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Space Photovoltaic Research And Technology 1995

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October 24-26, 1995
NASA Lewis Research Center
Cleveland, OH

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Planetary and Deep Space Requirements for Photovoltaic Solar Arrays[1]

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ABSTRACT

In the past 25 years, the majority of interplanetary spacecraft have been powered by nuclear sources. However, as the emphasis on smaller, low cost missions gains momentum, the majority of missions now being planned will use photovoltaic solar arrays. This will present challenges to the solar array builders, inasmuch as planetary requirements usually differ from earth orbital requirements. In addition, these requirements often differ greatly, depending on the specific mission; for example, inner planets vs. outer planets, orbiters vs. flybys, spacecraft vs. landers, and so on. Also, the likelihood of electric propulsion missions will influence the requirements placed on solar array developers.

The paper will discuss representative requirements for a range of planetary missions now in the planning stages. Insofar as inner planets are concerned, a Mercury orbiter is being studied with many special requirements. Solar arrays would be exposed to high temperatures and a potentially high radiation environment, and will need to be increasingly pointed off sun as the vehicle approaches Mercury. Identification and development of cell materials and arrays at high incidence angles will be critical to the design.

Missions to the outer solar system that have been studied include a Galilean orbiter and a flight to the Kuiper belt. While onboard power requirements would be small (as low as 10 watts), the solar intensity will require relatively large array areas. As a result, such mission will demand extremely compact packaging and low mass structures to conform to launch vehicle constraints. In turn, the large are, low mass designs will impact allowable spacecraft loads. Inflatable array structures, with and without concentration, and multi-band gap cells will be considered if available. In general, the highest efficiency cell technologies operable under low intensity, low temperature conditions are needed.

Solar arrays will power missions requiring as little as approximately 100 watts, up to several kilowatts (at Earth) in the case of solar electric propulsion missions. Thus, mass and stowage volume minimization will be required over a range of array sizes. Concentrator designs, inflatable structures, and the combination of solar arrays with the telecommunications system have been proposed. Performance, launch vehicle constraints, an cost will be the principal parameters in the design trade space.

Other special applications will also be discussed, including requirements relating to planetary landers and probes. In those cases, issues relating to shock loads on landing, operability in (possibly dusty) atmospheres, and extreme temperature cycles must be considered, in addition to performance, stowed volume, and costs.
1

[1] The work described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

14th Space Photovoltaic Research and Technology Conference
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Development of advanced Si and GaAs solar cells for interplanetary missions

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ABSTRACT

The deep space and planetary exploration project have been acquiring more and more importance and some of them are now well established both in ESA and NASA programs.
This paper presents the possibility to utilise both silicon and gallium arsenide solar cells as spacecraft primary power source for missions far from the Sun, in order to overcome the drawbacks related to the utilisation of radioisotope thermoelectric generators - such as cost, safety and social acceptance.

The development of solar cells for low illumination intensity and low temperature (LILT) applications is carried out in Europe by ASE (Germany) and CISE (Italy) in the frame of an ESA programme, aimed to provide the photovoltaic generators for ROSETTA: the cometary material investigation mission scheduled for launch in 2003. The LILT cells development and testing objectives are therefore focused on the following requirements: insolation intensity as low as 0.03 Solar Constant, low temperature down to -150 C and solar flare proton environment.

At this stage of development, after the completion of the technology verification tests, it has been demonstrated that suitable technologies are available for the qualification of both silicon and gallium arsenide cells and both candidates have shown conversion efficiencies over 25 % at an illumination of 0.03 SC and a temperature of -150 C. In particular, when measured at those LILT conditions, the newly developed "HI-ETA/NR-LILT" silicon solar cells have reached a conversion efficiency of 26.3 %, that is the highest value ever measured on a single junction solar cell.

A large quantity of both "HI-ETA/NR-LILT " silicon and "GaAs/Ge-LILT" solar cells are presently under fabrication and they will be submitted to a qualification test plan, including radiation exposure, in order to verify their applicability with respect to the mission requirements. The availability of two valid options will minimise the risk for the very ambitious scientific project.

The paper describes how the technical achievements have been possible with Si and GaAs LILT solar cells (including a comparison between measured and modelled I-V characteristics) and it presents the technology verification tests results.

Naval Research Laboratory's Programs in Advanced Indium Phosphide Solar Cell Development

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The Naval Research Laboratory has been involved in developing InP solar cell technology since 1988. The purpose of these programs was to produce advanced cells for use in very high radiation environments, either as a result of operating satellites in the Van Allen belts or for very long duration missions in other orbits. Richard Statler was technical representative on the first program, with Spire Corporation as the contractor, which eventually produced several hundred, high efficiency 2x2 cm^2 single crystal InP cells. The shallow homojunction technology which was developed in this program enabled cells to be made with AMO, one sun efficiencies >19%. Many of these cells have been flown on space experiments, including PASP Plus, which have confirmed the high radiation resistance of InP cells. NRL has also published widely on the radiation response of these cells and also on radiation-induced defect levels detected by DLTS, especially the work of Rob Walters and Scott Messenger. In 1990 NRL began another Navy-sponsored program with Tim Coutts and Mark Wanlass at the National Renewable Energy Laboratory (NREL), to develop a one sun, two terminal space version of the InP-InGaAs tandem junction cell being investigated at NREL for terrestrial applications. These cells were grown on InP substrates. Several cells with AM0, one sun efficiencies >22% were produced. Two 2x2 cm^2 cells were incorporated on the STRV 1A/B solar cell experiment. These were the only two junction, tandem cells on the STRV experiment.

The high cost and relative brittleness of InP wafers meant that if InP cell technology were to become a viable space power source, the superior radiation resistance of InP would have to be combined with a cheaper and more robust substrate. The main technical challenge was to overcome the effect of the dislocations produced by the lattice mismatch at the interface of the two materials. Over the last few years, NRL and Steve Wojtczuk at Spire have been developing a single junction InP on Si cell, in an ONR-sponsored SBIR program. Both cell polarities were investigated and the best efficiencies to date (~13% on a 2x4 cm^2 cell) were achieved with n/p cells. Earlier this year NRL began a program with ASEC to develop a two terminal InP-InGaAs tandem cell on a Ge substrate. RTI and NREL are subcontractors on this program.

The results of an ONR-sponsored study of the potential market for InP/Si cells will be discussed. Also the technical status of both the InP/Si and the InP-InGaAs/Ge programs will be given. The technical challenges still remaining will be briefly described.

STRAW MAN TRADE BETWEEN MULTI-JUNCTION, GALLIUM ARSENIDE, AND SILICON SOLAR CELLS

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Multi-junction (MJ), gallium arsenide (GaAs), and silicon (Si) solar cells have respective test efficiencies of approximately 24%, 18.5% and 14.8%. Multi-junction and gallium arsenide solar cells weigh more than silicon solar cells and cost approximately five times as much per unit power at the cell level. A straw man trade is performed for the TRMM spacecraft to determine which of these cell types would have offered an overall performance and price advantage to the spacecraft. A straw man trade is also performed for the multi-junction cells under the assumption that they will cost over ten times that of silicon cells at the cell level.

The trade shows that the TRMM project, less the cost of the instrument, ground systems and mission operations, would spend approximately $552 thousand dollars per kilogram to launch and service science in the case of the spacecraft equipped with silicon solar cells. If these cells are changed out for gallium arsenide solar cells, an additional 31 kilograms of science can be launched and serviced at a price of approximately $90 thousand per kilogram. The weight reduction is shown to derive from the smaller area of the array and hence reductions in the weight of the array substrate and supporting structure. If the silicon solar cells are changed out for multi-junction solar cells, an additional 45 kilograms of science above the silicon base line can be launched and serviced at a price of approximately $58 thousand per kilogram. The trade shows that even if the multi-junction arrays are priced over ten times that of silicon cells, a price that is much higher than projected, that the additional 45 kilograms of science are launched and serviced at $182 thousand per kilogram. This is still much less than original $552 thousand per kilogram to launch and service the science.

Data and qualitative factors are presented to show that these figures are subject to a great deal of uncertainty. Nonetheless, the benefit of the higher efficiency solar cells for TRMM is far greater than the uncertainties in the analysis.

