1995114127

N95-20543

NUCLEATION, GROWTH, AND STRAIN RELAXATION OF LATTICE-MISMATCHED III-V SEMICONDUCTOR EPITAXIAL LAYERS[1]

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Summary

We have investigated the early stages of evolution of highly strained 2-D InAs layers and 3-D InAs islands grown by metal-organic chemical vapor deposition (MOCVD) on (100) and (111)B GaAs substrates. The InAs epilayer / GaAs substrate combination has been chosen because the lattice-mismatch is severe (~ 7.2%), yet these materials are otherwise very similar. By examining InAs-on-GaAs composites instead of the more common $In_xGa_{1-x}As$ alloy, we remove an additional degree of freedom (x) and thereby simplify data interpretation. A matrix of experiments is described in which the MOCVD growth parameters -- susceptor temperature, TMIn flux, and AsH_3 flux -- have been varied over a wide range. Scanning electron microscopy, atomic force microscopy, transmission electron microscopy, and electron microprobe analysis have been employed to observe the thin film surface morphology. In the case of 3-D growth, we have extracted activation energies and power-dependent exponents that characterize the nucleation process. As a consequence, optimized growth conditions have been identified for depositing ~ 250 Å thick (100) and (111)B oriented InAs layers with relatively smooth surfaces. Together with preliminary data on the strain relaxation of these layers, the above results on the evolution of thin InAs films indicate that the (111)B orientation is particularly promising for yielding lattice-mismatched films that are fully relaxed with only misfit dislocations at the epilayer / substrate interface.

Introduction

In comparison with Si and Ge, III-V semiconductor alloys are well-suited for space photovoltaic applications because of improved radiation hardness and the potential for heterostructure devices with high power conversion efficiency. Unfortunately, the choice of starting substrate for the subsequent growth of III-V epitaxial layers is limited by the practical requirements of a large strength-to-weight ratio and low cost. The single crystal materials that satisfy these constraints -- Si, Ge, and, to a lesser degree, GaAs -- also possess lattice constants that differ significantly from those of the III-V semiconductor alloys of interest (fig. 1). Consequently, the lattice-mismatched epitaxial layer / substrate composite undergoes an elastic deformation that (1) causes a transformation from the desired 2-D layer-by-layer growth mode to a 3-D island mode and (2) provides the driving force for dislocation generation and propagation. The result is a rough surface and a high density of defects in the overlying epitaxial layers (fig. 2a). What is needed instead for device applications is a smooth 2-D surface with misfit dislocations at the epitaxial layer / substrate interface which relieve the strain caused by the lattice-mismatch, but do not thread the epitaxial layer and consequently degrade the device quality (fig. 2b).

Several different multi-step fabrication schemes have been attempted to improve the structural properties of lattice-mismatched epitaxial layers. In fact, the practices of using either a low-temperature buffer layer or a vicinal substrate to initiate growth, and of incorporating a compositionally graded layer or a superlattice dislocation filter between the substrate and active region, have all met with limited success (ref. 1 -4). Post-growth annealing techniques have also been explored but have proven less effective (ref. 5). Despite some encouraging results, even these multi-step methods have failed to yield defect densities low enough for high-performance minority carrier devices (< 10^4 cm^{-2}).

[1] The authors gratefully acknowledge the financial support of the National Science Foundation via the Presidential Faculty Fellowship Program (Grant # ECS-9253760) and of the NASA Graduate Student Researchers Program (Grant # NGT-50832).

Recent reports suggest that epitaxial growth conditions may strongly influence the kinetics of strain relaxation (ref. 6). Although the *minimum energy* configuration of a highly strained material is characterized by a rough, three-dimensional surface morphology, the exact nature of this *equilibrium* configuration, or even whether or not it develops at all, also depends on kinetic limitations. By implication, the efficacy of a particular buffer layer technique depends upon the experimental conditions during each step of the deposition process. In this paper, we describe the influence of the kinetic pathways of nucleation, growth, and strain relaxation on the surface morphology and the defect structure of highly-strained epitaxial thin films.

The Initial Stages of Deposition

While a comprehensive theoretical description of III-V heteroepitaxy which incorporates the complexities of MOCVD is lacking at present, a generic model of atomic deposition provides a useful reference (ref. 7). Figure 3 illustrates the initial stages of film deposition from single atoms which arrive at the substrate at a rate R and diffuse across the surface with diffusion coefficient D. The surface density of these single atoms (n_1) is then determined primarily by the competition between the arrival rate and the rate at which single atoms are lost to re-evaporation and incorporation into a growing island or pre-existing step edge. During the nucleation stage, single atoms can also couple to other atoms (binding energy E_j) to form sub-critical clusters of atoms whose density (n_j) is inversely proportional to the number of atoms in the cluster. Above a critical size i^*, the sub-critical cluster is more likely to grow into a stable island than to disintegrate. The density (n_x) and the geometry of these growing islands are the two most important parameters determining the surface morphology and defect structure of thicker epitaxial layers.

The three traditional modes of growth (ref. 8) can be described in terms of the island width-to-height ratio (w / h). In the limit of large w / h, the islands are two-dimensional even at the point of coalescence, and growth proceeds in a layer-by-layer fashion (Frank-van der Merwe). In the limit of small w / h, on the other hand, islands grow in a three-dimensional or islanding mode (Volmer-Weber). If the w / h ratio changes from a large to a small value as the islands evolve, then layer-by-layer growth is followed by islanding (Stranski-Krastanov). Growth may also proceed in a more complicated fashion for intermediate values of w / h. Specifically, as the island density increases and island coalescence begins, there is a range of w / h values which produces films that are nearly indistinguishable from those grown via the layer-by-layer mode.

As stated above, the density of growing islands is proportional to the density of critical clusters, which is inversely proportional to the number of atoms in the critical cluster and directly proportional to the density of single atoms and their binding energy. The processes depicted in Figure 3 can be quantitatively described by rate equations which govern the density of single atoms, sub-critical clusters, and stable clusters (growing islands) on the substrate surface and highlight the interrelation between nucleation and growth. Solving this set of equations in a self-consistent manner yields a nucleus saturation value (N_s)

$$N_s \sim N_o^{1-p} R^p \exp(E_a/kT),$$

where N_o is the density of absorption sites, E_a is an activation energy, and the exponent p is proportional to the critical cluster size (ref. 7).

In many cases, the stress in thick lattice-mismatched films is large enough to drive dislocation nucleation and propagation (ref. 2). However, the thickness at which dislocations nucleate and propagate in 2-D films is very sensitive to the kinetic pathways of epitaxial growth (ref. 9) and to heterogeneities in material properties (ref. 10). For example, recent work has shown that islands can form before the onset of dislocation generation (ref. 11). As these coherent islands grow, there is an increase in the driving force for dislocation generation. Thus, there is a direct connection between the evolving surface morphology and defect generation in highly-strained epitaxial layers.

Experimental Approach and Summary of Results

The InAs samples have been deposited in a horizontal-geometry MOCVD reactor at a base pressure of 100 torr, with an H_2 carrier gas flow of 12 slm and TMIn and AsH_3 sources. All growths have been performed simultaneously on (100) and (111)B Si-doped GaAs substrates. After a standard oxide desorption process, the substrate temperature (T_s) and AsH_3 flow (f_{AsH3}) are adjusted to the desired values, and the growth of InAs is initiated directly on the substrates by switching in a pre-stabilized TMIn flow (f_{TMIn}). The surface morphology has been observed by Nomarski optical microscopy (NOM), scanning electron microscopy (SEM), and atomic force microscopy (AFM). Transmission-electron microscopy (TEM) has also been performed to determine structural quality of the films. The constancy of the island density with time indicates that, except for the eventual decrease in density because of coalescence, the measured values are indeed the nucleus saturation densities. The pertinent results of these experiments are summarized in the following discussion.

The impact of substrate temperature, TMIn flow, and AsH_3 flow on InAs nucleation has been examined in a 2^3 factorial experiment on nominally 250-Å thick films. This approach is designed to efficiently evaluate the principal and interactive effects of a large set of variables (ref. 12). There are several noteworthy trends evidenced in the data of Table I. First, the island density on the (100) substrate is approximately 100x larger than that for the (111)B case. In addition, the island density on both substrates increases with either a decrease in T_s or an increase in f_{TMIn}, as shown in more detail in Figures 4a and 4b. An increase in f_{AsH3} also has a modest effect, but with the opposite sense for the two orientations. Next, the island geometry is completely different in the two cases (fig. 5a and 5b). For the (100) substrate, AFM reveals pyramids with a rectangular base aligned to the <011> crystallographic directions and side-walls best fitted by {111} planes. In contrast, the islands on the (111)B substrate are flat polygons with the base aligned to <211> directions, and extremely abrupt side-walls which are most likely {011} cleavage planes. The w / h values of the islands are also very different on the two substrate orientations, with a value of ~ 2 on the (100) substrate and ~ 50 for the (111)B case. The exponential dependence of N_s with T_s and the power dependence of N_s with f_{TMIn} agrees qualitatively with the conventional picture of nucleation. The lower densities on the (111)B substrate can be explained by assuming that the critical cluster size is larger than on the (100) substrate. However, the effect of AsH_3 flow on the nucleus saturation density cannot be accounted for via this simple single-species nucleation model.

