

THIN FILM GaAs FOR SPACE -- MOVING OUT OF THE LABORATORY

Paul M. Stella
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

Richard M. Kurland
Hans G. Mesch
TRW Space and Electronics Group
Redondo Beach, CA 90278

ABSTRACT

In 1991, NASA, -JPL, completed the APSA (Advanced Photovoltaic Solar Array) program, demonstrating a lightweight deployable flexible array wing capable of 130 W/kg specific performance, a substantial improvement over conventional flight hardware. The design was based on the use of thin (55 microns) silicon or thin (100 microns) GaAs/Ge solar cells (Reference 1). Further array performance enhancements will require the implementation of a new advanced solar cell. An effort has been initiated to develop array fabrication methods for use of ultrathin high efficiency large area thin film GaAs cells. Flexible substrate modules have been assembled for thermal cycle testing.

INTRODUCTION

In 1955, JPL initiated the APSA program to develop an array prototype that would utilize technology capable of very high specific performance. The effort culminated in the 1991 demonstration of a prototype deployable wing, designed, fabricated and tested by TRW, with a BOL (beginning of life) specific performance of over 130 W/kg (Figure 1). The design was based on the use of thin silicon (55 microns) and thin GaAs/Ge (90 microns) solar cells, both of which were assembled on the prototype wing (Figure 2). These cells were the highest specific performance production space cells available. They were purchased from space cell manufacturers and fabricated to space quality standards. Initial development of the thin silicon cells can be traced back to the mid/late 1970's and of the thin GaAs/Ge cells to the late 1980's. The APSA took full advantage of the high specific performances. Of interest, although the silicon and GaAs/Ge cell efficiencies were significantly different (13.8% and 18% AMO, respectively), the array specific performance remained at roughly 130 W/kg for either cell due to the difference in cell mass (thickness and density).

The APSA was designed to accommodate a wide variety of solar cells and further improvements will entail the use of new advanced cells. During the course of the APSA

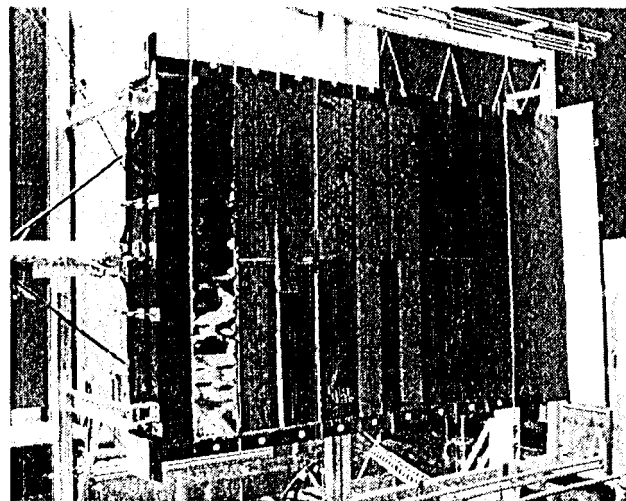


Fig. 1. APSA prototype wing

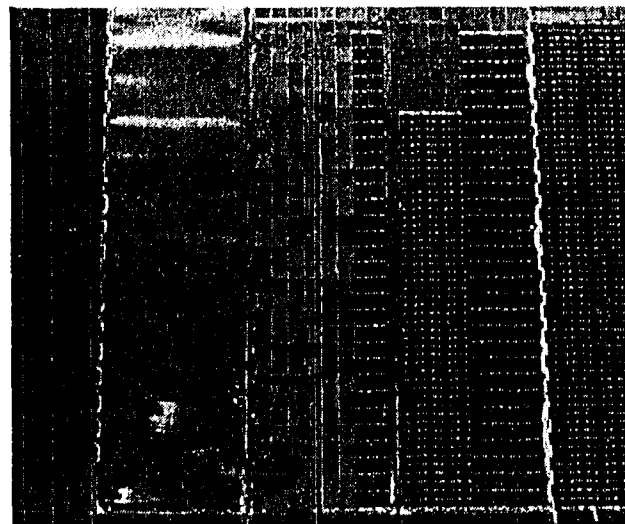


Fig. 2. APSA closeup showing thin silicon and GaAs/Ge solar cells

work, less developed cell technologies were identified that had the potential to enhance the array performance. A device that was felt to be the most mature was the peeled film (also referred to as CLEFT) GaAs cell presently fabricated in the U.S. by Kopin Corporation.