THE PROGRESS OF LARGE AREA $GaInP_2/GaAs/Ge$ TRIPLE JUNCTION CELL DEVELOPMENT AT SPECTROLAB

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In this paper we report the successful fabrication of large area, monolithic triple junction, n on p, $GaInP_2/GaAs/Ge$ cells. The highest open circuit voltage and cell efficiency (cell area: 4.078 cm^2) were measured at 2.573 V and 23.3%, respectively, under 1 sun, AM0 illumination. To our knowledge, this is the highest single crystal, monolithic, two terminal triple junction cell efficiency demonstrated. In addition, excellent uniformity across a 3" diameter Ge substrates has also been achieved. An average cell efficiency of 22.8% across the 3" diameter wafer has been measured.

We have also successfully fabricated welded cell-interconnect-cover (CIC) assemblies using these triple junction devices. The highest CIC efficiency was 23.2% (bare cell efficiency was 23.3%). The average efficiency for 25 CICs was 21.8%, which is very comparable to the 22.0% average bare cell efficiency before they were fabricated into the CICs.

Finally, we have measured temperature coefficient and 1 MeV electron irradiation data. These will be presented in the paper.

ABSTRACT

Status of MJ Cells - 22% Production 26% Development

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This paper describes our current activity in MJ space cells.

We will report on a development program where $GaInP_2$ and GaAs cells were grown on both GaAs and Ge substrates. We selected a P/N structure, GaInP2/GaAs grown on Ge substrates, a close fit to present GaAs/Ge manufactured cells.

We met the objective, 22% (AMO) minimum average efficiency, for cell area around $19.5cm^2$. A concurrent radiation specification required that the GaAs cell current be intentionally increased 5-10% over the $GaInP_2$ cell current, by modifying the 2J cell structure.

All the cells described were formed in a single growth run on a large production MOCVD reactor. We will discuss some of the tests used to improve the cell performance and throughput. A full set of space qualification tests was completed.

We will also describe typical in-line characterization tests used to check cell performance.

Several small panels with MJ cells have been made and delivered. Present effort is directed towards scaling-up of the 2J cells. We are also testing modified cell structures to increase 2J cell efficiency.

Under a NASA-Lewis RC-SBIR contract we evaluated several methods to add an active Ge interface to the 2J structure, to find the most repeatable method, with least effect on production procedures.

InP tunnel junction for InGaAs/InP tandem solar cells

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Chemical beam epitaxy (CBE) has been shown to allow the growth of high quality materials with reproducible complex compositional and doping profiles. The main advantage of CBE compared to metalorganic chemical vapor deposition (MOCVD), the most popular technique for InP-based photovoltaic device fabrication, is the ability to grow high purity epilayers at much lower temperatures (450°C - 530°C). We have previously shown that CBE is perfectly suited toward the fabrication of complex photovoltaic devices such as InP/InGaAs monolithically integrated tandem solar cells, because its low process temperature preserves the electrical characteristics of the InGaAs tunnel junction commonly used as an ohmic interconnect.

In this work using CBE for the fabrication of optically transparent (with respect to the bottom cell) InP tunnel diodes is demonstrated. Epitaxial growth were performed in a Riber CBE 32 system using PH_3 and TMIn as III and V precursors. Solid Be (p-type) and Si (n-type) have been used as doping sources, allowing doping levels up to 2 10^{-19} cm^{-3} and 1 10^{-19} cm^{-3} for n and p type respectively. The InP tunnel junction characteristics and the influence of the growth's conditions (temperature, growth rate) over its performance have been carefully investigated. InP p++/n++ tunnel junction with peak current densities up to 1600 A/cm^2 and maximum specific resistivities (V_p/I_p - peak voltage to peak current ratio) in the range of 10^{-4} Ω-cm^2 were obtained. The obtained peak current densities exceed the highest results previously reported for their lattice matched counterparts, $In_{0.53}Ga_{0.47}As$ and should allow the realization of improved minimal absorption losses in the interconnect InP/InGaAs tandem devices for Space applications. Owing to the low process temperature required for the top cell, these devices exhibit almost no degradation of its characteristics after the growth of subsequent thick InP layer suggesting minimal doping cross diffusion in the narrow space-charge region (~1-5 nm) of the device. The fabrication of tandem devices using InP tunnel diodes as interconnect is in progress and will be reported at the conference.

This work was supported by the state of Texas advanced technology program 93-03652-260 , 93-003652-236. The work at IST Inc. was supported by NASA SBIR Program NASW - 4093.

Abstract Submitted to the Space Photovoltaic Research and Technology Conference, NASA Lewis, Oct1995

The Role of Radiation Hard Solar Cells in Minimizing the Costs of Global Satellite Communications Systems

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An analysis embodied in a PC computer program is presented, which quantitatively demonstrates how the availability of radiation hard solar cells can minimize the cost of a global satellite communication system. The chief distinction between the currently proposed systems, such as Iridium, Odyssey and Ellipsat, is the number of satellites employed and their operating altitudes. Analysis of the major costs associated with implementing these systems shows that operation within the earth's radiation belts can reduce the total system cost by as much as a factor of two[1], so long as radiation hard components including solar cells, can be used. A detailed evaluation of several types of planar solar cells is given, including commercially available Si and GaAs/Ge cells, and InP/Si cells which are under development.

The computer program calculates the end of life (EOL) power density of solar arrays taking into account the cell geometry, coverglass thickness, support frame, electrical interconnects, etc. The EOL power density can be determined for any altitude from low earth orbit (LEO) to geosynchronous (GEO) and for equatorial to polar planes of inclination. The mission duration can be varied over the entire range planned for the proposed satellite systems. An algorithm is included in the program for determining the degradation of cell efficiency for different cell technologies[2] due to proton and electron irradiation. The program can be used to determine the optimum configuration for any cell technology for a particular orbit and for a specified mission life.

Several examples of applying the program are presented, in which it is shown that the EOL power density of different technologies can vary by an order of magnitude for certain missions. Therefore, although a relatively radiation soft technology can be made to provide the required EOL power by simply increasing the size of the array, the impact on the total system budget could be unacceptable, due to increased launch and hardware costs. In aggregate these factors can account for more than a 10% increase in the total system cost. Since the estimated total costs of proposed global coverage systems range from $1B to $9B, the availability of radiation hard solar cells could make a decisive difference in the selection of a particular constellation architecture.

1. T. Logsdon, "Mobile Communication Satellites", McGraw-Hill, 1995.
2. G.P.Summers, R.J. Walters, M.A. Xapsos, E.A. Burke, S.R. Messenger, P. Shapiro and R.L. Statler, "A New Approach to Damage Prediction for Solar Cells Exposed to Different Radiations", IEEE Proc. 1st World Conference on Photovoltaic Energy Conversion, Waikoloa, Hawaii 5-9, 1994, p.2068-2073.

High and Low Energy Proton Radiation Damage in p/n InP MOCVD Solar Cells

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InP p+nn+ MOCVD solar cells were irradiated with 0.2 MeV and 10 MeV protons to a fluence of $10^{13}/cm^2$. The degradation of power output, IV behavior, carrier concentration and defect concentration were observed at intermediate points throughout the irradiations. The 0.2 MeV proton irradiated solar cells suffered much greater and more rapid degradation in power output than those irradiated with 10 meV protons. The efficiency losses were accompanied by larger increases in the recombination currents in the 0.2 MeV proton irradiated solar cells. The low energy proton irradiations also had a larger impact on the series resistance of the solar cells. Despite the radiation induced damage, the carrier concentration in the base of the solar cells showed no reduction after 10 MeV or 0.2 MeV proton irradiations and even increased during irradiation with 0.2 MeV protons. In a DLTS study of the irradiated samples, the minority carrier defects H4 and H5 at E_v + 0.33 and E_v + 0.52 eV and the majority carrier defects E7 and E10 at E_c- 0.39 and E_c-0.74 eV, were observed. The defect introduction rates for the 0.2 MeV proton irradiations were about 20 times higher than for the 10 MeV proton irradiations. The defect E10, observed here after irradiation, has been shown to act as a donor in irradiated n-type InP and may be responsible for obscuring carrier removal. The results of this study are consistent with the much greater damage produced by low energy protons whose limited range causes them to stop in the active region of the solar cell.