Using these results, the surface morphology can be transformed from a 3-D into a 2-D surface. Figure 6 shows that lowering the temperature to 525 ^oC, increasing the TMIn flow to 720 sccm, and *increasing* the AsH_3 flow to 500 sccm leads to a nearly featureless 250 Å thick InAs layer on the (111)B substrate. Conditions were also found for a similar occurrence on (100) substrates. Figure 7 shows that the morphology transition on the (100) substrate is achieved by lowering the temperature to 475 ^oC, increasing the TMIn flow to 950 sccm, and *lowering* the AsH_3 flow to 82 sccm. While the films shown in 6b and 7b are both "specular," a more quantitative analysis has been obtained via AFM. The surface roughness of the strained (100) InAs layer (< 50 Å) is higher than that of (100) GaAs (< 10 Å) grown under similar conditions. However, in comparison to a (111)B GaAs layer, the surface roughness of the strained InAs is 30x lower. The flat surface and large w / h ratio of InAs islands on (111)B GaAs substrates is consistent with the observation that 2-D films form more readily (at higher temperature and lower TMIn flow) than on (100) substrates. The small w / h ratio of InAs islands on (100) substrates also accounts for the relatively large surface roughness. While TEM analysis indicates that both films are fully relaxed, the (100) film exhibits a large density of threading dislocations. However, for the (111)B InAs film, preliminary analysis reveals misfit dislocations only; no threading dislocations are observed in cross-sectional TEM images.

Conclusions

Using InAs-on-GaAs as a model high-strain system and a factorial design of experiments approach, we have demonstrated that the thin-film surface morphology is quite sensitive to epitaxial growth parameters. The temperature and TMIn effects can be described, at least qualitatively, by traditional one-species nucleation theory. However, a more complex model is needed to account for the effects of AsH_3 flow. Two-dimensional morphologies have been demonstrated on both (100) and (111)B substrate orientations; however, the (111)B orientation is more promising because only misfit dislocations are present at the epilayer / substrate interface.

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Table I : Matrix of Growths of InAs on GaAs - A 2^3 Factorial Design

Run Number	Growth Temp.(°C)	H_2 Flow in TMIn (sccm)	V/III	Island Density (cm^{-2}) (100) Substrate	Island Density (cm^{-2}) (111) Substrate
1	525	140	100	5.6×10^8	coalesced
2	600	140	100	1.4×10^8	1.9×10^6
3	525	720	100	1.0×10^9	coalesced
4	600	720	100	1.7×10^8	4.5×10^6
5	525	140	400	4.3×10^8	coalesced
6	600	140	400	4.9×10^7	2.7×10^6
7	525	720	400	6.7×10^8	coalesced
8	600	720	400	1.0×10^8	7.8×10^6

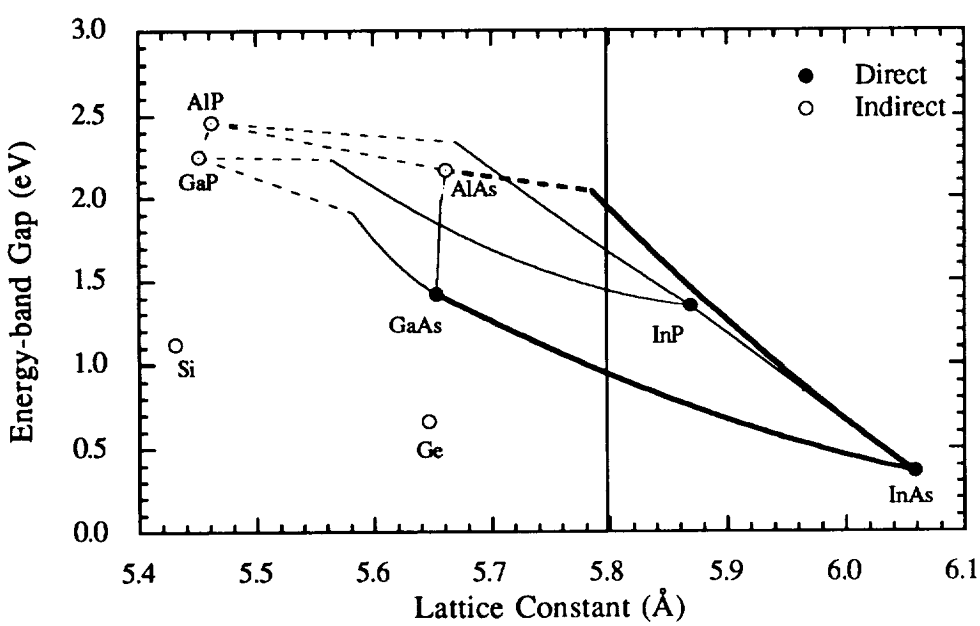


Figure - 1 Plot of energy-gap vs. lattice constant for elemental and III-V compound semiconductors and alloys. Note that InP has a lattice constant that is 3.8 % larger than that of GaAs and 8.1 % larger than Si. Also note that the $(Al_xGa_{1-x})_{0.65}In_{0.35}As$ alloy with a lattice constant of 5.8 Å covers an energy-gap range from 1 eV to 2 eV, which is the optimum energy-gap spectrum for a multijunction solar cell configuration.

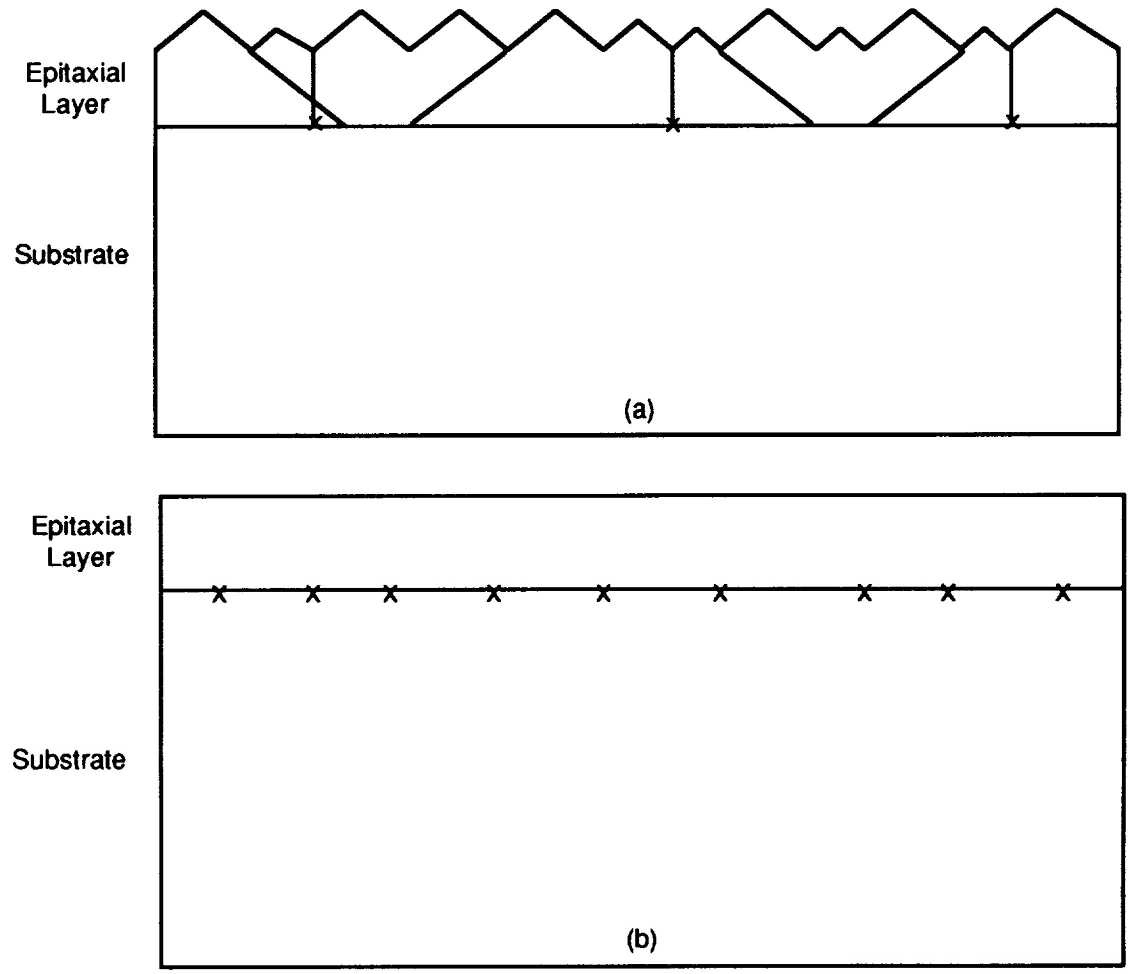


Figure - 2 (a) Relaxed epitaxial layer with a rough surface morphology and high threading dislocation density. (b) Relaxed epitaxial layer with only misfit dislocations.

