellites would not account for more than 5 to 10% of the total number of satellites at this time.

The basic types of satellites as outlined by Gray McCullagh are:

Major Types

A. Communication Satellite - 2 way communication. These are either fixed service (geostationary) or mobile.

B. Broadcast Satellite - 1 way broadcast only. These are geostationary.

C. Hybrid or A & B.

Minor Types

A. Spy

B. Radarsat

C. Search and Rescue

D. Weather

E. Military - much higher quality
   1. NATO has 3 - A, B & C

   2. UK to launch Skynet IV which will be 2 units

   3. USA - DND 5 satellites
      Navy 6 or 7
      Air Force ?

F. Scientific

- The likelihood of a Canadian Military Satellite in the foreseeable future is very small.

- Gray indicated that he was short staffed and couldn't provide me with all the help I would need but provided me with the attached and suggested that I review it and get back to him if I needed something further.

- Gray indicated the ITU (International Telecommunications Union) has a list of all satellites in space.

- Gray recommended that I contact Don Buchanan of DOC (same address) 996-9401 as he would be knowledgeable about the power requirements of various satellites. He also suggested that I contact Terry King of Spar, Ste. Anne de Bellevue (514) 457-2150, ext. 223, as he is their marketing person.

PLANNED AND PROPOSED SATELLITE SYSTEMS

(less USSR and Japan)

1. LSAT

- BSS and FSS
- frequency bands; 2 x 20/30 GHz switchable
  28/19 GHz
  19 and 29 GHz - propagation research
- Spar participating
- launch 1986.

2. USA

- a. Earth Radiation Budget Satellite (ERBS) - Space station - April 84 - 2GHz

b.	WESTAR V	- Jan. 83	- 6/4 GHz
c.	SATCOM I R	- July 83	- 6/4 GHz
d.	SATCOM II R	- December 83	- 6/4 GHz
e.	TELSTAR III A	- December 83	- 6/4 GHz
f.	TELSTAR III B	- December 84	- 6/4 GHz
g.	SPACENET I	- December 84	- 6/4 and 14/12 GHz
h.	USASAT 7 C	- July 85	- 6/4 and 14/12 GHz
i.	USASAT 7 D	- December 84	- 6/4 and 14/12 GHZ
j.	Advanced WESTAR 1	- July 85	- 6/4 and 14/12 GHz
k.	GSTAR I	- December 85	- 14/12 GHz
l.	GSTAR II	- December 86	- 14/12 GHZ
m.	MILSTAR	- 1990s	- 20/40 GHz, 7/8 GHz

3. Sweden and Norway - Tele-X - FSS and BSS experimental
- 17 and 14/12 GHz + 2 GHz
- DBS/data comms/video
- eirp 35, 46, 58 and 62 dBW
- launch 1986.

4. UK - a. UNISAT 1 - FSS and BSS
- 17/14 GHz
- 18 GHz for TV
- 12 GHz for North America
- eirp 28, 33, 50, 48.1, 46.7, 62.8, and 65.8 dBw
- mid-1986

b. SKYNET IV - 7/8 GHz - Military
43.5 - 45.5 GHZ
290-315 MHz
- eirp 27, 47, 55, 49 and 50 dBW
- Jun 85.

5. Switzerland - HELVESAT 1 - DBS
- 60 dBW
- 18/12 GHz
- 1986

6. Luxembourg - LUXSAT - DBS
- 48.75 dBW
- 18/12 GHz
- 1986

7. FRG - TVSAT - DBS
- 17/12 GHz

8. France - a. TDF 1 - BSS
- 18/12 GHz
- 1984/85

b. Telecom 1 A and 1B - FSS
- 37.5 dBW

9. Italy - SARIT - BSS
- 18/12 GHz
- 57 dBW
- mid-86

10. Europe - EUTELSAT I and II - FSS

11. ARABSAT - 6/4 and 2.5 GHz - FSS
- 1984

12. Saudi Arabia Broadcasting Satellite Systems (SABS)

- 1987 (?)

13. AFROSAT or AFSAT - possible regional satellite system for African states.

14. Mexico - SATMEX - FSS and BSS
- 6/4 and 14/12 GHz
- 1985

15. Colombia
- SATCOL - FSS
- 6/4 GHz
- under review by new government, could become type of regional satellite system including Venezuela and Ecuador.
- 1986 (?)

16. Brazil
- a. SBTS
  - FSS
  - 6/4 GHz
  - 47.5 dBW
  - 1985

  b. Remote Sensing Satellite - 1988-90

  c. Meteorological Satellite - 1988-90

17. Nigeria
- possible DOMSAT FSS
- probably 6/4 GHz
- not before 1986.

18. India
- INSAT II - FSS
- 6/4 and 2.5 GHz meteorological package
- 1983.

19. Indonesia
- PALAPA B I, 2 and 3
- 6/4 GHz
- likely regional application in ASEAN group
- 1983, 1984 and 1986

20. <u>China</u> - a. DOMSAT - FSS
- 6/4 GHz
- 1983/84

b. Broadcasting satellite - BSS
- 14/12 GHz
- no date

21. Australia - AUSSAT 1, 2 and 3 - FSS and BSS
- 14/12 GHz
- 1985

22. Korea - Possible BSS
- 14/12 GHz
- 1986-88

23. INTELSAT - IS VI - at least 10 flight models
- 1986 onward
- 6/4 and 14/12 GHz

24. INMARSAT - second generation in planning stages now, RFP Aug 83.

25. Military satellite systems for USA and NATO

26. Canada - a. MSAT - 1986 (?)
b. RADARSAT - 1990 ?
c. ANIK E and F - 1990 ?

January 14, 1983

Notes of conversation between Don Buchanan of DOC and Glen Case, January 12, 1983

Don felt that there are many sources of statistics for the number of satellites over the next decade and most were very close and that it would be impossible to determine which figure was best.

His estimate was as follows for domestic satellites - excluding Intelsat.

1982-1992 - 92 craft plus or minus 9 to 10

The actual for 1972 to 1982 was 70.

He felt that the existing number of satellites provided a good basis for forecasting future requirements.

Don broke the market down as follows:

A. Cylindrical spinner type

B. Body stabilized or panel type.

The average raw power requirement for satellites is about 1 KW but obviously the round ones would require 3 to 4 times more solar cells.

In the next 5 years he saw a move to larger panel types requiring 2 1/2 KW.

In summary he felt that 90% of all satellites would be of a commercial nature and 10% would be military. Of the 92 commercial satellites he felt that 10 to 20 would be of the 2 1/2 KW type and the balance would be in the 1 KW range. Of those in the 1 KW range, 60% would be of the cylinder type and 40% would be the panel type.

Don said that the people to contact about the market for our requirements would be the manufacturers of domestic satellites. They are

USA - Ford
Hughes
RCA
GE to a lesser extent

UK - British Aerospace

France - Spatial?

Canada - Spar

A good reference for the market is the Sept. 20, 1982 issue of Satellite Week that should be available at the DOC library.

THOMAS, R.E.
--Gallium arsenide solar cells for...