CASCADE SOLAR CELL WORKSHOP REPORT

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The Cascade Solar Cell Workshop defined and considered several issues related to the feasibility, research and development, and demonstration of a 30% AMO cascade solar cell. These issues are:

1. Maximum Achievable Efficiency and Recommended Cell Operating Conditions
2. General Considerations to Obtain Maximum Efficiency
   - A. Three active photovoltaic junctions vs two junctions
   - B. Radiation resistance
3. Device Structures
   - A. Monolithic cascade cell (two terminal)
     - (1) Materials selection
     - (2) Growth technique
     - (3) Device development strategy
     - (4) Important issues
       - (a) Suitable acceptor technology for OM-CVD growth of tunnel junctions
       - (b) Adequate transport, optical, and structural properties of various required compound semiconductor layers
       - (c) Suitable growth of ten or more epitaxial layers over large area required for three-junction structure
       - (d) Lattice defect generation and propagation through cascade structure
   - B. Hybrid cascade cell (four terminal)
     - (1) Materials selection
     - (2) Fabrication techniques
     - (3) Important issues
       - (a) Interconnect technology
       - (b) Proper connection to load
   - C. Spectral splitting device (three cells)
     - (1) Important issues
       - (a) Parts count
       - (b) Power/weight ratio

Based upon consideration of these issues, the workshop offers the following recommendations:

- A. Achievement of 30% AMO efficiency for a cascade cell exposed to 100 sun concentration and a temperature of 80°C is a reasonable long-range goal
- B. Initiate a long-range research program to develop a three-junction, monolithic, cascade cell
  - (1) Choose either AlGaAsSb-GaAsSb or AlGaInAs-GaInAs material system
  - (2) Emphasize OM-CVD epitaxial growth technique, perhaps combined with other technologies in the near term to obtain tunnel junctions
  - (3) Develop a two-junction device first
- C. Initiate a cascade solar cell modeling program to study and compare performance of two and four terminal cascade devices exposed to electron and proton irradiation
- D. Encourage and be open to new ideas for developing four terminal, hybrid, cascade cells exploiting novel component-cell interconnect technologies

DISCUSSION

Maximum Achievable Efficiency

The workshop agreed that, given certain solar cell operating conditions, a power conversion efficiency goal of 30% AMO is a reasonable and practical long-range target. The required cell operating conditions are solar concentration of 100 suns and a cell temperature of approximately 80°C.

General Considerations

One question which arises immediately is whether the 30% AMO goal can be achieved in a monolithic cascade cell with only two photovoltaic junctions (separated by one optically transparent, low resistance, interconnect junction), or will three photovoltaic junctions be required. While various theoretical modeling studies have shown that limit efficiencies in excess of 30% are possible with an optimum two-junction cell, practical efficiencies of 30% AMO are more likely to be achieved in a three-junction cell in the long term. The workshop did feel, however, that the maximum possible practical efficiency for a two-junction structure operating on a relatively cool concentrator system might reach 30%. Also, a practical AMO cell efficiency of approximately 27% realized in an optimum two-junction structure was felt by the workshop to be a worthwhile interim goal, due to the requirement for fewer semiconductor layers and only one interconnect junction.

A second issue addressed, related to the general approach, was the effect of energetic particle radiation upon degradation of the two-terminal, three-junction, monolithic cascade cell versus that of a hybrid cascade cell in which each of the three component cells are independently, electrically accessible to the load through a four-terminal connection. For the two-terminal cell, the total cascade cell degradation will follow that of the most sensitive component cell. However, the two-terminal cell can be designed for maximum EOL efficiency to minimize this problem. The four-terminal device allows each component cell to be connected independently to the load, therefore, in principle, minimizing the overall effect of the fastest degrading cell on the total system performance in a radiation environment. This approach, however, requires a complex, four-terminal, interconnect technology for the three component cells and requires a scheme for managing the cell output/load interface for the three component cells under changing output conditions. The workshop recommends that a theoretical cascade solar cell modeling program be initiated to study the relative merits and liabilities of the two-terminal monolithic structure compared to the hybrid four-terminal cascade solar cell. It was also felt that either the monolithic-grown or the hybrid structures would have definite weight advantage over approaches requiring use of separate and independent solar cells.