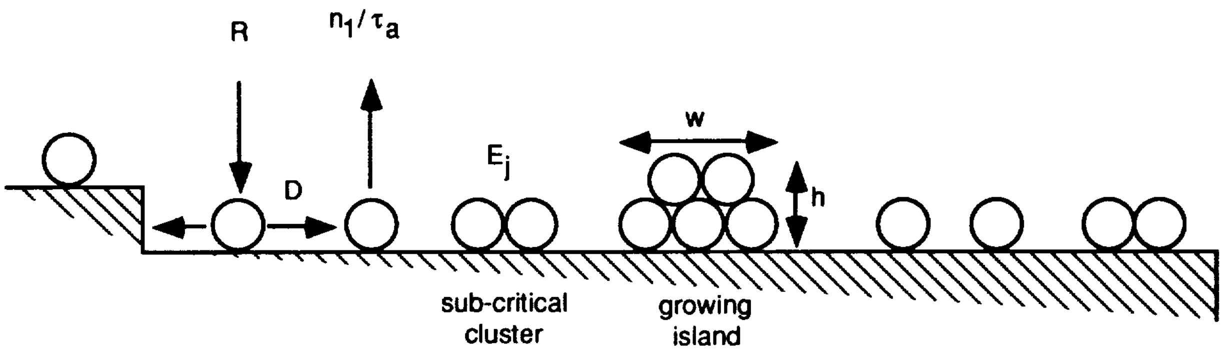
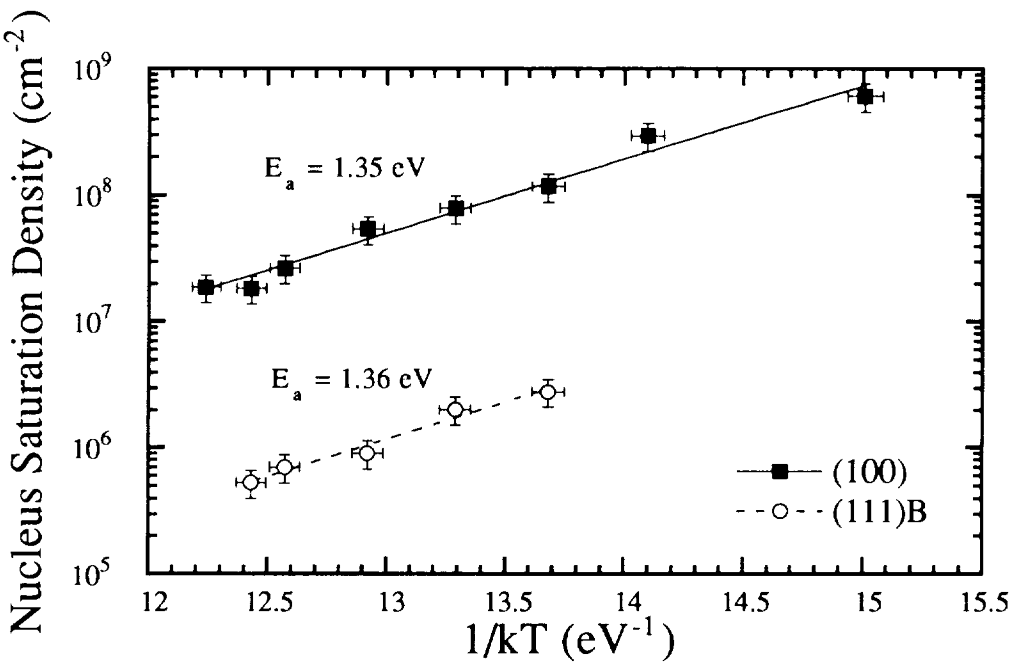
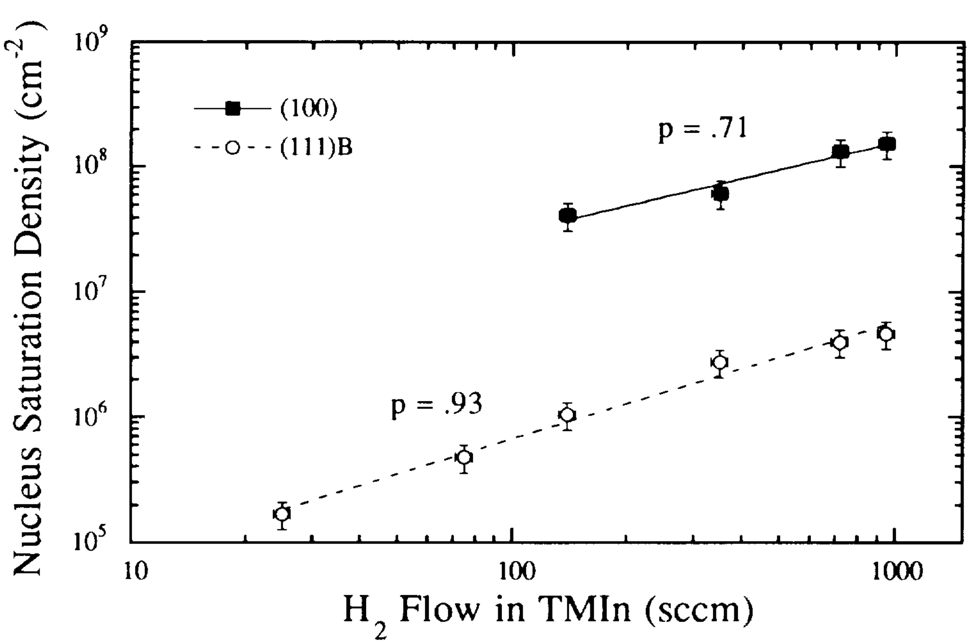


Figure - 3 A stepped surface with a sub-monolayer deposit consisting of single atoms, sub-critical clusters of atoms, and growing islands. Single atoms arrive at the substrate at a rate R, move across the surface with diffusion coefficient D, and can either re-evaporate at a rate n_1 / τ_a, form sub-critical clusters of atoms which are finally transformed into growing islands, or incorporate directly into a pre-existing step edge.



(a)



(b)

Figure - 4 Nucleus saturation density as a function of temperature in (a), and TMIn flow in (b).

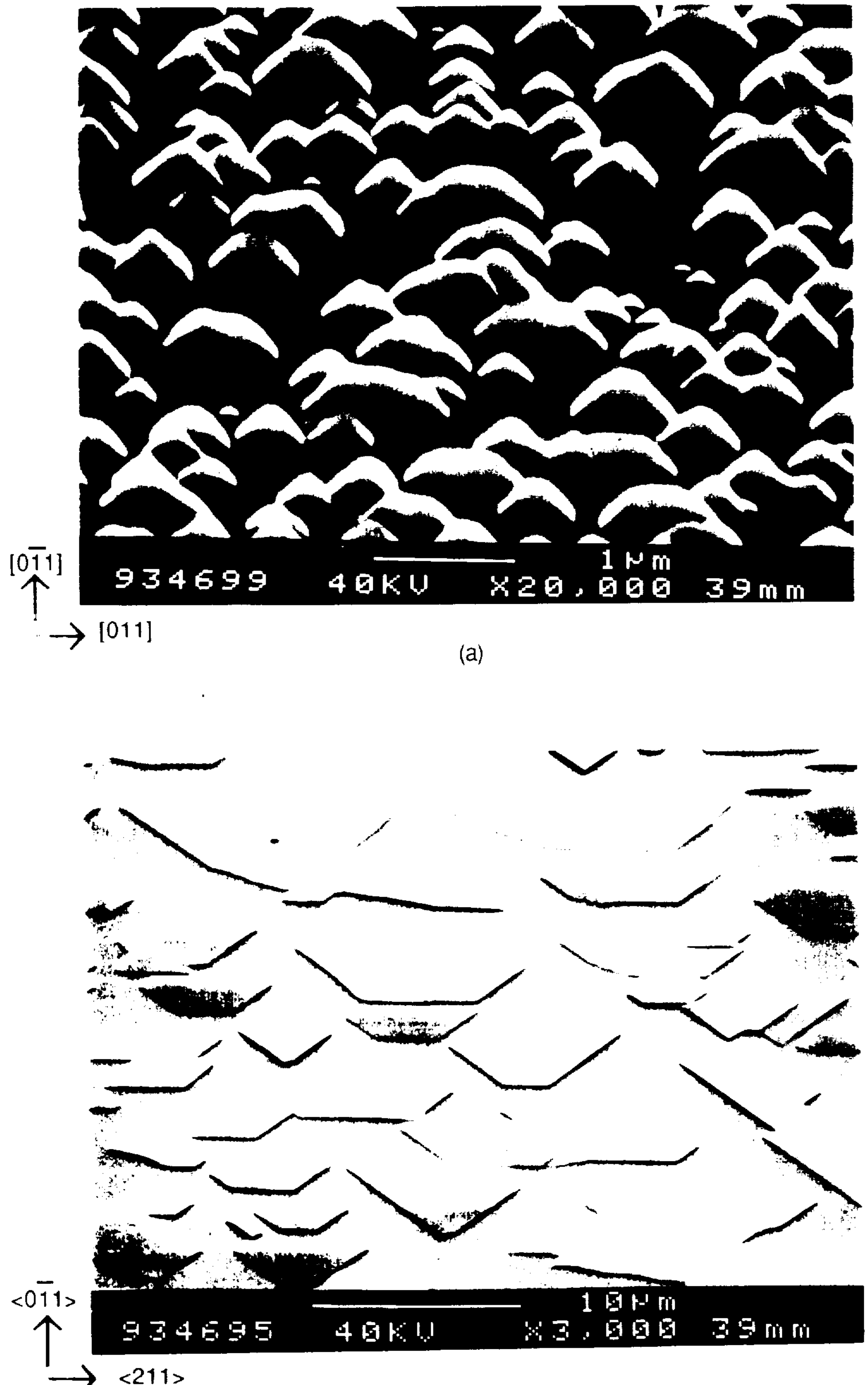


Figure - 5 InAs islands on a (100) oriented GaAs substrate in (a), and a (111)B substrate in (b). Growth conditions are T = 600 °C, f_{TMIn} = 140 sccm, f_{AsH3} = 100 sccm, t_{avg} ~ 100 Å.

