STATUS OF ROCKWELL-ERC HIGH EFFICIENCY SOLAR CELL PROGRAMS

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INTRODUCTION

Rockwell International's Electronics Research Center is engaged in a long term effort to develop practical high efficiency photovoltaic devices for both terrestrial and space applications.

The effort includes programs aimed at developing large area, high efficiency GaAs heteroface cells for low concentration ($\leqslant$10 SUNs) space applications and high concentration (100-1000 SUNs) terrestrial applications as well as other programs aimed at developing high efficiency ($>$25%) multicolor devices for use in similar applications. An additional program is aimed at achieving improved power-to-weight ratio by parting thin film solar cells from their growth substrates prior to their incorporation into an array assembly. There is potential for multiple reuse of the substrates which could lead to reduced costs for such devices.

Highlights of these programs and their interrelated contributions toward the goals of reducing specific weight, volume and cost of photovoltaic space power systems are discussed below. Overall goals are summarized and current programs and their funding sources are listed in Fig. 1.

MULTICOLOR SOLAR CELL PROGRAMS

Two approaches toward achieving high efficiency by means of multicolor, multiple bandgap devices are being pursued. The goal of the Air Force (APL) sponsored program is to demonstrate a device with 1 SUN AMO efficiency of ~25%. The approach has been to first survey a number of candidate materials combinations, growth techniques and converter designs and then choose the most promising combinations of these for final development to meet the performance goal. The materials combinations considered have been limited to closely lattice-match combinations of III-V compounds and/or Ge. The growth techniques examined have included LPE, conventional CVD, MO-CVD, and MBE. The candidate converter designs have all been variations on the theme of series connected subcells of appropriate high and low bandgap materials joined by an optically transparent tunnel junction ohmic contact.

Our current baseline configuration for such a device is shown schematically in Fig. 2. A significant feature of this design is the semi-transparent nature of the high bandgap $Al_xGa_{1-x}As$ subcell which allows an appropriate fraction of high energy photons to pass through to the underlying GaAs subcell. This is done to optimize the opposite trends of current matching and good AlGaAs subcell performance with variation of Al content. An additional feature of the design is the use of ultra thin tunnel junction structures of GaAs. By maintaining the n^+ and p^+ layer thickness $\leqslant 200Å$, the optical absorption losses in the tunnel junction are in the range of 1-2%. The use of GaAs rather than higher bandgap AlGaAs facilitates growth of low resistance structures.

Devices of this type have been fabricated having V_{oc} ~2.1 volts and conversion efficiencies ~2%. A typical plot spectral response as a function of electrical bias is shown in Fig. 3. The complicated interaction of the I-V characteristics of the two subcells and intervening tunnel junction is apparent in the plot.

The goal of the SERI sponsored program is primarily to demonstrate high efficiencies from multicolor devices at high concentrations under terrestrial illumination. However, success with this program could be directly applied to producing enhanced performance space cells.

The approach here is to attempt to fabricate two cell, non-lattice matched, monolithic stacked devices incorporating optimum pairs of individually grown subcells having bandgaps in the range of 1.6-1.7 eV and 0.95-1.1 eV. The high bandgap subcells are being grown by MO-CVD to produce layers of AlGaAs of appropriate thickness, composition and doping to give optimum performance heteroface homojunction structures. The low bandgap subcells are being similarly fabricated from AlGaAsSb compositions by LPE.

These subcells are then to be joined to form the final monolithic converter by an appropriate laser bonding technique. The bonding is also intended to produce the needed transparent intercell ohmic contact (IOC) and ultimately provide in-situ formation of an AlGaAsSb window layer, lattice-matched and epitaxial to the low bandgap cell. The overall device structure before and after the laser bonding operation is shown in Fig. 4.

The current status of the combined multibandgap effort is summarized in Fig. 5. Major future challenges remain in developing AlGaAs subcells with improved performance and developing improved intercell ohmic contacts using tunnel junctions and laser bonded structures. Because of the criticality of maintaining good current match between the individual subcells, it is anticipated that multibandgap devices may be more affected by radiation damage than are conventional single junction cells. It remains to be seen whether this will occur in practice.

PEELED FILM GaAs SOLAR CELLS

The objective of this program is to determine the technical merit and cost feasibility of basic process steps involved in the fabrication of GaAs peeled film solar cells. Several approaches to cell growth, bonding the cell to a low cost carrier, separating the cell from the reusable substrate, and processing methods are being investigated.