Device Structures - Monolithic Cell (Two-Terminal)

The workshop agreed upon the following criteria for selecting compound semiconductor materials for a three-junction, monolithic, cascade structure:

1. Material system must be lattice-matched through the entire active device structure. However, the active structure was not required to lattice-match the binary compound substrate.
2. The thermal coefficient of expansion must also be matched as closely as possible for the component semiconductor layers.
3. Given the assumed operating conditions (100 suns, 80°C), the minimum bandgap of the bottom cell should be 1.15 eV or a little less, and the minimum bandgap (direct) of the top cell should be 1.95 eV or larger.

It was agreed that only two compound systems come close to meeting these requirements: AlGaAsSb-GaAsSb (GaInAs) system and the AlGaInAs-GaInAs system. Various photovoltaic devices have been demonstrated in the AlGaAsSb-GaAsSb system grown by liquid-phase epitaxy (LPE), including a reasonable tunnel junction and a complete, two-junction, cascade structure (including two photovoltaic junctions separated by a tunnel junction). However, this material system grown by LPE usually (but not always) exhibits short electron diffusion lengths, and the photovoltaic junctions yield relatively low open-circuit voltages. Also, growth of this material system from GaAs to GaSb has been demonstrated using the preferred organometalic-chemical vapor deposition (OM-CVD) technique.

Layers of the relatively new material system AlGaInAs have recently been grown on GaInAs substrates using the OM-CVD technique and a p/n junction grown in GaInAs has been demonstrated. Theoretically, this system offers a somewhat larger energy top bandgap cell material, and is believed by some to be relatively easy to grow by OM-CVD. Yet, of various compound semiconductor systems considered for cascade solar cell research (or for other electron devices) AlGaInAs is by far the newest, and any problems with this system are yet to be identified.

The workshop felt that both material systems considered offered substantial promise to realization of a monolithic, three-junction cascade cell, and both should be considered as viable candidates.

The workshop agreed that a sensible overall strategy to the long-range development of a three-junction, monolithic cascade cell is to first demonstrate a relatively high efficiency, two-junction structure in one of the recommended compound systems. This approach allows demonstration of several significant solutions to key problems in a simpler device structure. It also provides a means for continued visible progress in a long-range program.

The workshop identified several key issues which must be addressed and resolved (perhaps singularly) in the development of a three-junction, monolithic cascade solar cell. These are:

(a) Development of a suitable acceptor impurity technology for the OM-CVD growth of the cascade devices, and particularly the tunnel junction. This acceptor must be available in the vapor phase in a compound which can be pyrolyzed at a relatively low temperature (600-700°C). It also must provide high doping concentration ($\sim 10^{19} cm^{-3}$) in preferable wide bandgap materials (not an absolute necessity) and have a low diffusion coefficient at 600-700°C.

(b) Demonstration of adequate transport, optical, and structural properties of the various required compound semiconductor layers. As mentioned above, the two material systems recommended by the workshop for development of the three-junction monolithic cascade cell are AlGaAsSb-GaAsSb (GaInAs) and AlGaInAs-GaInAs. The prime feature offered by both systems is their ability to nearly cover the assumed absorption wavelength region of interest (1.15 eV-2.05 eV) with direct bandgap material which is lattice-matched through the active structure. Yet the materials are not without their problems. The AlGaAsSb and GaAsSb systems grown by LPE have traditionally exhibited short electron diffusion lengths ($\ell_n \sim 0.5$ μm), and p/n junctions fabricated in these materials typically exhibit a relatively low open-circuit voltage (compared to their bandgap energy). However, somewhat larger values of ℓ_n have been observed for AlGaSb (Rockwell International, ERC, Thousand Oaks), for GaAsSb ($\ell_n > 1$ μm, Research Triangle Institute), and for GaSb ($\ell_n \cong 4$ μm, Physikalisches Institute, Universitat Stuttgart, F. R. G.).

Much speculation exists as to the origin of both the short electron diffusion lengths and the large p/n junction dark currents, but the workshop was not aware of any definitive evidence related to this problem. Therefore, the workshop agreed that in exploring an AlGaAsSb-GaAsSb (GaInAs) cascade cell, specific attention should eventually be addressed to understanding and solving these problems.