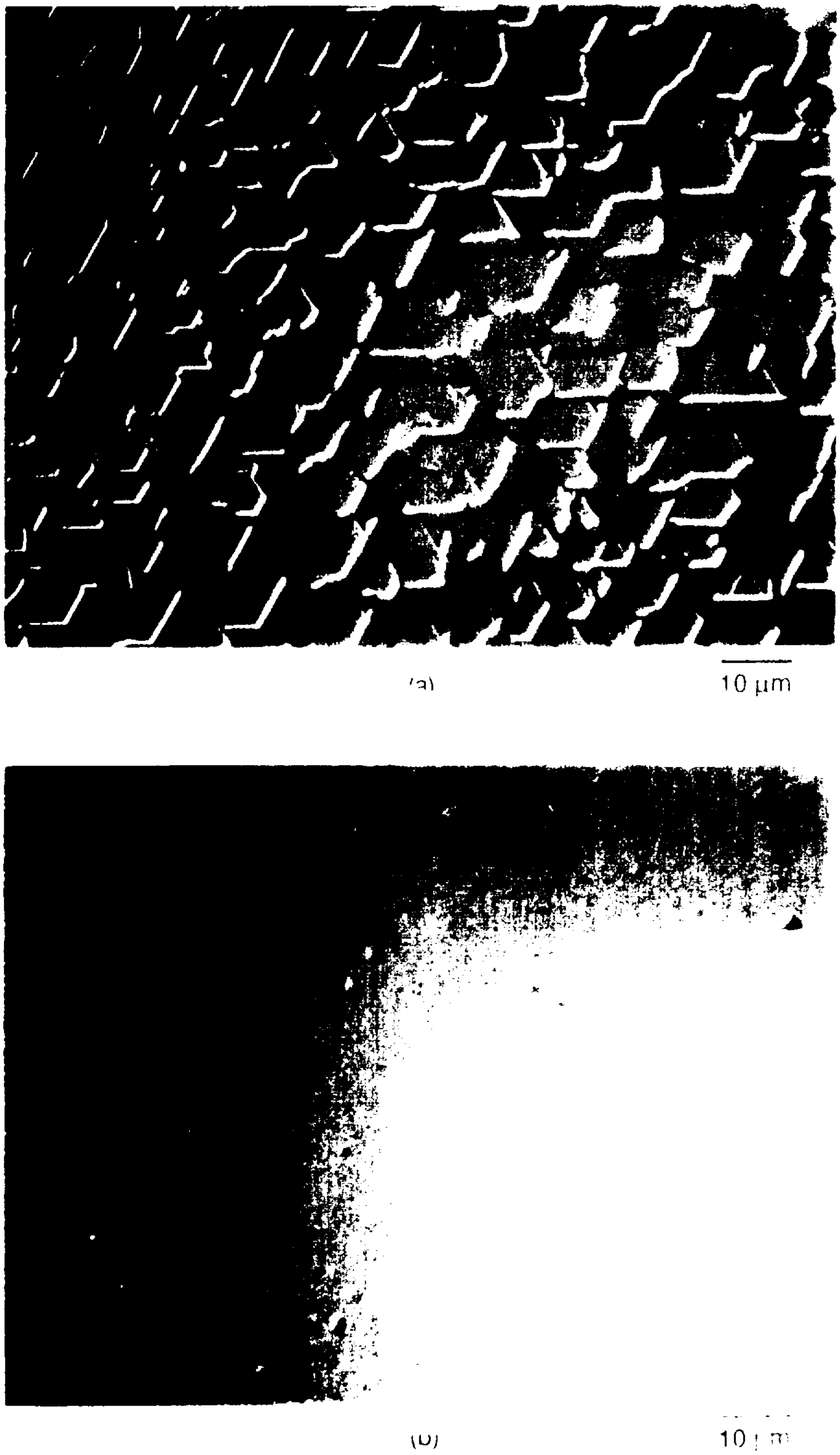
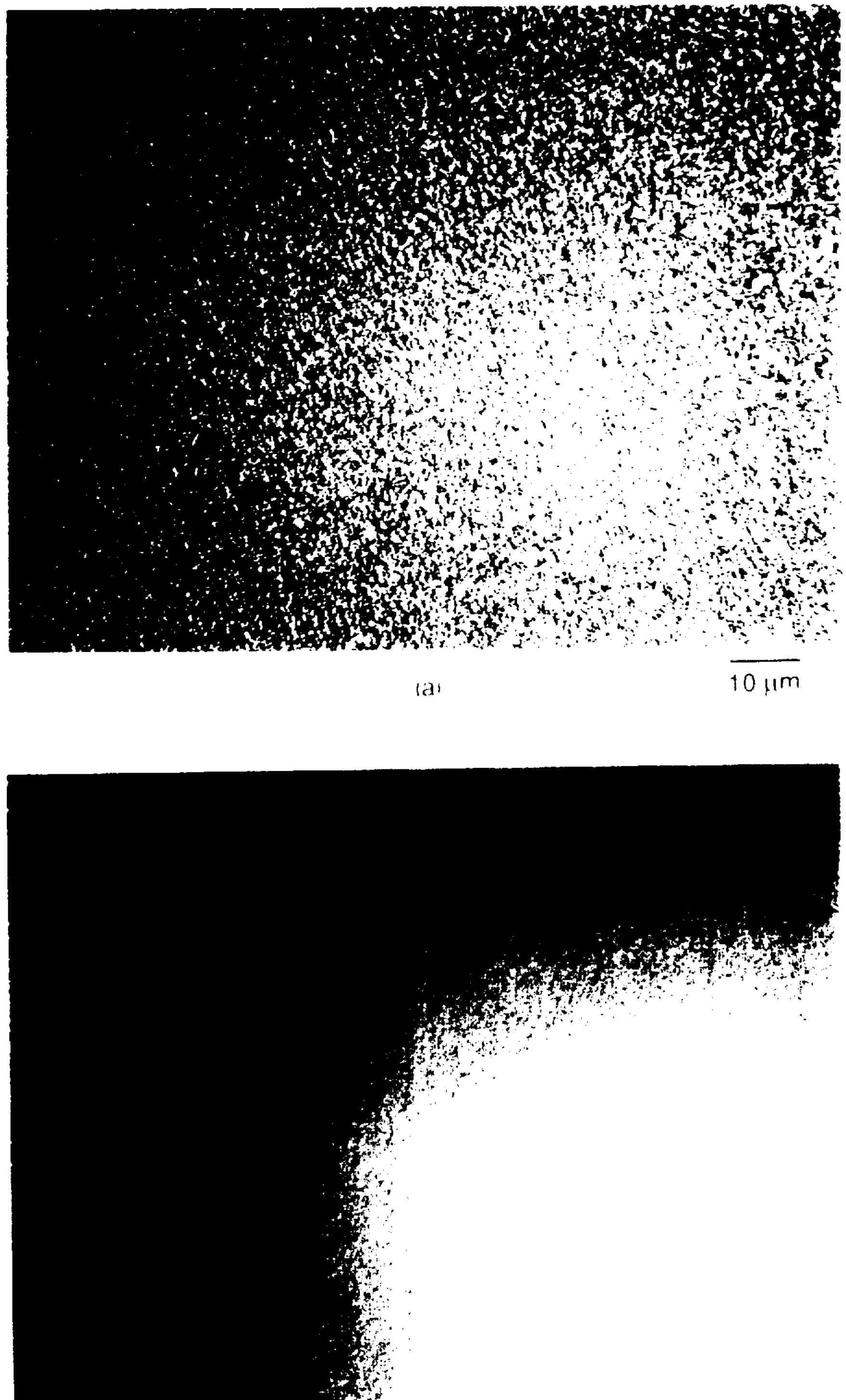


Figure - 6 Optical micrographs for the (111)B GaAs substrate depicting the transition from a 3-D morphology in (a) to a nominally 2-D InAs surface in (b). Growth conditions are T = 600 °C, f_{TMIn} = 140 sccm, f_{AsH3} = 100 sccm, t_{avg} ~ 250 Å for (a), and T = 525 °C, f_{TMIn} = 720 sccm, f_{AsH3} = 500 sccm, t_{avg} ~ 250 Å for (b).



(a) 10 μm

(b) 10 μm

Figure - 7 Optical micrographs for the (100) GaAs substrate depicting the transition from a 3-D morphology in (a) to a nominally 2-D surface in (b). Growth conditions are T = 525 ^{o}C, f_{TMIn} = 720 sccm, f_{AsH3} = 125 sccm, t_{avg} ~ 250 Å for (a), and T = 475 ^{o}C, f_{TMIn} = 950 sccm, f_{AsH3} = 82.5 sccm, t_{avg} ~ 250 Å for (b)

SUMMARY OF WORKSHOP ON InP: STATUS AND PROSPECTS

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This paper presents a summary of the workshop on InP solar cells. The overall purpose of this workshop was to:

1) determine the primary objective of the present InP research programs

2) establish the immediate prospects for use of InP solar cells

3) state the current status of the various InP research projects

4) identify the current major problem areas in the development of InP cell technology

This report address each of these topics in turn.