The advantage in array performance that could be expected by successful implementation of the thin film GaAs cell can be seen in Figure 3, where APSA specific power is plotted as a function of cell efficiency. The array structure was adjusted to maintain a 0.10 stiffness and 0.01 g strength as cell efficiency (and array area) were varied, as would occur in an actual mission design. The cell efficiencies are corrected for anticipated array operating temperatures. The mission application was selected as 10 years GEO (Geosynchronous Earth Orbit). The solid line shows the performance of the baseline thin silicon cell, starting at approximately 130 W/kg and degrading to 95 W/kg at EOL (end of life). The use of thin GaAs/Ge (115 microns for these calculations) shrinks the array area in accordance with the efficiency change (adjusted for operating temperatures), but still leads to a BOL performance of roughly 130 W/kg. The higher efficiency is offset by the higher cell mass. The better radiation characteristics provide a slightly higher (than silicon) BOL value of 100 W/kg.

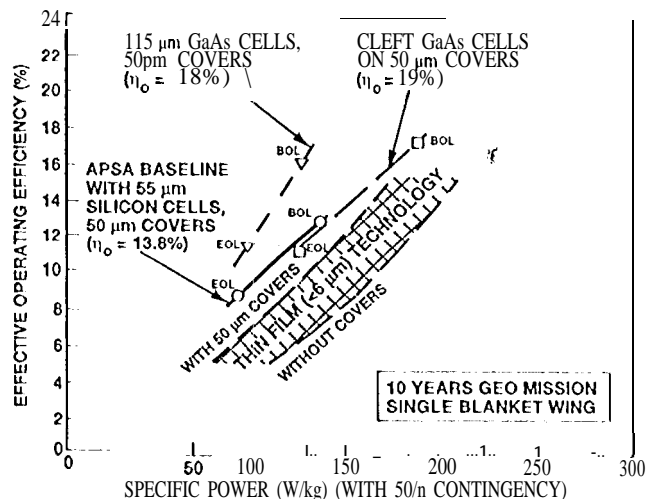


Fig. 3. Impact of cell technology on APSA performance

The replacement of the GaAs/Ge cell with a thin film GaAs cell of comparable efficiency allows for full utilization of the efficiency increase and as shown in the figure, the BOL performance increases to approximately 190 W/kg, a nearly 50% enhancement compared to the existing protoflight APSA array. Other cell technologies, such as idealized thin film materials, are projected to further improve on this value albeit at efficiencies which have yet to be demonstrated, particularly for a relatively large area high volume device.

This substantial performance improvement was felt to warrant development of initial handling and array assembly methods for thin film GaAs. Additionally, other materials, such

as InP, which have shown extremely attractive radiation behavior, might also be available at some future date in a peeled film format. Consequently, work on GaAs would provide valuable precursor information, much as work with thin silicon in the 1980's has led to a relatively rapid integration of thin GaAs/Ge in the 1990's.

Previous paths in moving laboratory cells into space use have followed two separate approaches. One, used by the DoD with GaAs, was to develop cell production and array assembly capabilities concurrently. This was the result of having a specific mission need and as a result of that, having sufficient (plentiful) funds. However, the situation with NASA cell/array development has generally followed a very different path, one governed by limited funds and lack of a specific mission need. Generally, program needs have followed from the demonstration of a space-ready component or device. This may change in the future with the current emphasis on smaller, more frequent missions.

In the approach used by JPL and NASA in development of the thin silicon cell and the APSA array, flight readiness followed a lengthy period of sequential cell production and array assembly efforts. The process of technology transfer begins after the development of a cell (or array concept) having some desirable properties (such as low mass). In the case of the solar cell, the succeeding steps then required establishing a repeatable and controllable cell fabrication process and the production of a relatively large quantity of "pilot line" cells. These cells were then made available to array manufacturers to develop handling and assembly methods verified by a demonstration of module fabrication. During this step, feedback was provided to the cell manufacturer as to which cell characteristics (contact area for example) were most troublesome and corrective actions were undertaken. Subsequent evaluation was then made at the array assembly stage. Module capability was verified through component tests, such as thermal cycling. As confidence increased at the array assembly level, manufacturing then began to work with the development engineers to develop a credible process. The time that elapsed between the initial development of pilot line thin silicon cells and the use of such devices on a spacecraft was on the order of ten years (References 2, 3).