Abstract Submitted to the Space Photovoltaic Research and Technology Conference, NASA Lewis, Oct 1995

Correlation of Electron and Proton Irradiation-Induced Damage in InP Solar Cells

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When determining the best solar cell technology for a particular space flight mission, accurate prediction of solar cell performance in a space radiation environment is essential. The current methodology used to make such predictions requires extensive experimental data measured under both electron and proton irradiation. Due to the rising cost of accelerators and irradiation facilities, such extensive data sets are expensive to obtain. Moreover, with the rapid development of novel cell designs, the necessary data is often not available. Therefore, a method for predicting cell degradation based on limited data is needed. Such a method has been developed at the Naval Research Laboratory based on damage correlation using "displacement damage dose" which is the product of the non-ionizing energy loss (NIEL) and the particle fluence.[1] Displacement damage dose is a direct analog of the ionization dose used to correlate the effects of ionizing radiations. In this method, the performance of a solar cell in a complex radiation environment can be predicted from data on a single proton energy and two electron energies, or one proton energy, one electron energy, and Co^{60} gammas. This method has been used to accurately predict the extensive data set measured by Anspaugh[2] on GaAs/Ge solar cells under a wide range of electron and proton energies[1]. In this paper, the method is applied to InP solar cells using data measured under 1 MeV electron and 3 MeV proton irradiations, and the calculations are shown to agree well with the measured data.

In addition to providing accurate damage predictions, this method also provides a basis for quantitative comparisons of the performance of different cell technologies. The performance of the present InP cells is compared to that published for GaAs/Ge cells. The results show InP to be inherently more resistant to displacement energy deposition than GaAs/Ge.

1 G.P. Summers, R.J. Walters, M.A. Xapsos, E.A. Burke, S.R. Messenger, P. Shapiro, and R.L. Statler, "A New Approach to Damage Prediction for Solar Cells Exposed to Different Radiations", IEEE Proc. 1st World Conference on Photovoltaic Energy Conversion, Waikoloa, Hawaii, Dec 5-9, 1994, p. 2068-2073.

2 B.E. Anspaugh, "Proton and Electron Damage Coefficients for GaAs/Ge Solar Cells", IEEE Proc. 22nd Photovoltaic Spec. Conf., Las Vegas, NV, Oct., p1593 (1991)

Diffusion Lengths in Irradiated N/P InP-on-Si Solar Cells

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ABSTRACT

Indium phosphide (InP) solar cells are being made on silicon (Si) wafers (InP/Si) to take advantage of both the radiation-hardness properties of the InP solar cell and the light weight and low cost of Si wafers compared to InP or germanium (Ge) wafers. The InP/Si cell application is for long duration and/or high radiation orbit space missions. InP/Si cells have higher absolute efficiency after a high radiation dose than gallium arsenide (GaAs) or silicon (Si) solar cells. In this work, base electron diffusion lengths in the N/P cell are extracted from measured AM0 short-circuit photocurrent at various irradiation levels out to an equivalent 1 MeV fluence of 10^{17} 1 MeV electrons/cm^2 for a 1 cm^2 12% BOL InP/Si cell. These values are then checked for consistency by comparing measured Voc data with a theoretical Voc model that includes a dark current term that depends on the extracted diffusion lengths.

Abstract submitted to the Space Photovoltaic Research and Technology Conference, NASA Lewis, October 1995

Electron and Proton Damage on InGaAs Solar Cells Having an InP Window Layer

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As part of a continuing program to determine the space radiation resistance of $InP/In_{0.53}Ga_{0.47}As$ tandem solar cells, n/p $In_{0.53}Ga_{0.47}As$ solar cells fabricated by RTI were irradiated with 1 MeV electrons and with 3 MeV protons. The cells were grown with a 3 μm n-InP window layer to mimic the top cell in the tandem cell configuration for both AM0 solar absorption and radiation effects. The results have been plotted against "displacement damage dose" which is the product of the nonionizing energy loss (NIEL) and the particle fluence.[1] A characteristic radiation damage curve can then be obtained for predicting the effect of all particles and energies.[1]

AM0, 1 sun solar illumination IV measurements were performed on the irradiated InGaAs solar cells and a characteristic radiation degradation curve was obtained using the solar cell conversion efficiency as the model parameter. Also presented are data comparing the radiation response of both n/p and p/n (fabricated by NREL) InGaAs solar cells as a function of base doping concentration. For the solar cell efficiency, the radiation degradation was found to be independent of the sample polarity for the same base doping concentration.

[1] G.P. Summers, R.J. Walters, M.A. Xapsos, E.A. Burke, S.R. Messenger, P. Shapiro, and R.L. Statler, "A New Approach to Damage Prediction for Solar Cells Exposed to Different Radiations", IEEE Proc. 1st World Conference on Photovoltaic Energy Conversion, Waikoloa, Hawaii, December 5-9, 1994, p. 2068-2073.

Photo-Recovery of Electron-Irradiated GaAs Solar Cells

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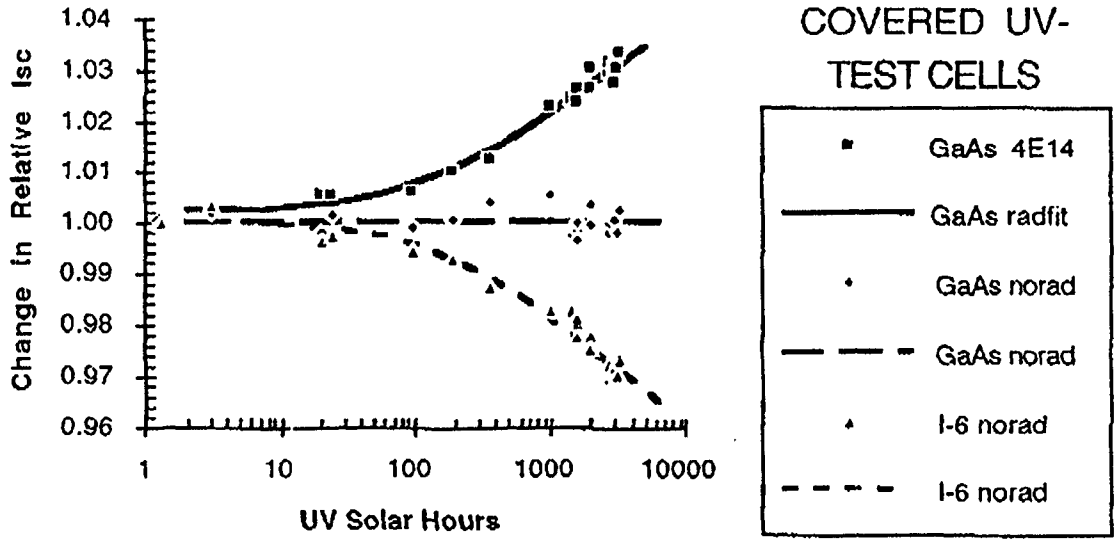
ABSTRACT

The first long-term (3000 hours) UV testing of unirradiated and 1 MeV electron-irradiated GaAs solar cells, with multilayer-coated coverslides to reduce solar array operating temperature, has produced some unexpected and important results[1]. Two results, independent of the coverslide coatings, are of particular importance in terms of the predictability of GaAs solar-array lifetime in space:

1. The GaAs/Ge solar cells used for this series of tests displayed a much higher radiation degradation than that predicted based on JPL Solar Cell Radiation Handbook data. Covered cells degraded more in Isc than did bare cells. Short-term illumination at 60°C did not produce significant recovery (~1%) of the radiation damage.
2. **However, electron radiation damage to these GaAs solar cells anneals at 40°C when exposed to ~1 sun AM0 UV light sources for extended periods. The effect appears to be roughly linear with time (~1% of Isc per 1000 UVSH), is large (≥ 3%), and has not yet saturated (at 3000 hours).** This photo-recovery of radiation damage to GaAs solar cells is a new effect and potentially important to the spacecraft community. The figure compares the effects of extended UV on irradiated and unirradiated GaAs solar cells with INTELSAT-6 Si cells. The effect and its generality, the extent of and conditions for photo-recovery, and the implications of such recovery for missions in radiation environments has not yet been determined.