1) OBJECTIVES

The primary objective of most of the programs in InP solar cells is the development of the most radiation hard solar cell technology. In the workshop, it was generally agreed that the goal is a cell which displays high radiation tolerance in a radiation environment equivalent to a 1 MeV electron fluence of about 10^{16} cm^{-2}. Furthermore, it is desired that the radiation response of the cell be essentially flat out to this fluence - i.e. that the power output of the cell not decrease from its beginning of life (BOL) value in this radiation environment.

It was also agreed in the workshop that the manufacturability of InP solar cells needs to be improved. In particular, since InP wafers are relatively dense and brittle, alternative substrates need to be developed. Research on hetero-epitaxial InP cells grown on Si, Ge, and GaAs substrates is currently underway. The ultimate goal is to develop hetero-epitaxial InP solar cells using a cheap, strong, and lightweight substrate.

2) PROSPECTS

The prospects for use of InP solar cells are primarily in high radiation earth orbiting satellites. There has been an expressed need in the Navy and in commercial interests (particularly in the communication industry) to fly satellites in orbits where the equivalent 1 MeV electron fluence for a five year mission is greater than 3×10^{15} cm^{-2}. Calculations made at the Naval Research Laboratory (NRL) and NASA Lewis have shown hetero-epitaxial InP cells grown on Si wafers to be the most cost-effective technology for these missions. Also, even low-earth-orbits (LEO), especially polar orbits, can be a severe radiation environment due to solar flares. A satellite power system based on radiation hard InP solar cells would be relatively insensitive to solar flares. Also, extending geostationary mission lives to beyond 10 years has been considered. Such a mission would experience a significant amount radiation. Radiation hard InP solar cell technology has the potential to significantly improve the performance of these missions.

Another area where InP solar cell technology has been considered is in the alpha and beta voltaic power sources. By there very nature, such devices are very sensitive to radiation effects. The radiation hardness of InP seems well suited for this application.

Although the focus of the present conference is space photovoltaics, the possibility of terrestrial applications for InP solar cells was identified. One particular application was that of a concentrator array. While no space system has ever used a concentrator array, terrestrial systems make ample use of this technology. Modeling results reported by the National Renewable Energy Laboratory (NREL) have shown the $InP/Ga_{0.47}In_{0.53}As$ tandem cell to be the best band gap combination for concentrator applications.

3) STATUS

The status of the present research in InP solar cells is best described by summarizing the current programs:

at NRL:

1) **Hetero-epitaxial InP on Si cells**
This is an SBIR program with Spire Corporation. Phase I was recently completed and phase II is currently underway. The goal of this project is to produce a large number (> 100) 2x2 cm cells with BOL efficiencies of 16% (1 sun, AM0, 25 C) which virtually do not degrade after an equivalent 1 MeV electron fluence of 10^{16} cm^{-2}.

2) **$InP/Ga_{0.47}In_{0.53}As$ Tandem Solar Cells**
This program includes NREL for the cell growth and NRL for the cell characterization. The current best cell efficiency is 22%. The program was not funded in FY 94 but has good chances for funding in FY 95. The next step in the program is to grow the tandem on a Si substrate.

3) **Basic Research - Annealing of Radiation Damage**
NRL has a basic research program studying displacement damage effects in InP solar cells. At present, the main research topic is the annealing characteristics of irradiated InP cells.

at NASA Lewis:

1) **Hetero-epitaxial InP on Si**
NASA is funding Matrix Sciences to grow InP cells on Si substrates. This is a phase two contract.

2) **Hetero-epitaxial InP on Ge**
NASA Lewis funded Spire Corporation to grow InP cells on Ge. This was a phase I

SBIR and has been completed.

3) **Hetero-epitaxial InP on Ge**
NASA Lewis also has an "in-house" program to develop InP cells on Ge substrates.

4) **Hydrogen Passivation**
NASA Lewis is funding Ohio State to study the effects of hydrogen on the dislocations which occur in a hetero-epitaxial cell.

at Space Vacuum Epitaxy Center, University of Houston:

The research at Space Vacuum Epitaxy Center is developing chemical beam epitaxy as a growth technique for photovoltaic devices. As part of this development, these researchers are growing $InP/Ga_{0.47}In_{0.53}As$ tandem cells.

4) PROBLEM AREAS

The main problem area encountered in the present research is that the heteroepitaxial cells must be p^+n cells while most cells grown to date have been n^+p cells. Therefore, the major research focus is in optimizing homojunction p^+n cells to the level of the n^+p cells.

Another research focus is the reduction of the deleterious effects of the dislocations which form in InP cells grown on Si, Ge, or GaAs substrates. The use of graded and possibly strained layers as an intermediating layer between the substrate and the cell active layers to prevent the propagation of the dislocations into the active region is being investigated. Also, the research at Ohio state is investigating the possibility of passivating the defect levels created by the dislocations with hydrogen.

SUMMARY

In general, the workshop concluded that the InP solar cells are being developed as an *enabling* technology which, by virtue of its superior radiation resistance, will allow space flights in high radiation orbits which are not possible with Si or GaAs solar cell technology.

SYSTEMS, ARRAYS AND APPLICATIONS WORKSHOP 1

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The charter of this workshop was to evaluate photovoltaic technologies from the broad perspective of future mission needs and operational requirements. We were given a set of six questions listed in Figure 1 to start the discussion, however; these were viewed as sample questions which didn't constrain our deliberations.

Our primary objective in discussing the provided questions and other items of interest to the group was to answer the question: How should NASA spend its scarce space power resources? It was clear from the papers presented in the main session and the depth of technical talent present in the audience, that there are significantly more good projects available than there is funding for. Thus NASA is faced with the problem of deciding whether to allocate their resources across a range of projects or to focus on a small subset of tasks that are mission enabling.

Our discussion arrived at two primary findings:

- NASA management has failed to articulate a vision of where the agency is going.
- Consequently, the questions listed in figure 1 are irrelevant.

The failure of management to provide leadership and a consistent direction is apparent in the space power arena. Photovoltaics has been the mainstay power source for U. S. space missions for the past thirty years. However, for the last decade, NASA (and the Air Force) has continually wasted more money on frivolous pursuits of nuclear, solar dynamic, and other poorly justified energy sources than they have invested in the photovoltaic arena. We must therefor face up to the reality that space photovoltaics research has slipped out of the mainstream and into the eddies.

We have seen the mission emphasis change yearly from missions to Mars, to missions to Earth. It has thus become traditional for the research centers to try to fund a little something for everybody and keep all options open. The subset of questions posed for this group follows that path ranging from interplanetary to near term LEO commercial missions and everything in between. Insufficient funding to make significant progress in a timely manner renders these efforts irrelevant to the ultimately selected mission.

The R&D technical community cannot expect to redefine the agency. The following suggestions can reposition space power to take maximum advantage of the resources that are available.

- **Set technology improvement goals at 100% minimum.**

  The key word for the 90's should be focus. Since the resources will be very limited go for the gold. Select only high risk, high payoff, mission enabling technologies for consideration. Anything less than 100% improvement at the system level is evolutionary and will not achieve rapid market acceptance.

- **Time to market (Faster) is just as important to technology efforts as commercial efforts.**

  The advantage scientists and engineers have over artists is that we shouldn't have to be dead to see our work applied and appreciated. Focus!

- **Efficiency**

  Efficiency drives everything: weight, volume, cost, etc.

- **Look for revolutionary, mission enabling systems.**

In order to tackle this suggestion, researchers and NASA center personnel will have to get out of their labs and offices and go talk to the users. Kind of a novel suggestion? Just remember, the customer is always right. Go find out what would generate new programs and public support. Tackle those problems. Focus!

- What should the maximum operating voltage of a solar array be?
- Are arc-proof arrays required for future space PV?
- Do we need new array technology for the next generation of commercial satellites? If so, what is required?
- Expendable arrays for complex missions -- Should arrays be expendable?
- What is the operational range of PV in the solar system -- PV for Pluto?
- Do we need new array technology for intermediate orbit applications?

[1]The following paper presents the general results of the workshop and does not necessarily represent the views of any individual participant or company.

FUTURE DIRECTIONS IN PV CELL DEVELOPMENT: SUMMARY OF THE WORKSHOP AT SPRAT-XIII

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Workshop co-chairs: Geoffrey A. Landis (NYMA/NASA Lewis) and Ed Gaddy (NASA Goddard)

MISSIONS

The "mission" of this workshop was to identify what areas of PV cell development would be most fruitful to direct NASA's scarce research money toward in order to have the greatest impact on future space power systems.