In the case of the thin film GaAs cell, the situation in the 1990's is certainly more difficult than in the early 1980's, inasmuch as program funding is generally much lower, and cell costs are higher on a per cell basis. This greatly restricts the quantity of cells available for process development and will require a greater commitment from the cell manufacturers and array manufacturers, to complement the NASA contribution.

DISCUSSION

In early FY 1992, separate conversations were held with Kopin Corporation and TRW personnel to determine the feasibility of assembling small flexible blanket test modules using peeled film GaAs cells. At the time, TRW was planning

to assemble test modules using thin silicon cells and sufficient material would be available for fabricating thin film GaAs modules.

Since both parties expressed interest, discussions were held between Kopin and TRW on the appropriate specification for the cells. JPL also entered into these talks in order to provide an overall scope for the effort based on technical objectives and funding limitations. A decision was made to go to a cell area of 2×4 in², in order to be compatible with cell sizes and tooling used on the APSA array. The GaAs active cell would be bonded by Kopin to a microsheet superstrate. The superstrates were 100 microns thick. Although we were interested in a 50 micron thick superstrate, it was felt that initially, it would be prudent to start conservatively and use a slightly thicker superstrate. Cell thicknesses would be on the order of 5 microns, with a DC93-500 adhesive layer (cell to superstrate) of 50 microns (Figure 4). All contacts would be accessible from the rear, the front contact interconnect pads "free standing" on the adhesive. All interconnections would be made in the area of the cell corners.

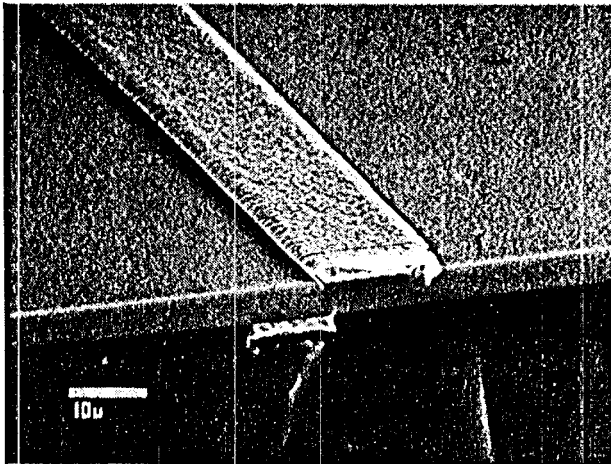


Fig. 4. Magnified view of thin film cell. Rear contact bar at top. Superstrate adhesive at bottom.

In order to maximize the quantity of cells to be delivered, a 16% minimum efficiency was specified, thereby keeping the yield high. Since the most critical measurement would be that of module degradation during subsequent thermal cycling, the absolute efficiency was not critical at this time, and it was necessary only to have reasonable fill factors and cell efficiencies. In addition, cells below 16% efficiency could be classified as mechanicals, and they would be used for establishing interconnection techniques and tooling setups. Ultimately, 26 cells and 16 mechanicals were forwarded to TRW. The average efficiency of the electrically acceptable cells was $17.8\% \pm 0.6\%$, based on measurements provided by Kopin. The highest performing cell was measured at 18.8%. Measurements of individual cells were not made at JPL, since a suitable test fixture was not available, and we did not wish to risk damaging any of the small quantity of cells. A histogram of electrically acceptable cell efficiency is shown in Figure 5.

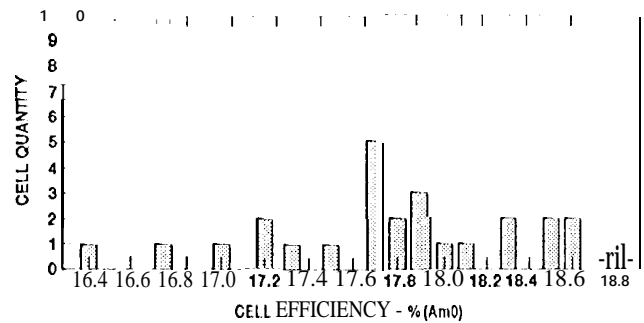


Fig. 5. Efficiency of delivered cells

During the period when cells were being fabricated by Kopin, TRW completed the design for the test modules. The module substrate consisted of a 50 micron thick Kapton substrate coated on both sides with germanium. A zone of 1.3 cm wide Kapton tape was located on the periphery of the 15 x 17 cm panel is a zone of 0.5 wide Kapton tape. Twelve cells, consisting of three four-cell series strings would be bonded to the substrate. A schematic is shown in Figure 6.

