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LARGE-AREA, HIGH-INTENSITY PV ARRAYS FOR SYSTEMS USING DISH CONCENTRATING OPTICS

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ABSTRACT: In this paper, we report on our efforts to fabricate monolithic interconnected modules (MIMs) using III-V semiconductors with bandgaps appropriate for the terrestrial solar spectrum. The small size of the component cells comprising the MIM allows for operation at extremely high flux densities and relaxes the requirement for a small spot-size to be generated by the optics. This makes possible a PV option for the large dish concentrator systems that have been developed by the solar thermal community for use with Stirling engines. Additionally, the highly effective back-surface reflector integrated into the MIM design is an effective tool for thermal management of the array. Development of this technology would radically alter the projections for PV manufacturing capacity because of the potential for extremely high power generation per unit area of semiconductor material.

Keywords: Concentrator - 1: High-Efficiency - 2: III-V - 3

INTRODUCTION

Most attempts to utilize photovoltaics for solar energy conversion using highly concentrated sunlight have involved very small devices and Fresnel lenses. The last decade has seen impressive progress in the state of the art for high efficiency III-V devices. GaAs-based multijunction devices are now entering production for space power applications. These devices have demonstrated efficiencies in excess of 30% under the simulated direct solar spectrum ASTM E 891 [1]. This level of performance makes them attractive candidates for terrestrial concentrator systems. Unfortunately, similar progress in the design, implementation, and reliability of the high-intensity tracking concentrator module has apparently not been demonstrated. A study comparing flat-plate and concentrator systems conducted by Arizona Public Service Company concluded that "concentrators have the potential to be the lowest-cost PV technology in sunny regions, but that potential has still not been realized [2]". The primary reason given for this statement was the lack of reliability of the systems under consideration. So, for concentrator PV technology, we have a situation where progress on the module, including the optics and the tracking mechanisms, has not kept pace with the development of the energy-conversion technology (high-efficiency PV devices).

Conversely, in the solar-thermal community, impressive progress has been made, over the past decade, in developing cost-effective, reliable means of concentrating sunlight. Dishes composed of single and multiple facets have been developed. Light weight stretched-membrane facets have been introduced. All of this innovation is being put into the service of a conversion technology that was patented by a Scottish minister (Stirling) in 1816. Clearly, a marriage between the concentrator technology developed by the solar-thermal community and the latest generation of high-efficiency photovoltaic energy converters would be of great interest for utility-scale solar-to-electric energy conversion. Several technological challenges have prevented photovoltaics from being used in this capacity in the past. The large spot size of the concentrated light (between 750 and 2000 cm^2) implies the need to fabricate a module composed of many tiny cells. The heat generated by the infrared component of the incident flux will degrade the performance of conventional PV devices. Creating a module of primarily series-connected devices could render it highly susceptible to non-uniform flux. This paper discusses a device design originally developed for thermophotovoltaic (TPV) energy conversion that could overcome the problems identified above and which has the potential to make PV a viable option for dish concentrator systems.

MONOLITHIC INTERCONNECTED MODULES (MIMS)

Thermophotovoltaic systems employ solid state photovoltaic devices to convert radiant energy from a heat source to electricity. Recent advances in low-bandgap PV devices have led to a resurgence of interest in this field. The elements of a typical TPV system are illustrated in Figure 1.

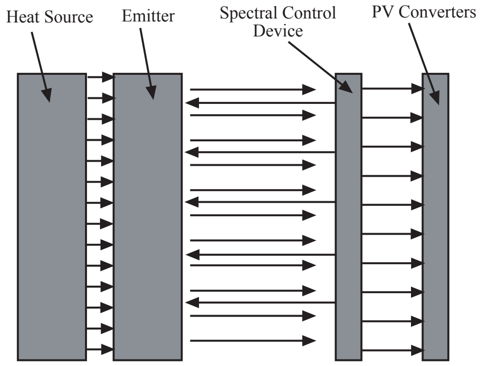


Figure 1: Block diagram illustrating key components of a TPV system.