A photograph of a 0.5 x 0.5 cm peeled film GaAs heteroface solar cell supported by (wrapped around) a porous alumina rod appears in Fig. 6. The important processing steps needed to produce peeled film cells are shown schematically in Fig. 7. The current status of our peeled film effort is summarized in Fig. 8. It still remains to show that acceptable efficiencies can be realized with these cells. It also remains to be determined what the best configuration is for supporting the cell structure during ultimate use.

GaAs EFFICIENCY IMPROVEMENT STUDY

The goal of this program is the achievement of high yields of high efficiency GaAs heteroface cells. To this end, the project is focused on identifying the efficiency limiting factors in cell materials and cell processing, and improving materials growth and cell fabrication methods so as to mitigate these factors. Specifically, the program plan calls for (1) developing an in-house capability for directly synthesizing up to 3" diameter GaAs boules by the liquid encapsulant method, (2) establishing 2" and 3" diameter MO-CVD (metal organic chemical vapor deposition) epitaxy as the method of solar cell layer growth, (3) studying the defects in the GaAs substrate and epigrown layers and correlating materials quality with the cell efficiency, and (4) as materials evidence for the results of this program, delivering a minimum number (150) 1 cm. diameter concentrator cells meeting specified performance characteristics to the sponsor.

Figure 9 shows the configuration of the current structure of our high efficiency MO-CVD grown GaAs heteroface solar cells. Figure 10 shows typical performance data for this type of cell. Such structures have been repeatedly grown on areas of up to ~2 in^2 with all 0.5 x 0.5 cm cell AMO efficiencies lying in the 18±1.5% range. Efforts are currently under way to scale up the MO-CVD reactor to accept 3" diameter substrates. 1.7 x 1.7 cm and 5 x 5 cm masks are being designed for fabrication of large area cells. Experiments are under way to explore potential advantages of lower temperature epitaxial growth. There is accumulating evidence that growth at ~650°C significantly reduces the detrimental effects of recombination centers which can rapidly diffuse from the substrate into the growing layers during higher temperature (~750°C) growth.

SPACE SOLAR CELLS

GOALS

- HIGH POWER/WEIGHT RATIO
- LARGE AREA DEVICES (5 CM x 5 CM)

CURRENT PROGRAMS

- STACKED MULTIBANDGAP SOLAR CELLS (APL)
- ADVANCED CONCENTRATOR CELLS (SERI)
- GAAs PEELED FILM SOLAR CELLS (SERI)
- GAAs EFFICIENCY IMPROVEMENT (SANDIA)
- BULK CRYSTAL GROWTH (NASA)
- ADVANCED SPACE CELL CONCEPTS (IR&D)

Fig. 1.