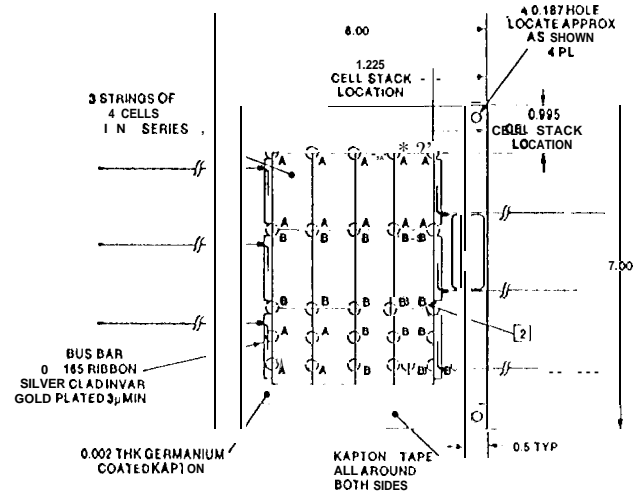


Fig. 6. Test module schematic (dimensions in inches unless otherwise identified)

When the initial group of cells were delivered to TRW during the fourth quarter of FY 92, TRW evaluated a number of interconnection methods. Due to the limited bond area, attempts were initially made to use thermo-sonic and ultrasonic bonding methods that were available in the microelectronics facility. 13 x 75 microns gold ribbon and 2S microns diameter aluminum wire interconnectors were used for these tests. All attempts failed. Detailed examination of the cells revealed that the soft DC 93500 adhesive underneath the contact zone was allowing the contact pad to move both laterally and downward under the bonding tool pressure. As a result, it was not possible to make an intermetallic bond between the contact pad and the interconnector.

A decision was then made to utilize a solder-based method. However, to minimize heat input to the contact area that might incur adhesive bubbling and to prevent leaching of gold from the cell contact, a low temperature indium-based solder (97% iridium, 3% silver) from Iridium Corporation of America, was used. A special 25 micron thick in-plane silver-plated Invar interconnector was designed for the cells. The interconnectors were cut by an Electrical Discharge Machining process, using the standard TRW interconnector stock. An assembled interconnector is shown in Figure 7. The indium solder was obtained as a round wire and formed into small, contact-sized flat preforms.

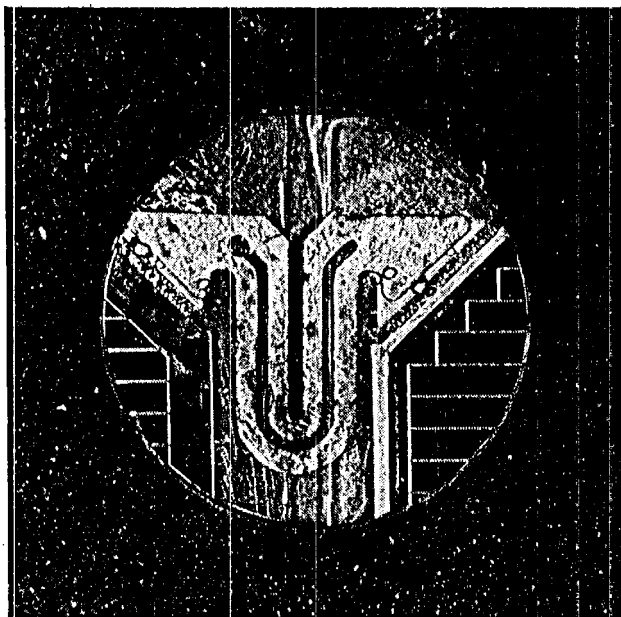


Fig. 7. View of cell interconnector through access hole in substrate

The actual solder joint was made by placing the low temperature solder preform between the thin gold cell contact and the silver-plated Invar interconnector. A small quantity of Alpha Metals #611 RMA Resin flux was applied to the gold and silver contacts. A Unitek Phase-maslc.r IV solder control unit supplied the heat pulse to an 0.2 mm diameter temperature-controlled solder electrode.