They include a heat source, a radiator, the PV converters, and an element referred to as a "spectral control" device. This element of the system is necessary because, despite the advances in low-bandgap semiconductors, the bulk of the spectrum generated by the heat source has energy below the response range of the PV devices. To achieve high system efficiency, some means of returning this portion of the flux back to the heat source is required. Spectral control may be achieved with a high-pass filter that is placed in front of the converters and reflects sub-bandgap photons back to the heat source while transmitting higher-energy photons for conversion. Spectral control may also be achieved by the use of a selective emitter that radiates within a narrow band, convertible by the PV devices. An alternative method of achieving spectral control is the use of a back-surface reflector (BSR) [3]. Another challenge associated with the design of TPV converters is that most systems are expected to be of a relatively large area illuminated with high flux. This results in very high current densities generated within the TPV converter. Parasitic I^2R power losses are a concern when dealing with high current densities and are exacerbated by the low voltage generated by the low-bandgap devices.

As a response to these challenges, monolithic interconnected modules (MIMs) are being developed for this application [4]. These devices use GaInAs with bandgaps as low as 0.5 eV and are currently being epitaxially grown by metalorganic vapor phase deposition (MOCVD) on semi-insulating Fe-doped InP substrates. They are comprised of a number of small devices, series-connected during the fabrication process. In this way, the voltage is increased, while the current generated by the MIM is limited to that which is generated within one of the component cells. Additionally, the use of a semi-insulating substrate facilitates the incorporation of an extremely efficient BSR as a spectral control device. Therefore, this single solid-state device incorporates two of the essential elements of a TPV system. It limits I^2R power losses by reducing the current while increasing the voltage, and it returns the sub-bandgap photons to the heat source very efficiently. The MIM employs interdigitated front and back contacts and a novel interconnect scheme that uses the grid fingers of the component cells as the interconnect structure [4]. This approach results in a high degree of flexibility in terms of current handling capacity and the output parameters of the device. Figure 2 is a simplified plan view of this design. It includes just two sub-cells for clarity. Most MIM designs are composed of many more. Indeed, the number of sub-cells per unit length is an adjustable parameter that allows one to determine the output voltage of the device because, in series, the voltages are additive. Figure 3 is a scanning electron micrograph (SEM) image of the grid finger interconnect structure.

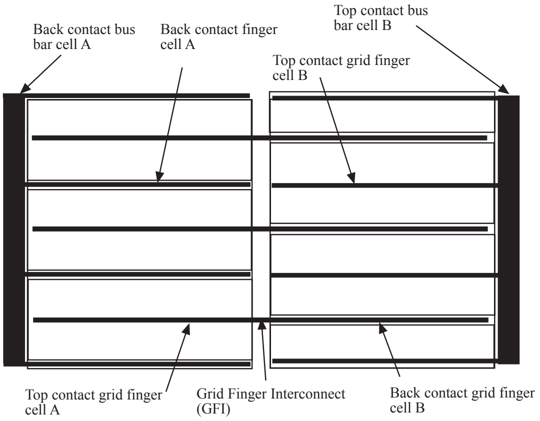


Figure 2: Simplified plan view of interdigitated MIM. This illustration shows only two cells. Actual MIMs typically have 4 to 24 cells.

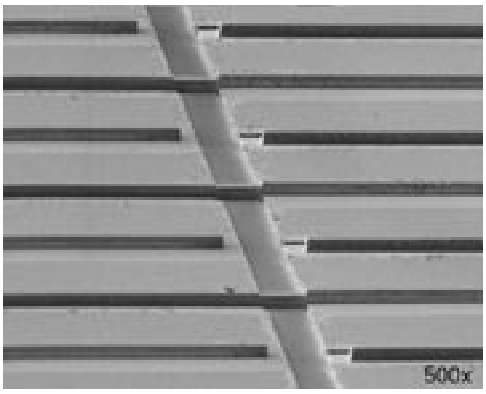


Figure 3: 500X SEM image of TPV MIM illustrating the grid-finger interconnect.

