A REVIEW OF AIR FORCE HIGH EFFICIENCY CASCADED MULTIPLE BANDGAP SOLAR CELL RESEARCH AND DEVELOPMENT

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SUMMARY

At the time of their conception, the cell stack systems to be discussed represent the best semiconductor materials combinations to achieve Air Force program goals. These systems will be investigated thoroughly in Phase I and most promising system, from the standpoint of high efficiency, will be taken into Phase II for further development with large area emphasized (at least 4 cm^2). The emphasis in the Air Force cascaded cell program is placed on eventual non-concentrator application. This use of the final cell design considerably relieves the low resistance requirements for the tunnel junction. In a high concentration application the voltage drop across the tunnel junction can be a very serious problem.

INTRODUCTION

Significant increases in silicon solar cell conversion efficiencies were observed in the early 1970's. These changes were due to modified N^+ diffusion techniques that resulted in much shallower P/N photovoltaic junctions which significantly increased the blue response of the cells. Further improvements brought about by increasing front surface absorption (texturing etch and better AR coats) and the effective and controlled introduction of a P^+ back surface region has raised the laboratory demonstrated silicon solar cell efficiencies up to 16% AMO at 25°C.

Within the last six years or so, improvements in the techniques for growth of III-V semiconductor materials on III-V substrates or Ge substrates has resulted in the demonstration of efficiencies greater than 18% AMO at 25°C for GaAs based solar cells with greater than 16% typically reproduced. Also, the radiation damage resistance of these structures looks very promising for space applications involving the earth's radiation belts.

However, space missions are growing in complexity with attendant growth in power needs. The silicon cell technology does not lend confidence in exceeding 18% in production and the GaAs cells most likely will not exceed 20% in a production environment. The growing power demand along with the growing realization of successful III-V semiconductor material growth technology has ressurected an old idea for very high conversion efficiency--namely the cascaded (series connected) multi-bandgap solar cell (ref. 1). Theoretical analyses of these structures projects conversion efficiencies in the low 30% range for two cell stacks and approaching 40% for three or more serially connected cells in a monolithic structure (ref. 2). The Air Force views this possible solar cell technology with guarded optimism but does realize the impact that high efficiencies can have on broadening the flexibility of future space missions. For this reason, the Air Force has initiated cascaded multiple bandgap research and development programs that will utlimately lead to a very high conversion efficiency space power system.

This paper details the what, why, and how of the development of the multi-bandgap solar cell for Air Force space applications.

AIR FORCE CASCADED SOLAR CELL DEVELOPMENT

The objective of the cascaded solar cell development is to fabricate and demonstrate cells with greater than 25% AMO conversion efficiencies measured at 25°C. The approach, within available and planned budgeting is to fund two contractors who have the responsibility to investigate four individual cascaded structures. The research and development conducted by the contractors is separated into two phases. In Phase I each contractor will determine the best semiconductor materials system with emphasis on conversion efficiency that will be taken in Phase II for the purpose of demonstrating greater than 25% AMO for cell sizes of at least 2 cm x 2 cm. Delivery of one hundred 2 cm x 2 cm solar cell assemblies at the close of the second phase is required. The program is twenty four months for each contractor with Phase I being a fourteen month duration. The specific contractors for this dual awarded program are Research Triangle Institute at Research Triangle Park, North Carolina and Rockwell International with facilities at both Anaheim and Thousand Oaks, California participating.

The payoff for cascaded cell technology is lower total area and total power systems and the establishment of a solar cell basis for future high voltage, high power systems. This particular type of cell has considerable payoff for low orbit application in cost also. For higher orbit application (such as half synchronous) the cost factor is projected to be the same as that for silicon and lower than GaAs single junction cells but with a considerably smaller panel size (ref. 3).

The major problem areas that plague the cascaded solar cell development are associated with the understanding of and the single crystal growth of certain III-V semiconductor materials in serial fashion that are not lattice matched (depending on the specific cell design). Also, the development of proper anti-reflective coatings and contact metalization materials combinations and deposition techniques are critical to making a useful device. In what follows, these problem areas will be discussed in relation to the structures as proposed by the two contractors.