Before analyzing what advances customers need, it is necessary to decide who are the customers for improved solar cells will be, and what orbits the cells will be required to operate in. The following list of customers was generated:

NASA:	Earth orbit missions:	Low Earth Orbit (LEO)
		Intermediate Earth Orbit
		Geosynchronous Earth Orbit (GEO)
	Solar-system exploration:	Inward (Sun, Mercury, Venus)
		Outward (Mars, Asteroids, Outer Planets)
Commercial	communications	LEO
		Molniya orbit
		GEO
Military	communications, navigation, observation	
Other Government Agencies	weather, navigation, observation	

It was decided that NASA research should be directed toward applications by NASA and commercial users. Representatives of the military and other government agencies at the workshop made no comment. Workshop co-leader Ed Gaddy of NASA Goddard Spaceflight Center suggested that there will be only a small number of NASA missions devoted to solar system exploration, and a large number of future missions to LEO and GEO orbits, where LEO missions will include many polar- and near-polar (sun synchronous) orbits. [The representatives from NASA JPL were all in the other session on array technology, so no one challenged this statement.] The consensus of the workshop was that commercial missions will also be primarily to LEO and GEO orbits. Thus, the overall consensus of the group was that the most important applications for future solar cells will be for satellites in the orbits which are important today: LEO and GEO.

Two strong trends were identified, with important implications for the future: a trend toward small satellites (less than a few kilowatts, as opposed to the 10 kW+ projects envisioned just a few years ago), and an industry-wide trend toward fast cycle times for development of new technology.

GOALS

The next question is: in which solar cell parameters are advances most needed by the user community?

The answer is: cost. Array volume and reliability of interconnects were mentioned, but the overwhelming answer of the participants was that cost is critical. However, in the ensuing discussion, it became clear that the important cost is not *cell* cost, but life-cycle *system* cost.

The typical purchase cost to users of solar arrays ranges from $1000 to $2000 per watt today. Some of this is non-recurring cost, since power requirements are different for each satellite. One vendor said that they are providing arrays for $800 per watt to a military customer, where the non-recurring cost is amortized over many satellites. Frank Ho provided the following "typical" numbers. For a GaAs array of a few kilowatts, roughly 25% of the cost of the power system is the cost of the solar panels. Of the panel cost, roughly half of the cost is cell cost (for GaAs/Ge cells). Thus, about 12% of the cost of a power system is attributable to the cost of the cells for (relatively expensive) GaAs cells, and a few percent for (relatively cheap) silicon cells. From this we conclude that cutting the cell cost can have at most a 12% impact on the power system cost, and, considering launch costs and other system costs, is likely to have a much lower impact. In itself, *cell cost is not a major issue.*

To achieve low system cost, the workshop participants suggested that the single most important factor is conversion efficiency, since an increased efficiency reduces the entire array cost. In addition, in order to get a new technology into the marketplace, investors require a low development cost, and a fast cycle time.

Lew Fraas emphasized that low development cost is critical. He said that Boeing estimated that the development cost to bring their 30% efficient tandem GaAs/GaSb concentrator system to market would be $100 M, and that this high cost made it impossible to attract investors. Representatives of the space-cell industry said that development of the GaAs on Ge cell [1,2] required "lots of millions of dollars" and took over three years, but that it had a strong selling point in that the cells already had a customer, since they were direct replacements for existing GaAs on GaAs cells developed for an unnamed (presumably military) customer.

It was also mentioned that low development cost means that the capital cost for production has to be reasonably low as well. There was a discussion of what low capital cost means, applied to space solar arrays. George Vendura of TRW pointed out that amorphous silicon may have a high capital cost if a new production facility must be built for the space product, but that TRW was pursuing a low capital cost approach for a-Si arrays by leveraging the huge (many megawatt) a-Si production capability in place for terrestrial markets. On the other hand, it was pointed out that a typical amorphous silicon production facility has a capital cost of about $10M. If this were expensed over a year's production of 50 kW, the cost would be $200 per watt. This is only a small fraction of the current space-cell production cost, and if other costs (such as the cost of assembling the array) were reduced, it might be acceptable.

The current industry trend is toward extremely fast cycle time: getting a product to market as swiftly as possible. Several of the participants suggested that for a new produce to fly, development time ought to be three years or less. Frank Ho said that getting MO-CVD GaAs cells to market took four years from the 1982 manufacturing technology (mantech) program. GaAs on Ge cells took three years after the mantech. Lew Fraas said that his experience at Boeing was that they had their research breakthrough in GaSb in 1989, found a flight opportunity in 1992 for a flight in 1994-- and the program was terminated by Boeing in 1992. The time scale of 5 years from technology to flight test was too long.

It was debated whether a 3 year cycle time was possible. It was concluded that it may be possible for developments with low technical risk and the ability to use existing system heritage, as the GaAs/Ge cell did, where system components other than the cell can be transferred unchanged.

It was concluded that space experience was the big stumbling block to short cycle times. It is important for NASA to use advanced cells on actual missions, in order to get the space heritage demanded by mission designers. A scientific satellite, for example, could be designed so that one of the panels of an array is made with advanced cells.

SOLAR CELL TECHNOLOGIES

Seven different advanced cell technologies were discussed in some detail.

Amorphous silicon, copper indium diselenide, and cadmium telluride thin films were discussed as systems that could have lower cost at the cell and array levels, and have the potential for very low mass and good radiation tolerance [3,4]. However, it was expected that to take maximum advantage of these systems, new array technologies would be needed. The workshop was divided on this issue.

Ultra-thin (5 micron) gallium arsenide was discussed. The costs were considered higher, but the reduced cell mass would improve the specific power of arrays.

High-efficiency monolithic tandem cells, such as $GaInP_2$ on GaAs/Ge [5], and GaAs on active germanium, were discussed as ways of improving efficiency. Since these cells could be used directly as replacement for existing GaAs/Ge cells in existing arrays, this was considered a very promising approach.

Indium phosphide was discussed, as well as the heteroepitaxial InP approaches such as InP/Ge and InP/Si. The cost is high today, but it was agreed that ultimately the cost of InP/Si or InP/Ge could be made competitive. It was agreed that these cells may have an application in orbits which see high radiation environments.

The concentrator approach was discussed. This is not a direct replacement into existing arrays, and may find some resistance from program managers due to pointing requirements. However, they have the potential for high efficiency and good radiation tolerance [6].

Finally, it was mentioned that new generation silicon cells with efficiency of 20% have performance as good as GaAs cells. However, the radiation tolerance of these cells is yet to be determined, and they are not yet space qualified.

Thermophotovoltaic (TPV) cells were mentioned as a promising new use for photovoltaics, but since there was a separate workshop on these concepts, they were not discussed in detail.

DISCUSSION SESSION

In the summary session, Geoffrey Landis took issue with the consensus that future systems will be primarily LEO and GEO. He suggested that the most significant commercial space system in the next decade will be the emplacement of a worldwide communications satellite network for portable telephone systems, with an investment of tens of billions of dollars, and that these satellite systems may be significantly different from currently operated GEO satellites. He presented results from an unpublished study [7] that shows that the number of satellites required to provide global phone coverage can be reduced by a factor of four if an intermediate orbit of 3200 kilometers is chosen instead of the low Earth orbit proposed. A page from these results is shown in figure 1.

Andrew Meulenberg agreed with this conclusion. He said that a study done by Comsat on behalf of Inmarsat concluded that Inmarsat could save nearly a billion dollars on their worldwide telephone satellite constellation "Inmarsat-P" due to the reduced number of satellites required if they went to intermediate orbits instead of low orbit. According to articles in *Space News* [8], the price of the Inmarsat-P system reduces from 3 billion dollars to 2 billion, and the number of satellites is reduced from 54 to 12-15, if intermediate orbit of 10,300 km is chosen instead of LEO. (This data point is shown to the right of the curve shown in figure 1). A recent study published in *Space News* indicated that there will be a market for as many as four of these worldwide communications satellites systems, and that these will produce a revenue of $9 billion per year [9].

These intermediate orbits see an intense radiation environment. At 3200 km, the radiation dose received from trapped protons in one day is approximately the same as that seen in geosynchronous orbit in a year! This implies that radiation tolerant solar cells may be critical components of future communications satellite networks, and thus could have considerable commercial value. Data presented by Landis showed that InP cells (and possibly other radiation-resistant cell types as well) may be able to stand up to this environment.

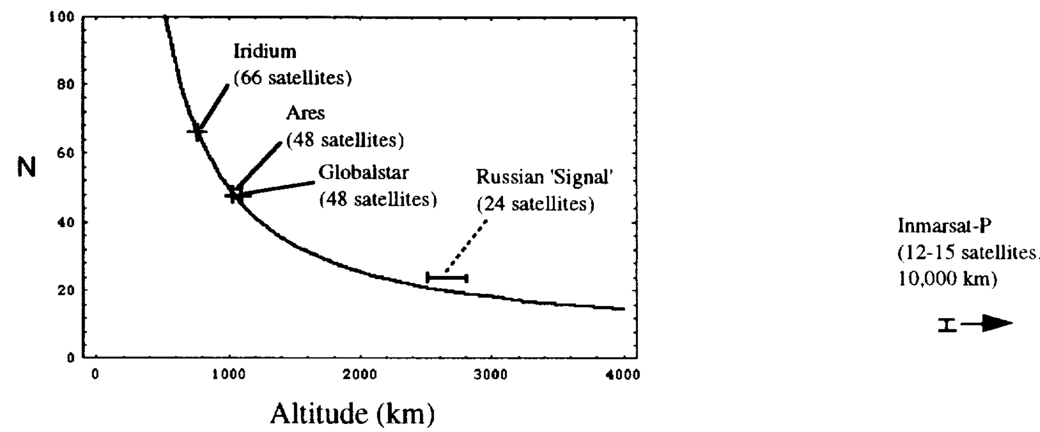

Figure 1. Number of satellites required for a phone network to provide worldwide continuous coverage, as a function of altitude (data from Bailey and Landis [1]). Solid line is theoretical curve, for polar-orbit satellite constellations; data points shown are for proposed American and Russian global coverage systems.