[1] A. Meulenberg, "Space Qualification of Blue-Red Reflector Coverslides" Final Report JTAED-9335-013 NASA /Goddard Space Flight Center

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INITIAL RESULTS FOR THE SILICON MONOLITHICALLY INTERCONNECTED SOLAR CELL PRODUCT

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This proprietary technology is based on AstroPower's electrostatic bonding and innovative silicon solar cell processing techniques. Electrostatic bonding allows silicon wafers to be permanently attached to a thermally matched glass superstrate and then thinned to final thicknesses less than 25 μm. These devices are based on the features of a thin, light-trapping silicon solar cell: ***high voltage***, *high current, light weight (high specific power) and high radiation resistance.*

Monolithic interconnection allows the fabrication costs on a per Watt basis to be roughly independent of the array size, power or voltage, therefore, the cost effectiveness to manufacture solar cell arrays with output powers ranging from milliwatts up to four watts and output voltages ranging from ***5 to 500 volts*** will be similar. This compares favorably to conventionally manufactured, commercial solar cell arrays, where handling of small parts is very labor intensive and costly. In this way, a wide variety of product specifications can be met using the same fabrication techniques.

Prototype solar cells have demonstrated efficiencies greater than 11%. An open-circuit voltage of 5.4 volts, fill factor of 65%, and short-circuit current density of 28mA/cm^2 at AM1.5 illumination are typical. Future efforts are being directed to optimization of the solar cell operating charateristics as well as production processing.

The monolithic approach has a number of inherent advantages, including reduced cost per interconnect and increased reliability of array connections. These features make this proprietary technology an excellent candidate for a large number of consumer products.

MONOLITHICALLY INTERCONNECTED GAAS SOLAR CELLS:
A New Interconnection Technology for High Voltage Solar Cell Output

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Photovoltaic linear concentrator arrays can benefit from high performance solar cell technologies being developed at AstroPower. Specifically, these are the integration of thin GaAs solar cell and epitaxial lateral overgrowth technologies with the application of monolithically interconnected solar cell (MISC) techniques. This MISC array has several advantages which make it ideal for space concentrator systems. These are high system voltage, reliable low cost monolithically formed interconnections, design flexibility, costs that are independent of array voltage, and low power loss from shorts, opens, and impact damage. This concentrator solar cell will incorporate the benefits of light trapping by growing the device active layers over a low-cost, simple, PECVD deposited silicon/silicon dioxide Bragg reflector. The high voltage-low current output results in minimal I^2R losses while properly designing the device allows for minimal shading and resistance losses. It is possible to obtain open circuit voltages as high as 67 volts/cm of solar cell length with existing technology. The projected power density for the high performance device is 5 kW/m^2 for an AM0 efficiency of 26% at 15X. Concentrator solar cell arrays are necessary to meet the power requirements of specific mission platforms and can supply high voltage power for electric propulsion systems.

It is anticipated that the high efficiency, GaAs monolithically interconnected linear concentrator solar cell array will enjoy widespread application for space based solar power needs. Additional applications include remote man-portable or ultra-light unmanned air vehicle (UAV) power supplies where high power per area, high radiation hardness and a high bus voltage or low bus current are important. The monolithic approach has a number of inherent advantages, including reduced cost per interconnect and increased reliability of array connections. There is also a high potential for a large number of consumer products. Dual-use applications can include battery chargers and remote power supplies for consumer electronics products such as portable telephones/beepers, portable radios, CD players, dashboard radar detectors, remote walkway lighting, etc.

Hydrogen Passivation of n+p and p+n Heteroepitaxial InP Solar Cell Structures

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High-efficiency, heteroepitaxial (HE) InP solar cells, grown on GaAs, Si or Ge substrates, are desirable for their mechanically strong, light-weight and radiation-hard properties. However, dislocations, caused by lattice mismatch, currently limit the performance of the HE cells. This occurs through shunting paths across the active photovoltaic junction and by the formation of deep levels. In previous work we have demonstrated that plasma hydrogenation is an effective and stable means to passivate the electrical activity of dislocations in specially designed HE InP test structures. In this work, we present the first report of successful hydrogen passivation in actual InP cell structures grown on GaAs substrates by metalorganic chemical vapor deposition (MOCVD). We have found that a 2 hour exposure to a 13.56 MHz hydrogen plasma at 275 C reduces the deep level concentration in HE n+p InP cell structures from as-grown values of $\sim 10^{15}$ cm^{-3}, down to $1\text{-}2 \times 10^{13}$ cm^{-3}. The deep levels in the p-type base region of the cell structure match those of our earlier p-type test structures, which were attributed to dislocations or related point defect complexes. All dopants were successfully reactivated by a 400 C, 5 minute anneal with no detectable activation of deep levels. I-V analysis indicated a subsequent ~ 10 fold decrease in reverse leakage current at -1 volt reverse bias, and no change in the forward biased series resistance of the cell structure which indicates complete reactivation of the n+ emitter. Furthermore, electrochemical C-V profiling indicates greatly enhanced passivation depth, and hence hydrogen diffusion, for heteroepitaxial structures when compared with identically processed homoepitaxial n+p InP structures. An analysis of hydrogen diffusion in dislocated InP will be discussed, along with comparisons of passivation effectiveness for n+p versus p+n heteroepitaxial cell configurations. Preliminary hydrogen-passivated HE InP cell results will also be presented.

submitted to *Space Photovoltaic Research and Technology Conference XIV*, NASA Lewis Research Center, October 24-26, 1995

The Growth of Low Band-Gap InAs on (111)B GaAs Substrates

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The use of low band-gap materials is of interest for a number of photovoltaic and optoelectronic applications, such as bottom cells of optimized multijunction solar cell designs (1), long wavelength light sources, detectors, and thermophotovoltaics. However, low band-gap materials are generally mismatched with respect to lattice constant, thermal expansion coefficient, and chemical bonding to the most appropriate commercially available substrates (Si, Ge, and GaAs). For the specific case of III-V semiconductor heteroepitaxy, one must contend with the strain induced by both lattice constant mismatch at the growth temperature and differences in the rates of mechanical deformation during the cool down cycle. Several experimental techniques have been developed to minimize the impact of these phenomena (i.e., compositional grading, strained-layer superlattices, and high-temperature annealing). However, in highly strained systems such as InAs-on-GaAs, three-dimensional island formation and large defect densities ($\geq 10^8$ cm^{-2}) tend to limit their applicability. In these particular cases, the surface morphology and defect density must be controlled during the initial stages of nucleation and growth.

At the last SPRAT conference, we reported on a study of the evolution of InAs islands on (100) and (111)B GaAs substrates (2). Growth on the (111)B orientation exhibits a number of advantageous properties as compared to the (100) during these early stages of strained-layer epitaxy. In accordance with a developing model of nucleation and growth, we have deposited thin (60 Å - 2500 Å), fully relaxed InAs films on (111)B GaAs substrates. Although thicker InAs films are subject to the formation of twin defects common to epitaxy on the (111)B orientation, appropriate control of the growth parameters can greatly minimize their density. Using this knowledge base, InAs films up to 2 μm in thickness with improved morphology and structural quality have been grown on (111)B GaAs substrates, thereby enabling the measurement of electronic and optical properties.

(1) R. E. Welser and L. J. Guido, Solar Energy Materials and Solar Cells **36**, 349 (1995).

(2) R. E. Welser and L. J. Guido, Proc. of SPRAT XIII, Cleveland, OH, June 14-16, 1994, p. 409.

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***Major Area:** High Efficiency Planar Solar Cells; **Mode of presentation:** oral*

DESIGN OF A THREE-LAYER ANTIREFLECTION COATING FOR HIGH EFFICIENCY INDIUM PHOSPHIDE SOLAR CELLS USING A CHEMICAL OXIDE AS FIRST LAYER

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ABSTRACT

It is well known that the behavior of III-V compound based solar cells is largely controlled by their surface, since the majority of light generated carriers (63% for GaAs and 79% for InP) are created within 0.2 μm of the surface of the illuminated cell. Consequently, the always observed high surface recombination velocity (SRV) on these cells is a serious limiting factor for their high efficiency performance, especially for those with p-n junction made by either thermal diffusion or ion implantation. A good surface passivation layer, ideally a grown oxide as opposed to a deposited one, will cause a significant reduction in the SRV without adding interface problems, thus improving the performance of III-V compound based solar cells. Another significant benefit to the overall performance of the solar cells can be achieved by a substantial reduction of their large surface optical reflection by the use of a well designed antireflection (AR) coating.