- MOCVD-GROWN ALGAAs AND GAAs SUBCELLS
- MBE-GROWN GAAs TUNNEL JUNCTION IOC
- TWO LAYER AR COATING

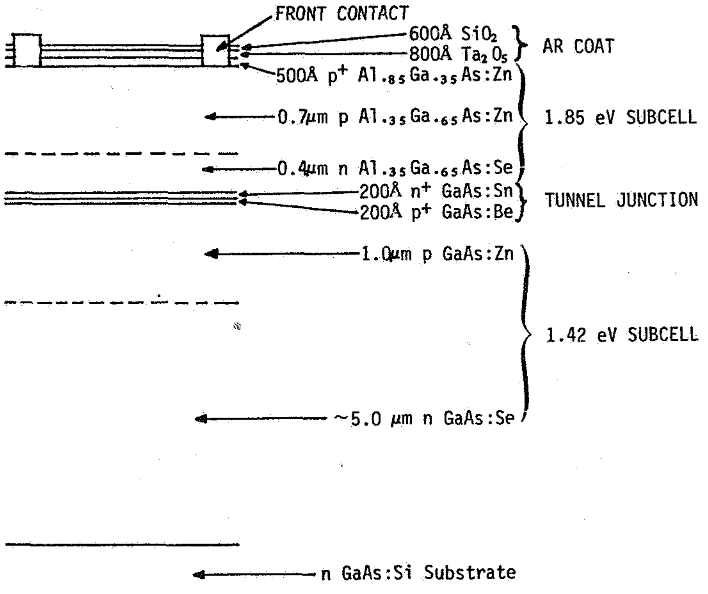
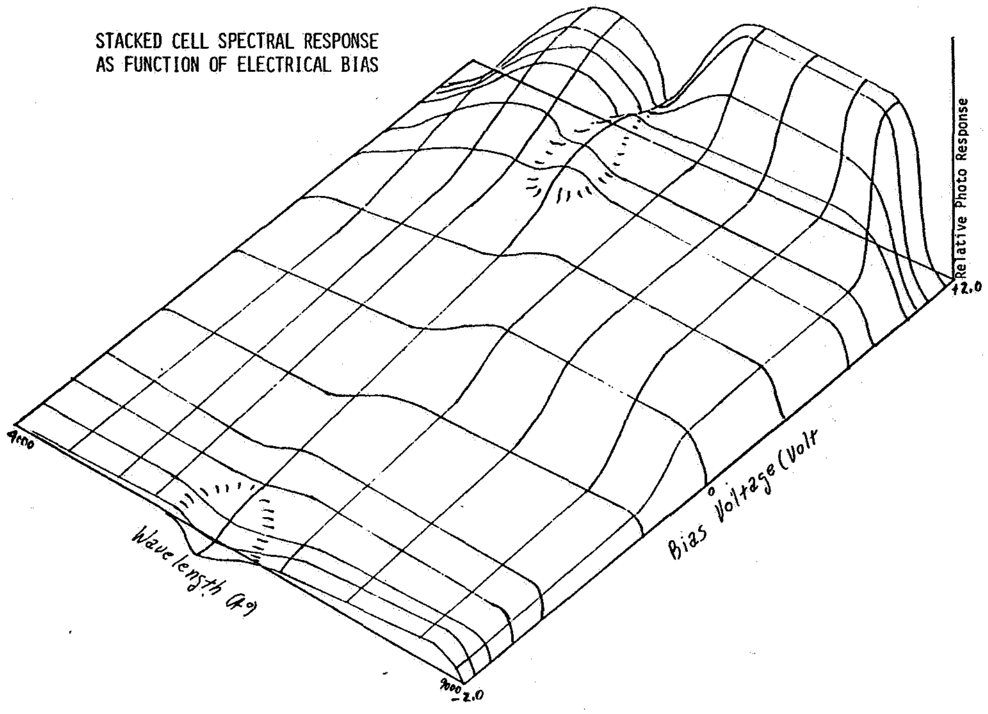


Fig. 2. Current baseline configuration of 2-cell SMBSC.



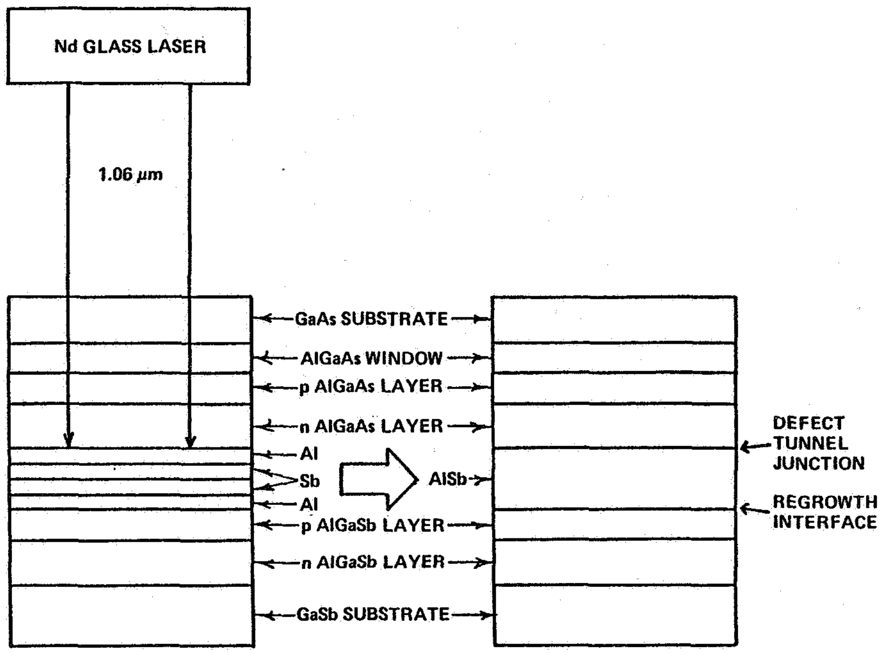


Fig. 4. Laser bonding.

AlGaAs SUBCELLS

- GOOD SPECTRAL RESPONSE ACHIEVED IN MO-CVD $Al_{.3}Ga_{.7}As$ SUBCELL
- HIGH SERIES RESISTANCE REMAINS A PROBLEM (FRONT CONTACT GRID)

INTERCELL OHMIC CONTACTS

- RELIABLE LOW RESISTANCE TUNNEL JUNCTIONS ACHIEVED WITH MBE
- LASER BONDING OF DISSIMILAR SEMICONDUCTORS DEMONSTRATED
- p DOPANT OTHER THAN Zn NEEDED FOR MO-CVD TUNNEL JUNCTIONS

COMPLETE CONVERTERS

- DIFFICULTIES IN ACHIEVING MATCHED HIGH CURRENT DENSITIES
- DEMONSTRATED EFFICIENCY ~2% vs. POTENTIAL EFFICIENCY ~24%
- LEVERAGED RADIATION DAMAGE IS A POTENTIAL CONCERN

Fig. 5. Current status of multibandgap solar cells.