Research Triangle Institute (RTI)

The four materials systems under investigation at RTI are illustrated in Figure (1). The bandgap for each material as well as the method of growth are provided. The fifth materials system is a modification of the second system and has considerable potential.

System I - GaInP Cell on GaInAs Cell

This structure has an GaAlAsSb window of greater than 2.0 electron-volt (ev) bandgap (indirect) on a GaInP top cell and tunnel junction (both 1.6 ev) on a lower cell made of GaInAs (.95 ev) in turn on either a GaAs single crystal substrate or a Ge substrate with a GaAs layer grown on. This structure employs liquid phase epitaxial (LPE) growth for the GaInAs and GaAlAsSb, and vapor phase epitaxial growth for the GaInP portion. The cell is lattice matched to the underlying GaAs layer or substrate by using graded layers (or lattice matching layers) with increasing amounts of indium. There may be as many as five such layers. There are essentially an infinite number of upper and lower cell combinations (GaInP on GaInAs) where the semiconductor lattices of each will be matched, however the matching of the upper and lower bandgaps is not optimum for efficiency in every case. Nevertheless the matching of the lattices can be achieved with a resultant 25% efficiency. The lattice matching of the GaAlAsSb window to the top cell can be achieved with little difficulty. The P electrical dopant in the GaInAs material is magnesium. The P dopant for the GaInP material has been tentatively selected to be cadmium. There is a variety of N dopants that can be used; both selinium and germanium are being investigated for the GaInAs and GaInP materials.

System 2 - GaAlAs Cell on an GaInAs Cell

This structure has an GaAlAs window of near 2 ev bandgap (indirect) on a closely lattice matched GaAlAs top cell and tunnel junction (both 1.6 ev) on a 1.2 ev bandgap GaInAs cell on an appropriate substrate as discussed above. This particular structure is attractive since the top contact metalization is reasonably well understood (ref. 4). The lattice mismatch between GaAlAs and GaInAs is less than 0.7% but is a somewhat troublesome problem to resolve in relation to maintaining high crystalline perfection. The P dopant for the GaAlAs material is germanium. As above the N dopant can be selected from a variety of choices.

System 3 - GaAlAsSb Cell on an GaInAs Cell

The GaAlAsSb window (2 ev bandgap) top cell and tunnel junction (1.6 ev bandgap) are all lattice matched and are lattice matched to .95 ev bandgap GaInAs lower cell. This system has particular problems, however. The control of miscibility gap in the GaAlAsSb material in the bandgap range of interest for the top cell and tunnel junction can negate the entire cell design. Recent data does suggest, though, that the miscibility problem may be confined to a smaller bandgap range than first thought (ref. 5). The contact materials systems are not know for GaAlAsSb at least from solar cell environmental considerations. It is anticipated that the P dopant for the GaAlAsSb material will be germanium.

System 4 - GaAlAsSb Cell on a GaAsSb Cell

This structure is lattice matched all the way down to the substrate where step grading of GaAsSb to the substrate lattice is required. The problems of miscibility and achieving the proper bandgap for the top cell and tunnel are the same as discussed in System 3. The GaAsSb lower cell (1.2 ev bandgap) has been fabricated with good diode shape but low open circuit voltage. The present thought is that the minority carrier lifetime in both layers is being limited by Sb vacancies. The P dopant for the GaAsSb material is germanium.

System 5 - GaAlAs Cell on a CaAs Cell

This structure is considered as a special case of System 2. The upper cell and tunnel junction must have a bandgap of 1.93 ev to achieve reasonable matching to the lower cell. The projected efficiency for this structure is over 25%. There are four significant advantages with this structure: (a) no serious match problems anwhere, (b) A Ta_2O_5 antireflective coating would be applicable since the bottom cell is GaAs, (c) The contact metalization systems for such semiconductor materials are reasonably well understood for solar cell application and (d) the entire structure can be placed on a germanium lower cell with potential efficiency under AMO of over 30%. Of course, if the System 5 structure was to be placed on a germanium lower cell, the latter, cell would have to have a GaAs layer grown on it to allow for LPE growth--or the lower tunnel and middle cell would have to be grown by vapor means. Again, the P dopant used in the GaAlAs materials system is germanium.