In this paper, we demonstrate the effectiveness of using a chemically grown thermally and chemically stable oxide, not only for surface passivation but also as an integral part of a 3-layer AR coating for thermally diffused p^+n InP solar cells. A phosphorus-rich interfacial oxide, $In(PO_3)_3$, is grown at the surface of the p^+ emitter using an etchant based on HNO_3, o-H_3PO_4 and H_2O_2. This oxide has the unique properties of passivating the surface as well as serving as an efficient antireflective layer yielding a measured record high AM0 open-circuit voltage of 890.3 mV on a thermally diffused InP(Cd,S) solar cell. Unlike conventional single layer AR coatings such as ZnS, Sb_2O_3, SiO or double layer AR coatings such as ZnS/MgF_2 deposited by e-beam or resistive evaporation, this oxide preserves the stochoimetry of the InP surface. We show that it is possible to design a three-layer AR coating for a thermally diffused InP solar cell using the $In(PO_3)_3$ grown oxide as the first layer and Al_2O_3 and MgF_2 as the second and third layers respectively, so as to yield an overall theoretical reflectance of less than 2%.

Since chemical oxides are readily grown on III-V semiconductors materials, the technique of using the grown oxide layer to both passivate the surface as well as serve as the first of a multilayer AR coating should work well for all III-V compound-based solar cells.

LIGHTWEIGHT, LIGHT-TRAPPED, THIN GAAS SOLAR CELL FOR SPACECRAFT APPLICATIONS:

PROGRESS AND RESULTS UPDATE

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Progress is reported with respect to the development of ultra-lightweight, high performance, thin, light trapped GaAs solar cells for advanced space power systems. Conversion efficiencies of over 17.7% have been demonstrated for a 3 μm thick, 1 cm^2 silicone bonded solar cell. This results in a specific power of over 1020 W/kg. Device parameters were 1.011 volts open circuit voltage, 80% fill factor, and a short-circuit current density of 29.5 mA/cm^2. In addition to silicone bonding, the use of electrostatic bonding to attach the coverglass support to the front surface enables an ultra-thin, all back contact design that survives processing temperatures greater than 750°C. This also results in a 10% reduction of the cell weight for a potential specific power of 1270 W/kg. All back contact, ultra-thin, electrostatically bonded GaAs solar cell prototypes have been completed demonstrating an open circuit voltage of 1 volt for a cell base thickness of 1 μm with a 0.5 μm emitter. This technology will result in a revolutionary improvement in survivability, performance, and manufacturability of lightweight GaAs solar cell products for future Earth-orbiting science and space exploration missions. The thin, electrostatically bonded, all back contact GaAs device technology has multiple uses for specialty high performance solar cells and other optoelectronic devices.

Laboratory Instrumentation and Techniques for Characterizing Multi-Junction Solar Cells for Space Applications

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Multi-junction solar cells are attractive for space applications because they can be designed to convert a larger fraction of AM0 into electrical power at a lower cost than single-junction cells. The performance of multi-junction cells is much more sensitive to the spectral irradiance of the illuminating source than single-junction cells. The design of high efficiency multi-junction cells for space applications requires matching the optoelectronic properties of the junctions to AM0 spectral irradiance. Unlike single-junction cells, it is not possible to carry out quantum efficiency measurements using only a monochromatic probe beam and determining the cell short-circuit current assuming linearity of the quantum efficiency. Additionally, current-voltage characteristics can not be calculated from measurements under non-AM0 light sources using spectral-correction methods. There are reports in the literature on characterizing the performance of multi-junction cells by measuring and convoluting the quantum efficiency of each junction with the spectral irradiance; the technique is of limited value for the characterization of cell performance under AM0 power-generating conditions.

We report the results of research to develop instrumentation and techniques for characterizing multi-junction solar cells for space. An integrated system is described which consists of a standard lamp, spectral radiometer, dual-source solar simulator, and personal computer based current-voltage and quantum efficiency equipment. The spectral radiometer is calibrated regularly using the tungsten-halogen standard lamp which has a calibration based on NIST scales. The solar simulator produces the light-bias beam for current-voltage and cell quantum efficiency measurements. The calibrated spectral radiometer is used to "fit" the spectral irradiance of the dual-source solar simulator to WRL AM0 data. The quantum efficiency apparatus includes a monochromatic probe beam for measuring the absolute cell quantum efficiency at various voltage biases, including the voltage bias corresponding to the maximum-power point under AM0 light bias.

The details of the procedures to "fit" the spectral irradiance to AM0 will be discussed. An assessment of the role of the accuracy of the "fit" of the spectral irradiance and probe beam intensity on measured cell characteristics will be presented. Quantum efficiencies were measured with both spectral light bias and AM0 light bias; the measurements show striking differences. Spectral irradiances were convoluted with cell quantum efficiencies to calculate cell currents as function of voltage. The calculated currents compare with measured currents at the 1% level. Measurements on a variety of multi-junction cells will be presented. The dependence of defects in junctions on cell quantum efficiencies measured under light and voltage-bias conditions will be presented. Comments will be made on issues related to standards for calibration, and limitations of the instrumentation and techniques. Expeditious development of multi-junction solar cell technology for space presents challenges for cell characterization in the laboratory.

ABSTRACT

Title: **Solar Cell Angle of Incidence Corrections**
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Literature on solar array angle of incidence corrections was found to be sparse and contained no tabular data for support. This lack along with recent data on 27 GaAs/Ge 4cm by 4cm cells initiated the analysis presented in this paper. The literature cites seven possible contributors to angle of incidence effects: cosine, optical front surface, edge, shadowing, UV degradation, particulate soiling, and background color. Only the first three are covered in this paper due to lack of sufficient data.

The cosine correction is commonly used but is not sufficient when the incident angle is large.

Fresnel reflection calculations require knowledge of the index of refraction of the coverglass front surface. The absolute index of refraction for the coverglass front surface was not known nor was it measured due to lack of funds. However, a value for the index of refraction was obtained by examining how the prediction errors varied with different assumed indices and selecting the best fit to the set of measured values. Corrections using front surface Fresnel reflection along with the cosine correction give very good predictive results when compared to measured data, except there is a definite trend away from predicted values at the larger incident angles. This trend could be related to edge effects and is illustrated by a use of a box plot of the errors and by plotting the deviation of the mean against incidence angle. The trend is for larger deviations at larger incidence angles and there may be a fourth order effect involved in the trend. A chi-squared test was used to determine if the measurement errors were normally distributed. At 10 degrees the chi-squared test failed, probably due to the very small numbers involved or a bias from the measurement procedure. All other angles showed a good fit to the normal distribution with increasing goodness-of-fit as the angles increased which reinforces the very small numbers hypothesis.

The contributed data only went to 65 degrees from normal which prevented any firm conclusions about extreme angle effects although a trend in the right direction was seen. Measurement errors were estimated and found to be consistent with the conclusions that were drawn.

A controlled experiment using coverglasses and cells from the same lots and extending to larger incidence angles would probably lead to further insight into the subject area.

LOW INTENSITY LOW TEMPERATURE (LILT) MEASUREMENTS AND COEFFICIENTS ON NEW PHOTOVOLTAIC STRUCTURES

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ABSTRACT

Past NASA missions to Mars, Jupiter and the outer planets were powered by radioisotope thermal generators (RTGs). Although these devices proved to be reliable, their high cost and highly toxic radioactive heat source has made them far less desirable for future planetary missions. This has resulted in a renewed search for alternate energy sources, some of them being photovoltaics (PV) and thermophotovoltaics (TPV). Both of these alternate energy sources convert light/thermal energy directly into electricity. In order to create a viable PV and TPV data base for planetary mission planners and cell designers, we have compiled low temperature low intensity (LILT) I-V data on single junction and multi-junction high efficiency solar cells. The cells tested here represent the latest photovoltaic technology. Using this LILT data to calculate dI_{sc}/dT, dV_{oc}/dT, dFF/dT, and also as a function of intensity, an accurate prediction of cell performance under the AM0 spectrum can be determined. When combined with QUantum efficiency at Low Temperature (QULT) data, one can further enhance the data by adding spectral variations to the measurements. This paper presents an overview of LILT measurements and is only intended to be used as a guideline for material selection and performance predictions. As single junction and multi-junction cell technologies emerge, new test data must be collected. Cell materials included are Si, GaAs/Ge, GaInP/GaAs/Ge, InP, InGaAs/InP, InP/InGaAs/InP, and GaInP. Temperatures range down to as low as -175°C and intensities range from 1 sun down to .02 suns.