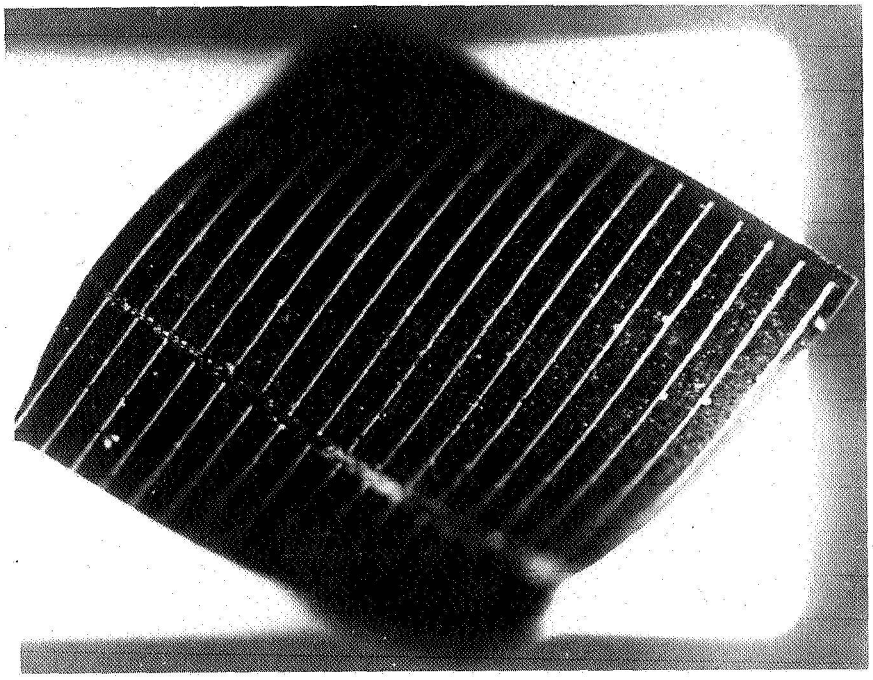


Fig. 6.

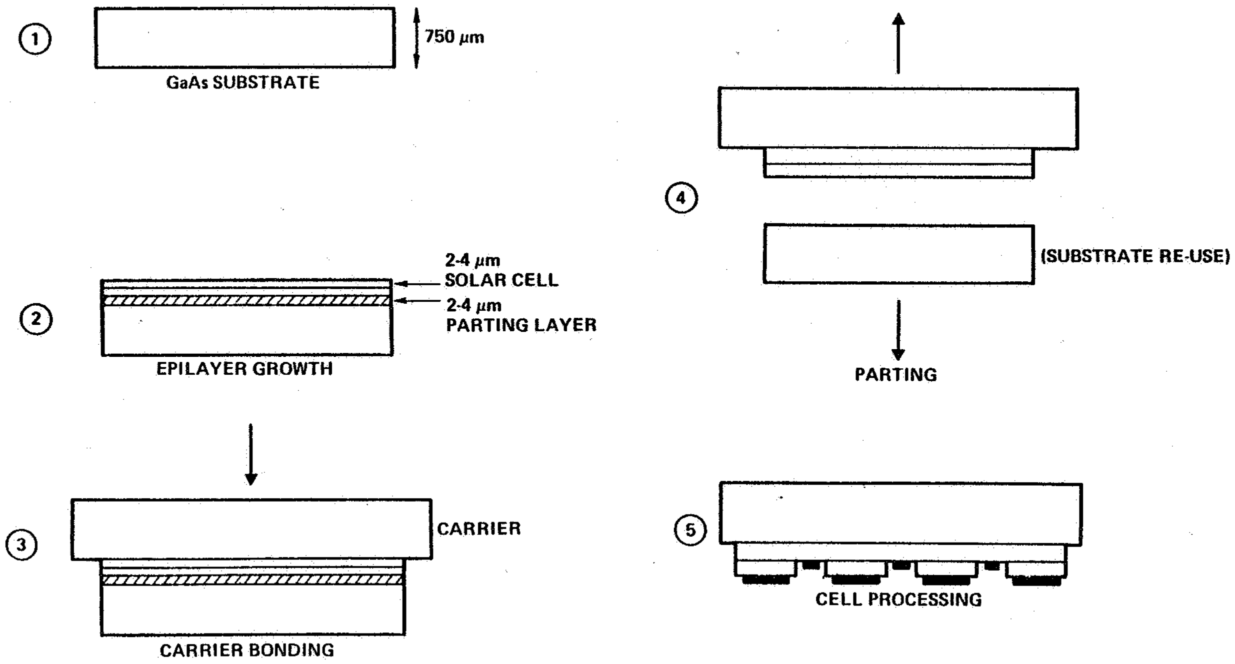


Fig. 7. Schematic of a GaAs peeled film solar cell fabrication process.