A second issue, that of a miscibility gap existing for both $GaAs_{1-x}Sb_x$ and $Ga_{1-y}Al_yAs_{1-x}Sb_x$ for $x > 0.20$, is not viewed as a problem for the monolithic cascade cells. This is because bandgap values of interest can be achieved for $x < 0.20$, for which single-phase growth occurs.

The AlGaInAs-GaInAs system offers (theoretically) a larger spread of direct bandgap energies on a constant lattice-parameter line than does the AlGaAsSb system (1.15 eV to 2.05 eV versus 1.15 eV to 1.90 eV, respectively), which possibly offers an advantage to the AlGaInAs system for achieving the optimum bandgap values. Also, it is suggested that the AlGaInAs system is relatively easy to grow since Al substitutes readily for Ga in the quaternary crystal. However, this is a relatively new material system, for which the growth parameters (OM-CVD) are now being established. Experimental data for bandgap energies (direct and indirect), minority carrier lifetimes and diffusion lengths, and p/n junction properties as functions of material composition are yet to be determined. Also, fabrication of a p/n junction is yet to be accomplished in AlGaInAs, although there are no apparent reasons why this should not be successful.

(c) A third important issue is the suitable growth of ten or more epitaxial layers over a large area for the three-junction cascade cell. Growth of multiple layers of thin material has been demonstrated repeatedly by the OM-CVD process. The problem becomes one of growing all layers at relatively low growth temperatures, to stabilize impurity diffusion problems of the two required tunnel junctions, while maintaining adequate transport properties to the optically absorbing/carrier collection layers.

(d) Lattice defect generation and propagation through the cascade structure is also seen to be an important issue. The problem of large p/n junction dark currents causing a low V_{oc} in the AlGaAsSb system may well be due to a 1.2% lattice mismatch between the $GaAs_{.9}Sb_{.1}$ p/n junction (a = 5.72 Å) and the GaAs substrate (a = 5.65 A), even though substantial caution is exercised to grow several lattice-matching layers between the substrate and the p/n junction. Also, defect formation in the highly-doped tunnel junctions is quite likely, which may then propagate into the charge generation and collection layers grown on top of these disordered layers.

Device Structures - Hybrid Cascade Cell (Four Terminal)

The hybrid cell is one which is still monolithic in the sense that the component cells are connected in optical and electrical series, but is hybrid in the sense that the cell uses a component-cell interconnect technology which does not involve growth of semiconductor materials (i.e., does not use a tunnel junction). The interconnect layer must be optically transparent, have a very low electrical resistance, and be accessible to the external world. In addition, the materials used in bonding individual cells together must be thermally (thermal expansion coefficient) and chemically compatible with the bonded cells. However, since growth of semiconductor layers is not involved in fabrication of the interconnect layer, the component cells do not need to be lattice matched.

The advantages of this approach are obvious. First, a wide selection of component-cells is now available, each of which can be optimized to meet its own requirements without having to be lattice matched to the other component cells. Also, the condition of current match between component cells may be relaxed somewhat (since each component cell is separately connected to the load). This means that degradation of one component of a hybrid cell in an electron or proton radiation environment may have less impact on the degradation of the photovoltaic system compared to the monolithic cascade cell system.

The key challenges of the hybrid cell are development of an adequate component-cell interconnect technology and proper connection of a four-terminal cell to the load. Each component-cell of a hybrid structure needs to be connected to the load in such a way that unequal variations in component-cell output yields a minimum variation in power delivered to the load.

One example of a hybrid, four terminal cell would use Si (1.1 eV) for the low bandgap cell, GaAs (1.44 eV) for the middle bandgap cell, and $Al_{.35}Ga_{.65}As$ (1.95-2.00 eV) for the high bandgap cell.

The workshop agreed that the hybrid approach is attractive, and recommends that new ideas related to the interconnect technology be encouraged and supported.

<u>Device Structures</u> - Spectral Splitting Device (Three-Cells)

The spectral splitting concept was only briefly considered as an alternative technology to obtaining high efficiency, cascade structures. It was suggested that a two-cell version of this approach is closer to realization of relatively high efficiency, but that a three-cell version would require additional development, particularly of the beam splitting optics. Other issues identified were a comparatively large parts count and the impact of three separate cells together with beam splitting optics on overall system power-to-weight ratio important to space application.