For module assembly, twelve cells were loaded (glass side up) into a positioning fixture with cavities. This held four cells in series and three cell strings in parallel. The spacing between the cells was maintained by use of 0.04 cm wide shims in both the series and parallel directions. Once the cells were aligned, all cells were lifted from the fixture using a thin perforated steel plate with Kapton tape. Prior to the cell lifting, Kapton tape was applied to one side of the steel plate so that the sticky side of the tape was allowed to contact each GaAs cell's glass surface through two holes in the steel plate. The fragile cell assemblies remained stuck to the steel plate throughout the, soldering of the interconnectors to the cell contacts and the final

cell-to-substrate bonding operation. Once the cells were bonded to the substrate using Nu-Sil Technology (CWI-1142 adhesive), the Kapton tape was carefully removed from the thin steel plating, releasing the module assembly.

Microscopic inspection of the modules did not reveal any broken cells. However, one cell had a gold cell contact severed from the cell during the flux removal operation and some lesser damage was observed on other cell contacts. The problem was eventually avoided by modifying the flux removal process.

Module electrical performance was measured using a large area pulsed xenon solar simulator, normally used for TRW's conventional array acceptance testing. A recently flown 2 x 2 cm² GaAs solar cell (not a peeled film cell) was used to calibrate the light source. A temperature coefficient of 2.13 mV/°C was used to correct the module performance to 28° C from the test temperature of 22° C.

Although TRW did not perform cell preassembly electrical measurements due to lack of a suitable test fixture, it would appear that some module assembly degradation did occur with respect to the cell data provided by Kopin Corporation.

The magnitude of this varied from string to string. For the lower performance module, two of the three series strings had open circuit voltages (VOc) of approximately 3.3 volts, well below that was expected from series connecting four one volt (VOc) cells. However, the remaining cell string and all strings on the higher performance module all had voltages of approximately 4 volts. This suggests some shorting of the two low voltage circuits. The average efficiency of the four "non shorted" cell strings (based on total cell area) was 17.1 %, and that of the highest string, 18%. This later value can be compared with the average efficiency of the four cells before assembly (measured by Kopin) of 18.6%, suggesting an assembly loss of roughly three percent. In view of normal measurement errors and typical panel assembly losses, this would indicate a negligible degradation for this particular circuit string. Front and rear views of a completed module are shown in Figures 8 and 9.

The average assembly loss for the four non-shortened strings was five percent, somewhat poorer than standard array assembly, but certainly an encouraging level for this initial assembly.

ALTERNATIVE INTERCONNECTING EVALUATIONS

As mentioned earlier, non-solder interconnecting methods were tried, but were unsuccessful due to flexing with the cell/ superstrata silicone adhesive. During the course of this work, Kopin delivered a small quantity of cells with a clear epoxy adhesive used in place of the silicone. Microelectronic wiring methods were evaluated for these cells as alternatives to the standard solar cell assembly methods. Both the thermo-sonic bonding with 13 x 75 microns gold ribbon and 25 microns wire, and ultrasonic bonding with 25 microns diameter aluminum wire