SECOND INTERNATIONAL WORKSHOP ON SPACE SOLAR CELL CALIBRATION AND MEASUREMENT TECHNIQUES SUMMARY

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ABSTRACT

The First International Workshop on Space Solar Cell Calibration and Measurement techniques was held in December of 1994 following the PVSC conference. Attendees include representatives from Space Agencies in the United States, Japan, and Europe. The objective of the workshop will be to establish a set of protocols for making interlaboratory comparison measurements, defining universally accepted values for the AM0 solar constant and spectral intensity distribution. A set of recommendations for laboratory measurement practices, and developing a plan for regularly updating calibration and measurement practices and techniques used by the participating organizations and agencies. Topics discussed at the first workshop will be summarized and presented at the second workshop which include, AM0 Solar Constant and Spectrum, Laboratory Practices, Multibandgap measurement techniques, and an International Round Robin for solar cells. This paper includes a summary of both the first and second workshops

Review of Recent Thermophotovoltaic (TPV) Research at Lewis Research Center

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Since the late 1980's the Photovoltaic Branch at the Lewis Research Center has been conducting research in Thermophotovoltaics (TPV). The work began with an investigation of select emitters. It was expanded to include research on indium gallium arsenide ($In_xGa_{1-x}As$) photovoltaic cells and the development of a computer model for TPV systems. This paper will present recent results for the rare earth thin film selective emitters, $In_xGa_{1-X}As$ photovoltaic cells, and TPV systems results.

High Efficiency Radioisotope Thermophotovoltaic Prototype Generator

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A radioisotope thermophotovoltaic generator space power system (RTPV) is a lightweight, low-cost alternative to the present radioisotope thermoelectric generator system (RTG). The fabrication of such an RTPV generator has recently become feasible as the result of the invention of the GaSb infrared sensitive photovoltaic cell.

Herein, we present the results of a parametric study of emitters and optical filters in conjuction with existing data on gallium antimonide cells. We compare a polished tungsten emitter with an Erbia selective emitter for use in combination with a simple dielectric filter and a gallium antimonide cell array. We find that the polished tungsten emitter is by itself a very selective emitter with low emissivity beyond 4 microns. Given a gallium antimonide cell and a tungsten emitter, a simple dielectric filter can be designed to transmit radiant energy below 1.7 microns and to reflect radiant energy between 1.7 and 4 microns back to the emitter. Because of the low long wavelength emissivity associated with the polished tungsten emitter, this simple dielectric filter then yields very respectable system performance. Also as a result of the longer wavelength fall-off in the tungsten emissivity curve, the radiation energy peak for a polished tungsten emitter operating at 1300 K shifts to shorter wavelengths relative to the blackbody spectrum so that the radiated energy peak falls right at the gallium antimonide cell bandedge. The result is that the response of the gallium antimonide cell is well matched to a polished tungsten emitter.

We propose, therefore, to fabricate an operating prototype of a near term radioisotope thermophotovoltaic generator design consisting of a polished tungsten emitter, standard gallium antimonide cells, and a near-term dielectric filter. The Jet Propulsion Laboratory will design and build the thermal cavity, and JX Crystals will fabricate the gallium antimonide cells, dielectric filters, and resultant receiver panels. With 250 Watts of heat input, we expect this prototype to produce over 30 Watts of electrical energy output for a system energy conversion efficiency of over 12%. This low risk, near term design provides advances relative to present radioisotope thermoelectric generators and has the additional advantage of allowing component and system development and testing to begin immediately. Improved cells and filters can easily be incorporated in this baseline system if they should become available in the future.

InGaAsSb/GaSb Thermophotovoltaic Cells

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AstroPower is developing InGaAsSb thermophotovoltaic (TPV) devices. This photovoltaic cell is a two-layer epitaxial InGaAsSb structure formed by liquid-phase epitaxy on a GaSb substrate. The (direct) bandgap of the $In_{1-x}Ga_xAs_{1-y}Sb_y$ alloy is 0.50 to 0.55 eV, depending on its exact alloy composition (x,y); and is closely lattice-matched to the GaSb substrate. The use of the quaternary alloy, as opposed to a ternary alloy — such as, for example, InGaAs/InP — permits low bandgap devices optimized for 1000 to 1500 °C thermal sources with, at the same time, near-exact lattice matching to the GaSb substrate. Lattice-matching is important since even a small degree of lattice mismatch degrades device performance and reliability and increases processing complexity.

For bandgaps of 0.52 eV, internal quantum efficiencies as high as 95% have been measured at a wavelength of 2 microns. At 1 micron wavelengths, internal quantum efficiencies of 55% have been observed. The open-circuit voltage at currents of 0.3 A/cm^2 is 0.220 volts and 0.260 V for current densities of 2 A/cm^2. Fill factors of 56% have also been measured. These preliminary results lead to the conclusion that the GaSb-based quaternary compounds provide a viable and high performance energy conversion solution for thermophotovoltaic systems operating with 1000 to 1500 °C source temperatures.

Multijunction InGaAs Thermophotovoltaic Power Converter

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ABSTRACT

The experimental performance of a multijunction monolithic $In_{0.53}Ga_{0.47}As$ power converter under blackbody irradiation is reported. Eight InGaAs PN junctions grown epitaxially on a semi-insulating wafer were monolithically integrated in series to boost the ~ 0.4 V photovoltage per typical InGaAs junction to over 3 volts for the 1 cm^2 chip. This chip was originally designed and characterized for free-space 1.3 μm laser power beaming. This is the first report of such a multijunction TPV. This is not a traditional tandem cell in which the junctions are stacked vertically. The junctions are each about 1mm long by 1 cm wide and are **laterally** connected across the 1 cm^2 device area. This multijunction design has the potential for lower I^2R power loss since the smaller PN junction area limits the current to one-eighth that of the equivalent surface area. In essence, the current is traded for voltage to avoid the I^2R loss, analogous to the way power utlities avoid I^2R loss in high-tension power lines, by transforming the high current, low voltage generated at a power plant into a high voltage at a low current before transmitting the power over great distances.

GALLIUM PHOSPHIDE ENERGY CONVERTERS

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Gallium phosphide (GaP) energy converters may be succesfully deployed to provide new mission capabilities for spacecraft. Betavoltaic power supplies based on the conversion of tritium beta decay to electricity using GaP energy converters can supply long term low-level power with high reliability. High temperature solar cells, also based on GaP, can be used in inward-bound missions greatly reducing the need for thermal dissipation. Results are presented for GaP direct conversion devices powered by Ni-63 and compared to the conversion of light emitted by tritiarated phosphors. Leakage currents as low as 1.2×10^{-17} A/cm^2 have been measured and the temperature dependence of the reverse saturation current is found to have ideal behavior. Temperature dependent IV, QE, R_{sh}, and V_{oc} results are also presented. These data are used to predict the high-temperature solar cell and betacell performance of GaP devices and suggest appropriate applications for the deployment of this technology.

Characterization Testing Of MEASAT GaAs/Ge Solar Cell Assemblies

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The first commercial communications satellite with gallium-arsenide on germanium (GaAs/Ge) solar arrays is scheduled for launch in December 1995. The spacecraft, named MEASAT, was built by Hughes Space and Telecommunications Company for Binariang Satellite Systems of Malaysia. The solar cell assemblies consisted of large area GaAs/Ge cells supplied by Spectrolab Inc. with infrared reflecting (IRR) coverglass supplied by Pilkington Space Technology. A comprehensive characterization program was performed on the GaAs/Ge solar cell assemblies used on the MEASAT array. This program served two functions; first to establish the database needed to accurately predict on-orbit performance under a variety of conditions; and second, to demonstrate the ability of the solar cell assemblies to withstand all mission environments while still providing the required power at end-of-life. Characterization testing included measurement of electrical performance parameters as a function of radiation exposure, temperature, and angle of incident light; reverse bias stability; optical and thermal properties; mechanical strength tests, panel fabrication, humidity and thermal cycling environmental tests. The results provided a complete database enabling the design of the MEASAT solar array, and demonstrated that the GaAs/Ge cells meet the spacecraft requirements at end-of-life.