Some further comments of note from the discussion of the workshop summary:

Geoffrey Sommers said that telephone satellites will not have a lot of fancy electronics; they will be simple relays, and could be built so that the electronics will be (relatively) radiation tolerant. Thus, if the solar arrays could be made radiation tolerant, it would indeed be possible to utilize high-radiation orbits.

Irving Weinberg said that radiation-tolerant cells such as InP are important for commercial applications in GEO, not just intermediate orbits. He said that a satellite in GEO accumulates a radiation dose of 10^{15} electrons over ten years, and that this results in degradation in power of 30 to 40 percent. Further, he notes that the next generation of commercial satellites are going to extended lifetimes of fifteen years and longer, making radiation-limited lifetime important.

Finally, Lew Fraas concluded by reminding us that research aimed at near-term markets is a job for industry. The government should think in the long term, and fund technology development, so that we maintain a technology base for industry to draw on in the future.

CONCLUSIONS

Cost is the main issue for space photovoltaics, but *cell* cost is only a minor (10%) component of the cost. The parameter that is most desired out of next-generation photovoltaic technology is high conversion efficiency. To get a product to market required fast cycle time and a low development and qualification cost. One thing that aids low development cost the ability to directly replace existing cells in existing array designs, so that a new array design doesn't have to be developed.

There is a good argument that development of radiation tolerant cell technology could open up a new range of intermediate orbits, with potentially high commercial value. This may be a strong argument for continued development of InP and other radiation tolerant cell designs.

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ARRAY TECHNOLOGIES WORKSHOP I

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The following is a summary of responses to questions posed to the workshop and related discussions. Approximately 40 people attended the workshop and included representatives of satellite design and fabrication companies, cell development and manufacturing companies, panel development and manufacturing companies, Universities, and several government organizations. Commercial, DoD, and civil applications were all well represented by workshop attendees, as were rigid, flexible, and concentrator array technologies. Most of the time in the workshop was spent discussing questions 1 and 2, the remaining questions received only minimal deliberation.

Question 1. What will determine the selection of a specific array type (rigid, flexible, concentrator)?

Workshop attendees all agreed that the first criteria for selecting an array on any satellite program is past use. This is because of the cost of designing and qualifying any new technology, which can add about $15M to the cost of a satellite program and add risk. Any time a new technology is integrated into a spacecraft design, there are many "what ifs" that must be studied and answered which is the cause of the high cost.

There are only two ways that a new array technology will be used on a spacecraft in nearly all circumstances: 1) the technology "enables" the mission or 2) The technology provides system level benefits that overcome the extra cost and risk. Enabling technology means that the new technology allow the mission to be accomplished when no existing technology will. For example, concentrator array technology may be enabling for some non-nuclear deep space missions or for orbital missions in the radiation belts. The second criteria allows spacecraft builders to take advantage of new technology if the risk/benefit analysis shows significant system level payoff for integrating a new array technology. In general, the new array technology must provide about a 2X improvement in an important parameter (volume, cost, mass, etc.) to meet this criteria. Otherwise, spacecraft builders do not feel it is worthwhile to accept the extra cost and risk of integrating a new technology.

One positive sign that was discussed is that there appears to be a growing number of opportunities for space experiments and demonstrations that will help new array technologies overcome the past use criteria.

After past use, the next issue for a new array technology is schedule. Many satellites are being designed, built, and launched on a 2-3 year schedule now and if a technology option can not meet the schedule for a program, the program will not wait. Another similar go/no go criterion on many satellite programs is stowed volume and configuration. The array must be able to be packaged into the planned launch vehicle or it will not be considered.

After passing through the above gates, the criteria for selecting an array technology are cost, then area, then mass. It was noted that array mass tends to be much less important than the other criteria for most satellites. Area is important due to several considerations like the spacecraft moment of inertia's impact on the attitude control subsystem and the need for drag makeup propellant in low orbits.

The workshop also spent time discussing the growing importance of small satellites in the marketplace and the need for new technologies to be compatible with this trend. There was no consensus on the definition of what is a "small satellite." Some of the definitions offered included power below 1 kW, program cost below $50M, and a satellite that can be launched on a Pegasus. It was also noted that there may be an misperception about the importance of small satellites in the marketplace. For example, many of the new LEO communications constellations will include large numbers of satellites, but the satellites do not come close to any of the above definitions of small satellites. Teledesic at 11 kW (BOL) and Ellipsat at about 5 kW (EOL) were cited as examples.

Other topics discussed in the course of answering the first question included the variety of possible concentrator arrays (concepts with concentration ratios of anywhere from 1.5X to 1000X have appeared recently in the literature), the relationship between array stiffness and pointing tolerance, the ability of concentrator arrays to perform under spacecraft error conditions, and the fact that the number of satellites in a constellation and other constellation parameters changes the criteria for selection and the importance of each criteria.

A concentrator array's ability to locate and track the sun when a spacecraft tumbles was the highlight of the other topics, as it followed up on discussion started in the morning session. Significant comments included suggestions about using hybrid arrays or body mounting a backup panel to overcome this problem. It was also noted that the degree of the potential problem was spacecraft dependent contingent on factors such as what percentage of the spacecraft's power is necessary to keep the spacecraft alive until the attitude problem is solved and the relative cost of losing one spacecraft (critical in a one of a kind science mission, but somewhat less important in a large constellation). It was also noted that a program may be willing to take the risk if the concentrator array provides enough system level cost and mass benefits.

Finally, the workshop attendees agreed that the team that developed GaAs/Ge should be congratulated as it is an excellent model of how to achieve wide use of a new spacecraft technology in a short time span. The downside of this success is that any new technologies might require the same size budget and commitment to be successful.

Question 2. Are 300 W/kg, 300 W/m^2, and $300/W achievable goals for rigid, flexible, and concentrator arrays? If not, what is practically achievable for each array type?

Many of the workshop participants were very hesitant to specify numbers for these parameters for any of the array types. Many reasons were given:

- Specific numbers vary greatly depending on orbit, design life, what's included (whole array or panel), amount of funding to be invested, timeframe, design of the spacecraft, etc.
- Many times, it is not smart to optimize the mass or other parameters at the panel or array level - trades must be done at the spacecraft level and include other parameters such as reliability, cost, etc.
- Performance predictions depend on what assumptions are made including how good predicted performance is, assumed investment to be made in the technology, etc. (can result in "fantasy" predictions)

- Some of the parameters may be possible, but can not be practically achieved on a real spacecraft due to real world considerations (e.g. APSA technology was demonstrated at 130 W/kg, but implemented on EOS at 32 W/kg)

With the above qualifiers, the group did fill out the table below to specifically answer the question. The column of "300 days" was added to stress the growing importance of delivering array hardware in less than one year (from receipt of the specification and order) to meet short spacecraft program schedules. In each box in the table, there are two sections. The upper section is the capability of each technology today. The lower section is the workshop's assessment of what is practically achievable in the foreseeable future for each array type, for each parameter. If the word "yes" appears, it means that 300 is achievable, if not, the number or range represents what is achievable.

Array Type (Now/Possible)	300 W/m²	300 W/kg	300 $/W	300 Days
Rigid	150 - 200 / Yes	50 - 75 (20) / 150 - 250	1500 (Si) 2-3000 (GaAs) / 1500	Yes / Yes
Flexible	150 + / Yes	16 - 66 / 200 - 250	1700 - 6000 / Yes	Yes / Yes
Concentrators	>200 (exper.) / Yes	150 / 200 - 250	4-500 (Proj.) / Yes	N/A / Yes

Several observations were made about the table once it was completed. First, there is surprisingly little difference between the array types for some of the parameters such as in W/m^2. After reflection, this is probably due to the ability of each array type to use similar photovoltaic cell technology, although implementing advanced cell technology is different for each array type. Another observation that got a lot of discussion is that flexible array mass is strongly dependent on satellite integration. Some examples quoted were Hubble at 16 W/kg, Hubble technology available today at 24 W/kg, EOS at 32 W/kg, SAFE at 66 W/kg, and APSA at 130 W/kg.

Flexible array mass is also very dependent on the power level. For any satellite design, there is a crossover power level above which flexible arrays are lighter than rigid arrays and below that point they are heavier. However, where this point is depends strongly on the assumptions you make and on the spacecraft design. Two studies were quoted: an ESA study that set the crossover at 7 kW (later updated to 15 kW) and a JPL study that placed the crossover at 700 W. This shows the importance of studying options for a specific satellite with available technology to select the optimum array type.

A final comment was made about the reality of the numbers. Even though 50+ W/kg is possible with current rigid array technology, the actual specific power is usually 20 - 25 W/kg on real satellites. Therefore, all the numbers on the table should be taken with the disclaimers listed at the beginning of this section in mind.

Question 3. Why is there no general consensus amount the industry with regard to the future trends in array technology and is there (or should there be) a trend toward standardizing array technology to be applicable to a variety of missions?

As was evident in the answer to question 2, different missions and spacecraft designs drive the design trades. This results in different types of arrays (rigid or flexible) being the best solution for different programs. Another important point from question 2 is that some parameters for the different types of arrays tend to be similar, which results in no one type of array standing out over the others for a wide variety of missions.