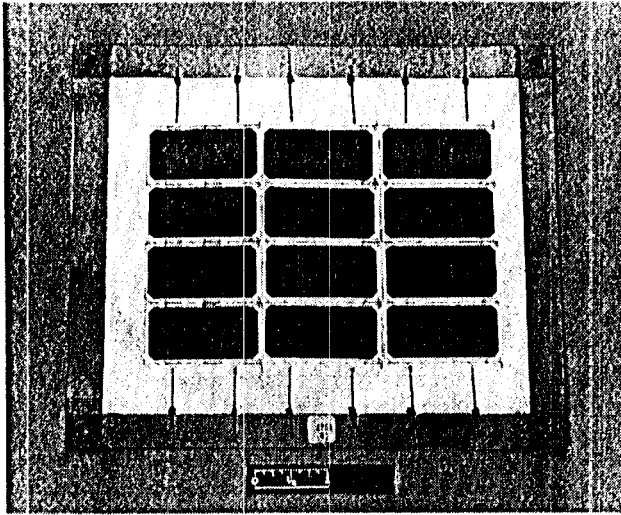


Fig. 8. Front view of test module

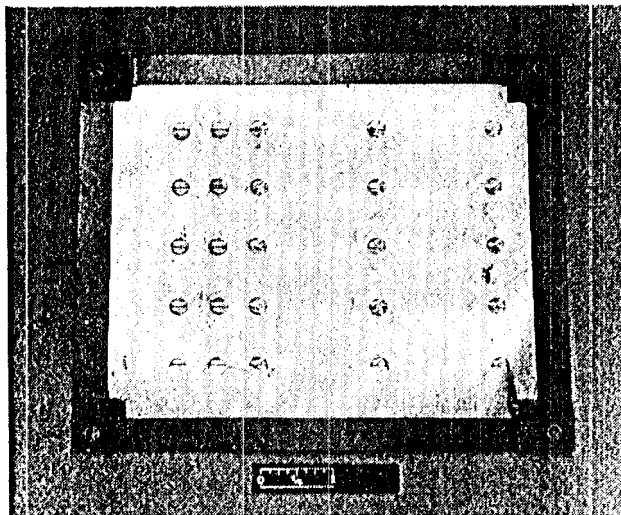


Fig. 9. Rear View of Test Module

provided acceptable interconnections. The best results were achieved with thermo-sonic bonding and the gold ribbon, followed by ultrasonic bonding of the aluminum wire.

Both approaches have advantages and disadvantages. The thermo-sonic technique requires heating the cell to 125°C, then sonically "scrubbing" the ribbon into the gold contact pad on the cell. The ultrasonic method does not require heat, but poses a potential intermetallics problem with aluminum wire on a gold contact pad. Results show that contacts can easily be made either to the large pad or to the thin metallic strip running between pads. It is even possible to contact directly to the very thin grid lines, so that minimal contact pad area is required. Based on the above experimenting, no changes would be needed in the basic design of the Kopin cell if a space quality rigid adhesive could be used to replace the present silicone system.

The contact pads could even be reduced in size in the future. This would also allow the option of placing several wire/ribbon interconnectors on each pad, which are located at the corners of the cell and/or placing several additional wire/ribbon interconnectors along the entire 4cm length of the cell.

MODULE THERMAL CYCLING -- TBD

Following assembly, both modules were shipped to JPL where visual inspection was performed verifying the TRW observations. Modules were then shipped to NASA-I LeRC for thermal cycling in their fast thermal cycle test chamber. Although there was some concern in shipping the fragile test modules by normal carrier, safe arrival at LeRC indicated that normal JPL "fragile" packaging practices are sufficient.

It is intended to subject the modules to a series of LEO and GEO simulating thermal cycles starting in mid-1993. Testing was expected to last up to six months. It is not known at this time how well the modules will perform and cycling to failure is a possibility. However, if successful, the modules will need to survive the equivalent of 30 years GEO and five years LEO, figures of merit achieved by previous APSA test modules using thin silicon solar cells.

CONCLUSIONS

Initial steps have been taken to understand handling and assembly characteristics for the fabrication of lightweight flexible substrate modules using large area thin film GaAs cells. Future implementation of such cells could lead to space array specific performance of nearly 200 W/kg.

The present work, although promising, indicates that significant additional work will be required to establish production capabilities. Hand assembly, suitable for the fabrication of small modules, would not be appropriate for larger array bed assemblies. Interconnecting of cells appears to be especially critical. Due to the design of the free standing cell contact, only low temperature, low pressure soldering methods were found to be suitable. Even for this method, temperature and pressure control of the solder control is mandatory. Flux cleaning must take into consideration the fragile nature of the contact/ interconnection assembly.

The peeled film cell was found to be sensitive to pressure and heat requiring the development of special handling procedures, including the use of only Teflon tweezers. Cell handling and assembly could probably be improved through use of thicker superstrate glass and a thinner adhesive bondline, or through use of a more rigid adhesive. Flexibilities in the present system allow for fracture inducing displacements to occur more readily than with more conventional cells. Cell replacement methods have not been worked out for the present module design. The use of a substrate with an appropriate hole pattern (beneath each interconnection) would probably allow for cell replacement and might also be used to implement a more efficient panel assembly method. This suggests that the present

peeled film Ga As cell design is better utilized with a thin flexible substrate, rather than a conventional honeycomb design which would prohibit access to the rear side contacts following circuit to substrate bonding. The success of the present assembly method will soon be determined through a series of thermal cycling tests. Results will be used to point out any cell/assembly modifications that might be required.

In spite of handling difficulties and cell quantity constraints, high efficiency cell strings were assembled with assembly losses estimated to be on the order of five percent or less. This value is quite encouraging especially when consideration is taken for "real time" process development and the normal mismatches that occur when using small cell quantities.

It is clear that this effort is still in an early stage. Directions for future development have, and will, be established through module assembly and testing. Successful development of array assembly processes have the potential of providing high areal power densities (187. cells) and a significant improvement in specific performance (up to approximately 200 W/kg).

ACKNOWLEDGMENT

The work described in this paper presents the results of research carried out by TRW Space and Electronics Group for the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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