THE ASTRO EDGE SOLAR ARRAY FOR THE NASA SSTI CLARK SPACECRAFT

- "better, faster, cheaper" solar array technology here today -

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ABSTRACT

The *Astro Edge* solar array is a new and innovative reflective low concentrator power generating system which has been selected for the CTA Incorporated/ Lockheed Martin Clark spacecraft under the NASA Small Spacecraft Technology Initiative (SSTI) program. In support of this program, Astro Aerospace Corporation has produced one qualification and two flight solar array wings to support a July 1996 launch.

The *Astro Edge* solar array was selected as a new technology to benefit future NASA, military and commercial missions by providing high specific power, high deployed stiffness, low stowed volume, low risk, and cost reduction features which meet the agency's "better, faster, cheaper" goals. This novel array accounts for five of the thirty-six advanced technologies which the Clark spacecraft will demonstrate.

A brief SSTI *Astro Edge* solar array program overview is presented. Completed qualification and acceptance testing is discussed. Finally, the major discriminators which make the *Astro Edge* solar array "better, faster, cheaper" technology are provided.

ABSTRACT

ADVANCED SOLAR PANEL DESIGNS

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This paper describes solar cell panel designs that utilize new high efficiency solar cells along with lightweight rigid panel technology. The resulting designs push the W/kg and W/m^2 parameters to new high levels. These new designs are well suited to meet the demand for higher performance small satellites.

This paper reports on progress made on two SBIR Phase I contracts. One panel design involved the use of large area (5.5cm x 6.5cm) GaAs/Ge solar cells of 19% efficiency combined with a lightweight rigid graphite fiber epoxy isogrid substrate configuration. A coupon (38cm x 38cm) was fabricated and tested which demonstrated an array specific power level of 60 W/kg with a potential of reaching 80 W/kg.

The second panel design involved the use of newly developed high efficiency (22%) dual junction $GaInP_2/GaAs/Ge$ solar cells combined with an advanced lightweight rigid substrate using aluminum honeycomb core with high strength graphite fiber mesh facesheets. A coupon (38cm x 38cm) was fabricated and tested which demonstrated an array specific power of 105 W/kg and 230 W/m^2.

The paper will address the construction details of the panels and an analysis of the component weights. A strawman array design suitable for a typical small-sat mission is described for each of the two panel design technologies being studied. Benefits in respect to weight reduction, area reduction, and system cost reduction are analyzed and compared to conventional arrays.

SPACE QUALIFICATION OF IR-REFLECTING COVERSLIDES FOR GaAs SOLAR CELLS

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ABSTRACT

Improvements to GaAs solar array performance, from the use on solar cell coverslides of several reflecting coatings that reject unusable portions of the solar spectrum, are quantified. Blue-red-rejection (BRR) coverslides provide both infrared rejection (IRR) and ultraviolet rejection (UVR). BRR coverslides were compared to conventional antireflection (AR) and ultraviolet (UV) coated coverslides. A 2% improvement in peak-power output, relative to that from AR-coated coverslides, is seen for cells utilizing BRR coverslides with the widest bandpass. Coverslide BRR-filter bandpass width and covered-solar-cell short-circuit current is a function of incident light angle and the observed narrower-bandpass filters are more sensitive to change in angle from the normal than are wide-bandpass filters.

The first long-term (3000 hours) UV testing of unirradiated and 1 MeV electron-irradiated GaAs solar cells, with multilayer-coated coverslides to reduce solar array operating temperature[1], has indicated that all multilayer coatings on coverslides and solar cells will experience degradation from the space environment (UV and/or electrons). Five types of coverslide coatings, designed for GaAs solar cells, were tested as part of a NASA-sponsored space-flight qualification for BRR, multi-layer-coated, coverslides. The response to the different radiations varied with the coatings. The extent of degradation and its consequences on the solar cell electrical characteristics depend upon the coatings and the radiation. In some cases, an improved optical coupling was observed during long-term UV exposure to the optical stack. The benefits of multi-layered solar-cell optics may depend upon both the duration and the radiation environment of a mission.

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[1] A. Meulenberg, "Space Qualification of Blue-Red Reflector Coverslides" Final Report JTAED-9335-013 NASA /Goddard Space Flight Center

Thursday
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Workshop reports
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One Year of Flight Data From the PASP-Plus Experiment

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NASA Lewis Research Center
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The PASP-Plus (Photovoltaic Array Space Power Plus Diagnostics) program is a photovoltaic experiment which is flying on the Air Force satellite APEX (Advanced Photovoltaic and Electronics Experiments). The satellite was launched on Aug. 3, 1994 with a Pegasus low-cost launch vehicle. There are two other small experiments on APEX, however, PASP-Plus is the largest, uses the most power, and accounts for the largest portion of the data requirements. The satellite is in an elliptical orbit with an apogee of 2552 km and a perigee of 363 km. The inclination is 70 degrees.

The PASP-Plus experiment consists of twelve photovoltaic panels containing a total of sixteen separate cell modules. Two of the modules are concentrator modules, while the rest are planar. There are several different solar cell types flying on PASP-Plus including silicon, GaAs on germanium substrates, InP, amorphous silicon, and three multi-bandgap cells.

The purpose of this paper is to present some of the data from the first year of the PASP-Plus flight. Cell performance and module thermal performance will be discussed as well as other relevant data.

Parasitic Current Collection by PASP Plus Solar Arrays

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S-Cubed Division of Maxwell Laboratories

Solar cells at potentials positive with respect to a surrounding plasma collect electrons. Current is collected by the exposed high voltage surfaces: the interconnects and the sides of the solar cells. This current is a drain on the array power that can be significant for high-power arrays. In addition, this current influences the current balance that determines the floating potential of the spacecraft. One of the objectives of the Air Force (PL/GPS) PASP Plus (Photovoltaic Array Space Power Plus Diagnostics) experiment is an improved understanding of parasitic current collection. We have done computer modeling of parasitic current collection and have examined current collection flight data from the first year of operations.

Prior to the flight we did computer modeling to improve our understanding of the physical processes that control parasitic current collection. At high potentials, the current rapidly rises due to a phenomenon called snapover. Under snapover conditions, the equilibrium potential distribution across the dielectric surface is such that part of the area is at potentials greater than the first crossover of the secondary yield curve. Therefore, each incident electron generates more than one secondary electron. The net effect is that the high potential area and the collecting area increase.

We did two-dimensional calculations for the various geometries to be flown. The calculations span the space of anticipated plasma conditions, applied potential, and material parameters. We used the calculations and early flight data to develop an analytic formula for the dependence of the current on the primary problem variables. The analytic formula was incorporated into the EPSAT computer code. EPSAT allows us to easily extend the results to other conditions.

PASP Plus is the principal experiment integrated onto the Advanced Photovoltaic and Electronics Experiments (APEX) satellite bus. The experiment is testing twelve different solar array designs. Parasitic current collection is being measured for eight of the designs under various operational and environment conditions. We examined the current collected as a function of the various parameters for the six non-concentrator designs. The results are similar to those obtained in previous experiments and predicted by the calculations.

We are using the flight data to validate the analytic formula developed. The formula can be used to quantify the parasitic current collected. Anticipating the parasitic current value allows the spacecraft designer to include this interaction when developing the design.

This work is supported by the Air Force Materiel Command.