Rockwell International (RI)

The four systems proposed by RI are based on the GaAlAs/GaAs cell structure. Two of the four systems are two cell stacks and the other two are three cell stacks. Figure (2) provides the information pertaining to the system materials compositions. The fifth system is the GaAlAs cell on a GaAs cell; fabricated using MO-CVD.

System 1 - GaAs Cell on a Ge Cell

The window, top cell and the tunnel junction for this system are lattice matched materials with bandgaps of greater than 2 ev for the window, 1.43 ev for the top cell and a Ge heteroface tunnel junction and bottom cell. The Ge cell has two bandgaps; one direct at .8 ev and one indirect at .67 ev. For the Ge cell, the direct bandgap controls the light generated current and the indirect bandgap controls the cell voltage characteristics. Indeed, the above remark should be qualified in that the direct and indirect bandgaps contribute roughly equally to the light generated current. Since the GaAs top cell will limit the overall stacked cell, external current, the division of light generated current in the cell is a moot issue as long as the tunnel is sufficiently thin. The conduction of majority carriers through the tunnel is accomplished primarily by defect states and the rest by band to band. The major problems are with System 1 is growth of the GaAs on the Ge cell. The best suited method to date is deposition from the vapor phase with MO-CVD the most attractive. Since this stack design strongly depends on cascade cell voltage, achievement of open circuit voltages for the Ge cell must approach .3 volts. Good quality Ge material and careful processing techniques are of paramount importance. However, for research purposes, if reasonable, cell voltage characteristics can be achieved with successful cascade action with the GaAs materials applied, then the technology for this structure will have been established--requiring mostly refined deposition techniques and quality of material and process controls. The P dopant in the Ge is boron. The P and N dopants in the GaAs material are zinc and selinium respectively.

System 2 - GaAs Cell on a GaInAs Cell

This system can be constructed in several different ways. The method selected by RI is to fabricate the GaAl window and GaAs top cell on an N^+ GaAs substrate. On the opposite side of the substrate, a P^+ InP layer can be grown followed by a GaInAs bottom cell. This approach resolves the potential lattice mismatch problem throughout the cell by restricting the mismatch to the wafer backside. There the InP P^+ layer will serve as the positive conductivety side of a combined defect states and band to band tunnel. During growth of the P^+ InP layer by LPE, the majority of lattice defects will be pinned to the growth interface resulting in a good quality single crystal surface which is lattice matched to the GaInAs bottom cell of bandgap around .8 ev. The P dopant for the GaInAs will most likely be germanium. The N dopant can be chosen from a wide selection.

System 3 - GaAlAs Cell on a GaAs Cell on a GaAsSb Cell

This structure is a three cell stack with the top cell and tunnel bandgaps near 2 ev placed on a GaAs cell inturn placed on a GaAs substrate. On the reverse side of the substrate a 1 ev cell is grown. The lattice matching of GaAs to the GaAsSb is resolved with a P^+ GaAlAsSb layer between. The bottom cell can also be a Ge cell wherein the Ge P^+ layer is put down by decomposition of $GeCl_4$. A four cell stack is possible using the GaAsSb 1 ev cell followed by a Ge cell on the substrate backside. However, the complexity is considerable. The problems associated with the third system are primarily restricted to demonstration of the high bandgap cell and tunnel and achievement of a quality GaAsSb cell. Included in the problem is the selection of the appropriate dopants so as to maintain their distributions during cell stack processing.

System 4 - GaAlAs Cell GaAs Cell on a GaInAsP Cell

This stack is essentially the same as system 3 except for the GaInAsP bottom cell. This design still permits the growth of a fourth cell that serves as the bottom cell. The connection of the GaAs substrate to the GaInAsP cell can be accomplished via the P^+ InP layer as in the second system.

System 5 - AlGaAs Cell on a GaAs Cell

The remarks to be made here are essentially those of system 5 of RTI. However, the difference is that RI is investigating the structure using MO-CVD. This structure does have potential for a three cell stack using a Ge cell as the bottom generator. The P and N dopants used in this system are zinc and selinium respectively.