- FEASIBILITY OF PRODUCING A PEELED FILM GaAs SOLAR CELL DEMONSTRATED
- GLASS BONDING OF PEELED FILM STRUCTURES UNDER DEVELOPMENT
- REUSABILITY OF GaAs SUBSTRATE CONFIRMED
- PERFORMANCE OF PEELED FILM DEVICE NOT MEASURED

Fig. 8. Current status of peeled film solar cells.

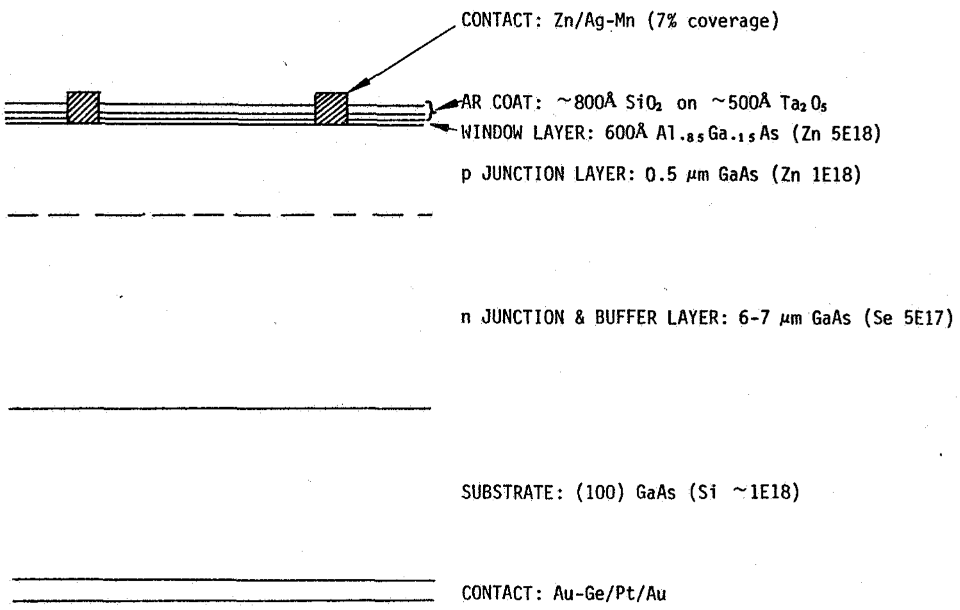
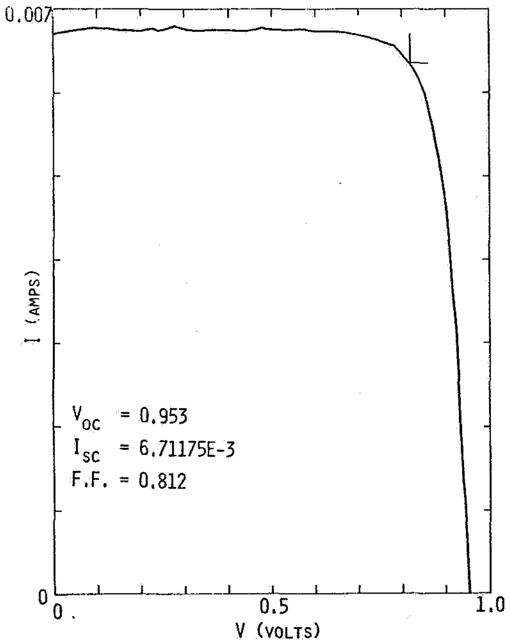


Fig. 9. Schematic structure of high efficiency GaAs solar cell grown by MO-CVD.



MO-CVD GaAs HETEROFACE CELL

0.5 cm x 0.5 cm MESA

2" DIAMETER WAFER

V_{OC} = 0.953

J_{SC} (1 SUN, AMO) = 33.5 mA/cm^2

F.F. = 0.812

η (1 SUN, AMO) = 19.2%

Fig. 10. GaAs efficiency improvement studies.