HIGH-VOLTAGE SPACE-PLASMA INTERACTIONS MEASURED ON THE PASP PLUS TEST ARRAYS

Donald A. Guidice*

The Photovoltaic Array Space Power Plus Diagnostics (PASP Plus) experiment was developed by the Air Force's Phillips Laboratory with support from NASA's Lewis Research Center. It was launched on the Advanced Photovoltaic & Electronics EXperiments (APEX) satellite on 3 Aug 94 into a 70 deg inclination, 363 km by 2550 km elliptical orbit. This orbit allows the investigation of space plasma effects on high-voltage operation (leakage current at positive voltages and arcing at negative voltages) in the perigee region. PASP Plus is testing *twelve* solar arrays. There are four planar Si arrays: an old standard type (used as a reference), the large-cell Space Station Freedom (SSF) array, a thin "APSA" array, and an amorphous Si array. Next are three GaAs on Ge planar arrays and three new-material planar arrays, including InP and two multijunction types. Finally, there are two concentrator arrays: a reflective-focusing *Mini-Cassegrainian* and a Fresnel-lens focusing *Mini-Dome*. PASP Plus's diagnostic sensors include: Langmuir probe to measure plasma density, an electrostatic analyzer (ESA) to measure the 30 eV-30 keV electron/ion spectra and determine vehicle negative potential during positive biasing, and a transient pulse monitor (TPM) to characterize the arcs that occur during the negative biasing. Through positive biasing of its test arrays, PASP Plus investigated the *snapover* phenomenon, which took place over the range of +100 to +300 volts. It was found that array configurations where the interconnects are shielded from the space plasma (i.e., the concentrators or arrays with "wrap-through" connectors) have lower leakage current. The concentrators exhibited negligible leakage current over the whole range up to +500 V. In the case of two similar GaAs on Ge arrays, the one with "wrap-through" connectors had lower leakage current than the one with conventional interconnects. Through negative biasing, PASP Plus investigated the arcing rates of its test arrays. The standard Si array, with its old construction (exposed rough-surface interconnects), arced significantly over a wide voltage & plasma-density range. The other arrays arced at very low rates, mostly at voltages greater than -350 V and plasma densities near or greater than 10^5 cm^{-3}. As expected according to theory, arcing was more prevalent when array temperatures were cold (based on biasing in eclipse).

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SPRAT-14 Conference:

Abstract

Preliminary Chaotic Model of Snapover on High Voltage Solar Cells

High voltage power systems in space will interact with the space plasma in a variety of ways. One of these, Snapover, is characterized by sudden enlargement of the current collection area across normally insulating surfaces generating enhanced electron current collection. Power drain on solar array power systems results from this enhanced current collection. Optical observations of the snapover phenomena in the laboratory indicates a functional relation between bia potential and surface glow area. This paper shall examine the potential of modeling the relation between glow area and bia potential as a consequence of the fold/cusp bifurcation in chaos theory. Successful characterizations of snapover as a chaotic phenomena may provide a means of snapover prevention and control through chaotic synchronization.

An Update on SCARLET Hardware Development & Flight Programs

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SCARLET (**S**olar **C**oncentrator **A**rray with **R**efractive **L**inear **E**lement **T**echnology) is one of the first practical photovoltaic concentrator array technologies that offers a number of benefits for space applications (i.e. high array efficiency, protection from space radiation effects, a relatively light weight system, minimized plasma interactions, etc.). The line-focus concentrator concept, however, also offers two very important advantages: (1) low-cost mass production potential of the lens material and (2) relaxation of precise array tracking requirements to only a single axis. These benefits offer unique capabilities to both commercial and government spacecraft users, specifically those interested in high radiation missions, such as MEO orbits, and electric-powered propulsion LEO-to-GEO orbit raising applications.

SCARLET is an aggressive hardware development and flight validation program sponsored by the Ballistic Missile Defense Organization (BMDO) and NASA Lewis Research Center. Its intent is bring the technology to the level of performance and validation necessary for use by various government and commercial programs. The first phase of the SCARLET program culminated with the design, development and fabrication of a small concentrator array for flight on the METEOR satellite. This hardware will be the first in-space demonstration of concentrator technology at the "array level" and will provide valuable in-orbit performance measurements. The METEOR satellite is currently planned for a September/October 1995 launch. The next phase of the program is the development of large array for use by one of the NASA New Millennium Program missions. This hardware will incorporate a number of the significant improvements over the basic METEOR design. This presentation will address the basic SCARLET technology, examine its benefits to users, and describe the expected improvements for future missions.

Insolation and Dust Experiment on Mars Pathfinder

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We have designed and built a solar-cell based sensor for the Mars Pathfinder, to be launched to Mars in December 1996, which will measure the solar insolation on the surface of Mars and the amount of dust deposition on a solar cell coverglass. The sensor will fly as part of the solar array of the "Sojourner" micro-rover. Together, the solar insolation and dust instruments have a mass of less than 60 grams and require an exposed area of 15 cm^2. Next generation instruments will be even smaller. The flight instruments hs completed qualification testing and is now being integrated onto the spacecraft.

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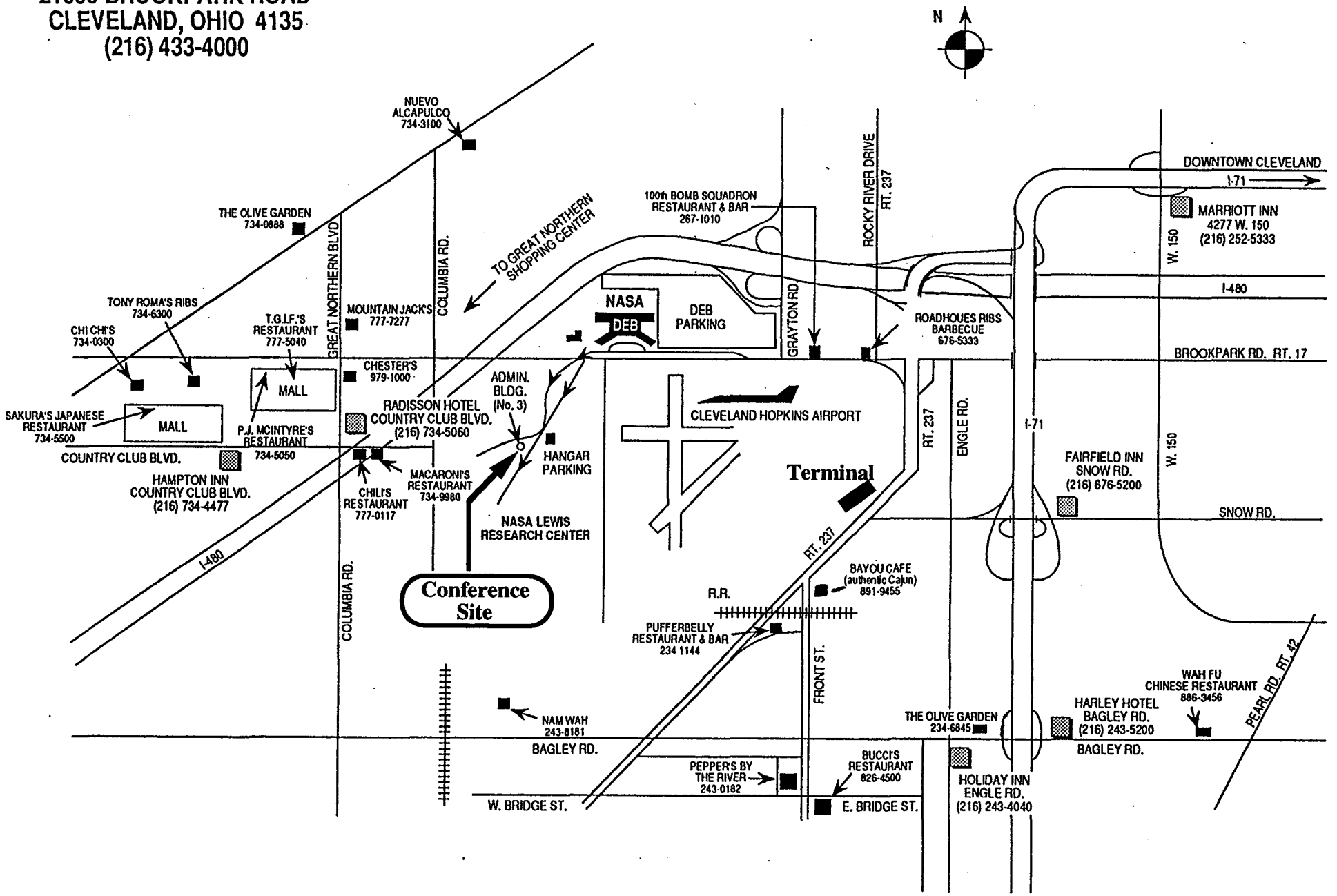

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The Fourteenth Space Photovoltaic Research and Technology conference was held at the NASA Lewis Research Center from October 24–26, 1995. The abstracts presented in this volume report substantial progress in a variety of areas in space photovoltaics. Technical and review papers were presented in many areas, including high efficiency GaAs and InP solar cells, GaAs/Ge cells as commercial items, high efficiency multiple bandgap cells, solar cell and array technology, heteroepitaxial cells, thermophotovoltaic energy conversion, and space radiation effects. Space flight data on a variety of cells were also presented.

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