CONCLUDING REMARKS

The most difficult problems in both contractual programs are (1) growth of quality semiconducting layers under lattice mismatching conditions and (2) proper control of the P and N dopants in the tunnel junctions during layer growths. All of the cascade cell designs by RTI can possibly use only the anti-reflective coating. The two three-cell stack concepts of RI can potentially use one anti-reflection coating; the other two systems most likely will require at least a three layer anti-reflective coating to ensure sufficient absorption beyond one micron wavelength. The metallization schemes for these cell designs have not yet been defined except for the case of the GaAlAs/GaAs combinations.

All of the systems except the GaAs/Ge combination discussed have potential for exceeding the 25% AMO @ 25^{o}C goal. The GaAs/Ge system most likely will show slightly over 20% in the best case. It is interesting to note that both contractors view the high bandgap GaAlAs cell on a GaAs cell as a viable candidate - an attractive realization of this view is that the material combination is being quite successfully investigated using totally the LPE technology in one case and MO-CVD in the other.

REFERENCES

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5. Private communication between author and S. Bedair of Research Triangle Institute.

	BOTTOM CELL	TUNNEL JUNCTION	TOP CELL	WINDOW	BASIC PROCESS	COMMENTS -
SYSTEM 1	GaInAs (.95EV)	GaInP (1.6EV)	GaInP (1.6EV)	AlGaAsSb (>2EV)	LPE & VPE	GaInP DIFFICULT TO GROW
SYSTEM 2	GaInAs (1.2EV)	GaAlAs (1.8EV)	GaAlAs (1.8EV)	GaAlAs (>2EV)	LPE	GaAlAs NOT LATTICE MATCHED TO GaInAs
SYSTEM 3	GaInAs (.95EV)	AlGaAsSb (1.6EV)	AlGaAsSb (1.6EV)	AlGaAsSb (~2EV)	LPE	AlGaAsSb DIFFICULT TO GROW AND DOPE
SYSTEM 4	GaAsSb (1.2EV)	AlGaAsSb (1.8EV)	AlGaAsSb (1.8EV)	AlGaAsSb (>2EV)	LPE	CHOICE OF BANDGAP LIMITED FOR BOTTOM CELL
SYSTEM 5	GaAs (1.43EV)	GaAlAs (1.93EV)	GaAlAs (1.93EV)	GaAlAs (>2EV)	LPE	BANDGAP AND TUNNEL GROWTH DIFFICULT

FIGURE 1 - RESEARCH TRIANGLE INSTITUTE'S CELL SYSTEMS

	BOTTOM CELL	TUNNEL JUNCTION	TOP CELL	WINDOW	BASIC PROCESS	COMMENTS
SYSTEM 1	Ge (.67 INDIR) (.8EV DIR)	P+ Ge/ N+ GaAs HETERO	GaAs (1.43EV)	GaAlAs (>2EV)	MO-CVD	QUALITY GaAs GROWTH ON Ge DIFFICULT
SYSTEM 2	GaInAs (.7EV)	P+ InP/ N+ GaAs HETERO	↓	↓	LPE	QUALITY InP LAYER GROWTH DIFFICULT
SYSTEM 5	GaAs (1.43EV)	GaAlAs (1.93EV)	GaAlAs (1.93EV)	↓	MO-CVD	HIGH BANDGAP GaAlAs DIFFICULT TO GROW

	BOTTOM CELL	LOWER TUNNEL	MIDDLE CELL	UPPER TUNNEL	TOP CELL	WINDOW	BASIC PROCESS	COMMENTS
SYSTEM 3	GaAsSb (1EV)	P+AlGaAsSb/ N+GaAs HETERO	GaAs (1.43EV)	AlGaAs (~2EV)	AlGaAs (~2EV)	AlGaAs (>2EV)	MO-CVD	Sb VACANCIES APPEAR TO REDUCE LIFETIME
SYSTEM 4	InGaAsP (1EV)	P+InP/ N+GaAs HETERO	↓	↓	↓	↓	LPE	InP LAYER A PROBLEM AS ABOVE

FIGURE 2 - ROCKWELL INTERNATIONAL'S CELL SYSTEMS