With regard to standards, it was generally agreed that there will never be a "standard solar array." This is because mission requirements vary significantly and because individual aerospace companies want to advertise an edge or a benefit with their design. However, there essentially are already several mini-standards, as each major aerospace company uses their own standard array design when they bid most programs.

It was noted that in lieu of standard arrays, the best way to reduce program costs would be to standardize an all-encompassing set of requirements to minimize the non-recurring testing required for each program. This could have a major impact on program costs since the recurring cost of the solar arrays is typically a small part of the total cost to a program.

Question 4. What are the operational pointing requirements for concentrator arrays? Is two axis tracking worth the effort or are linear concentrators better?

In general, at least $\pm 2^{\circ}$ of sun acceptance angle at the individual concentrator level should allow the use of standard, off-the-shelf array components such as sun sensors and array tracking gimbals. The exact requirement for this angle is dependent on several factors including manufacturing precision of the concentrator elements, positioning accuracy of the concentrators into the panel, panel to panel alignment, gimbal pointing accuracy, sun sensor accuracy, thermal distortions, and tolerance of defects in the concentrator concept. A well managed error budget taking all these factors into account will result in determination of the allowable acceptance angle for a given concentrator design.

For a linear concentrator, a sun acceptance angle of at least ± 20 to 30° in the linear axis allows easy integration into a wide range of satellites, as this is a typical requirement on satellites that only track the sun in one axis (mission design and attitude control result in maintaining nominal pointing in the other axis).

As was discussed in question 1, it was again noted that minimizing the time for sun acquisition is an important consideration in designing a satellite concentrator array. This is important to minimize the impact of possible attitude control subsystem problems and to minimize the required battery size for initial operation of the spacecraft when deployed from the launch vehicle.

Regarding 2 axis vs. 1 axis tracking concentrator arrays, the trade on which will better meet a spacecraft's requirements is very mission dependent. However, in general there is more applicability for single axis tracking concentrators. One reason for this is the cost and reliability of a 2 axis tracker. Another is that many spacecraft now use only a single axis tracker and changing to a two axis tracking system can have significant impact on other spacecraft subsystems and the overall design concepts. DoD and NASA have decided to move forward with the single axis systems first due to several factors including lower development and recurring costs, applicability to a wider range of satellites (any satellite that can use a two axis concentrator can also use a one axis system, but the reverse is not true), and lower risk for flight testing a full size array. Once the technology is demonstrated, an individual program may decide that the benefits of two axis technology is worth the added investment to optimize that spacecraft.

Question 5. What are the advantages of integrating the solar array into the overall satellite to further optimize the satellite and is there interest in doing this?

(Due to time limitations, there was not a lot of discussion about this question.) The advantages of complete integrated design of the array into a satellite vary by the individual satellite and mission. Some examples include direct drive of high voltage (300V) electric propulsion thrusters to eliminate the power conditioners and optimizing the voltage to match high load users to minimize cable and electronics mass. It was generally agreed that every company is already looking for ways to do this for every satellite, and it is really required for companies to stay competitive.

WORKSHOP SUMMARY

THERMOPHOTOVOLTAICS AND NON-SOLAR ENERGY CONVERSION

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The workshop was well attended (about 20) with the discussion limited to alpha/betavoltaics and thermophotovoltaics (TPV). TPV was the major part of the discussion. Both space and terrestrial applications were presented for TPV at various power levels. However, alpha/betavoltaics appear to be limited to very low power (mw) level applications. Reference 1 lists several low power applications for betavoltaics.

ALPHA/BETAVOLTAICS

In an alphavoltaic or betavoltaic energy converter charge carriers are produced in a p-n junction semiconductor by alpha particles or beta particles rather than photons as in a conventional photovoltaic energy converter. One of the key issues discussed for these devices was radiation damage. For a betavoltaic device the threshold for damage begins for beta particles with energies greater than 200-300 KEV. Promethium (P_m^{147}) and tritium (H^3) were mentioned as possible beta sources with energies less than the damage threshold. For beta sources with energies greater than the damage threshold, strontium (Sr^{90}) and thallium (Tl^{204}) were mentioned. Since the half life for each of these sources is long, the potential lifetime for an alpha/betavoltaic device is long. Both InP and SiC were discussed as possible semiconductor materials suitable for alpha/betavoltaics. To make these devices feasible, the radiation damage problem must be solved.

THERMOPHOTOVOLTAICS (TPV)

The TPV discussion centered around possible applications and the key research areas.

TPV Applications

TPV has both low power (≤ 100 w) and high power space applications. The low power applications are for deep space missions such as the Pluto flyby where the thermal energy is supplied by radioisotope decay. For higher power applications such as earth orbit or a moon base, solar energy can be used as the thermal source. In this case TPV has an advantage over the conventional PV-battery system since thermal energy storage can be used. The TPV system thus will have a lower mass, especially for a moon base if the lunar soil can be used as a storage material.

It is the commercial applications of TPV that has caused the great interest in TPV in the last several years. Although the discussion was limited on this subject the following applications were mentioned: portable power supplies for recreational vehicles and Army field units, cogeneration of electrical power for natural gas appliances such as electrical power for furnace blowers, and hybrid electrical vehicles.

TPV Research

Two important developments have made efficient TPV energy conversion at moderate temperatures (< 2000 K) possible. One is low bandgap energy (< 1eV) PV cells such as GaSb and InGaAs and the other is efficient selective emitters. Research in these areas was thus the main topic of discussion. For high temperature (≥ 2000K), high efficiency can be attained using Si PV cells.

There are two approaches to attaining an efficient TPV emitter. First of all a selective emitter that emits mainly in the wavelength region where the PV cells have maximum efficiency and secondly a grey body emitter with a band pass filter to make the emitter behave like a selective emitter. Discussion was centered on rare earth selective emitters. The mantle type emitter[2] made of small (5-10 μm) diameter rare earth oxide fibers, such as Yb_2O_3, has demonstrated good efficiency. Research is continuing on the fiber emitter with different geometry than the mantle. Also, a new rugged, rare earth-garnet emitter shows promising spectral emittance.[3]

Currently there is considerable research on low bandgap energy PV cells. Probably the most developed low bandgap energy, E_g, cell is GaSb with E_g = .72 eV. Also being actively researched is $In_xGa_{1-x}As$ on InP substrates. This system yields $.36 \leq E_g \leq 1.42$ eV depending on the value of x. Also, just beginning is research on $In_xGa_{1-x}Sb$ which has $.17 \leq Eg \leq .72$eV depending on the value of x and $In_xGa_{1-x}As_ySb_{1-y}$, which has $.17 \leq E_g \leq 1.42$eV depending on the value of x and y. This later quantenary system will allow lattice matched growth on GaSb substrates in the energy range $.3 \leq E_g \leq .72$eV. Two other PV materials that are not currently being considered, but should be considered, are $Hg_xCd_{1-x}Te$ and Ge. The HgCdTe system allows lattice matched growth for $0 \leq E_g \leq 1.56$eV. The main advantage of Ge (E_g = .66 eV) is that it potentially should be the lowest cost.

Most people felt that low bandgap energy PV cell development will occur before an efficient emitter is developed. The main reason for this is the large amount of cell research compared to emitter research. For an efficient TPV system both an efficient emitter and PV cell are required.

CONCLUSION

Both low bandgap energy PV cell research and emitter research are required to make efficient TPV energy conversion possible. The many potential applications of TPV more than justify the research effort. Alpha/betavoltaic energy conversion will be viable if the radiation damage problem can be solved.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1994	Conference Publication

4. TITLE AND SUBTITLE

Proceedings of the XIII Space Photovoltaic Research and Technology Conference (SPRAT XIII)

5. FUNDING NUMBERS

WU–233–01–0A
C–NAS1–19592
C–NAS3–26703
C–NAS3–27004
G–NAG3–1466

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–9083

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CP–3278

11. SUPPLEMENTARY NOTES

Responsible person, George C. Rybicki, organization code 5410, (216) 433–8473.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 33

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The Thirteenth Space Photovoltaic Research and Technology (SPRAT) Conference gathered representatives from 26 commercial corporations, 8 universities and 7 governmental agencies, including Europe, for two and a half days of presentations and discussions regarding the status and future of space photovoltaics. The conference was well attended, with over 100 attendees, and included 38 technical papers, 6 program reviews and 5 workshop discussions. The effects of shrinking research and development budgets were evident in the focus and tone of this SPRAT. Most attendees appeared to be oriented toward near term, system oriented projects and fewer were involved in long term, high risk research. It was generally agreed that space power requirements would continue to move toward smaller (<2kW) power levels. Most future applications are believed to be in traditional orbits (LEO, GEO) although interesting opportunities may be found in high radiation, mid-altitude orbits useful for global communication networks. New solar cell devices and materials will be difficult to introduce unless they are mission enabling, or offer significant cost and/or performance benefits. The attendees were unable to come to a consensus regarding the type of array (eg. rigid, concentrator, flexible) suitable for specific missions. Many factors outside the realm of photovoltaics influence the selection process. These topics and many more are covered in the following pages of this record.

14. SUBJECT TERMS

Photovoltaics; Space power; Solar cells

15. NUMBER OF PAGES

452

16. PRICE CODE

A20

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	