PROTOTYPE GaAs MIMs

The characteristics that make the MIM an attractive solution to the challenges presented by TPV power conversion have the potential to overcome the obstacles to using PV converters with solar dish concentrator systems. Traditionally, one of the difficulties associated with using PV in these systems is the relatively large, high-intensity spot size of the illuminated area at the receiver. Monolithic integration offers a solution to that problem. I^2R power losses are minimized by fabricating high-voltage, low-current MIM devices. Additionally, the highly efficient BSR that was the spectral control element in the TPV system, becomes an effective tool for thermal management in the high-intensity solar PV application. The sub-bandgap photons that would have been converted to heat are now reflected out of the power conversion unit in an almost specular fashion . This offers the opportunity for clever engineering to use this portion of the spectrum efficiently. Finally, the effects of non-uniform illumination may be minimized by choosing a size for the MIM over which the illumination is relatively uniform. The flexibility in the output parameters of the MIM means that the required output voltage may be achieved by a single device that fits within this area of uniform illumination. The fabrication technology developed for the GaInAs on InP-based material system, can be readily transferred to the GaAs-based material system, which has bandgaps more appropriate for the terrestrial solar spectrum.

We have fabricated small (0.25-cm^2) prototype MIMs from GaAs device structures grown on double-side polished Cr-doped semi-insulating GaAs substrates. Figure 4 shows a cross-sectional schematic of the device structure. It is, in most respects, a typical GaAs double-heterostructure employing GaInP as both the window and back-surface field layers. The exception is the inclusion of a GaAs back contact layer that provides for lateral current flow between the back contact grid fingers. These initial efforts were attempted using an n/p structure. Future efforts will include fabrication of p/n devices because of an asymmetry in the absorption properties of the n and p type material. Free-carrier absorption is more severe in the p-type material due to the larger effective mass of the holes. Therefore, to optimize the performance of the BSR, the p-type layer needs to have minimal thickness. The back-contact layer needs to be thicker than the emitter.

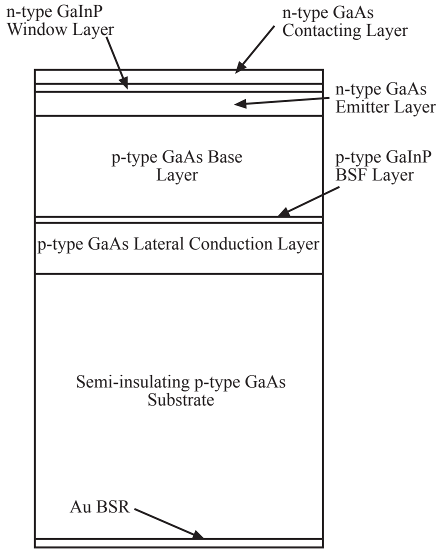


Figure 4: Cross-sectional schematic of GaAs double-hetero structure used for MIM fabrication.

because the distance between back-contact fingers is typically greater than the distance between front-contact fingers. Common MIM grid designs use multiple front-contact fingers for each back-contact finger. Therefore a p/n configuration is preferred. The prototype GaAs MIM is composed of four component cells, using the interconnect structure described above. No attempt has yet been made to optimize the grid design for the anticipated operating conditions in the system.

Figure 5 is a reflectance curve for a Au BSR on a semi-insulating Cr-doped GaAs substrate. Addition of the thin, active device layers will marginally impact this performance. It is seen that very good performance is obtained for this BSR. For the terrestrial application, 41% of the incident flux in the direct-normal spectrum has a wavelength greater than 867 nm (the band edge of GaAs), which may then be used for co-generation purposes.

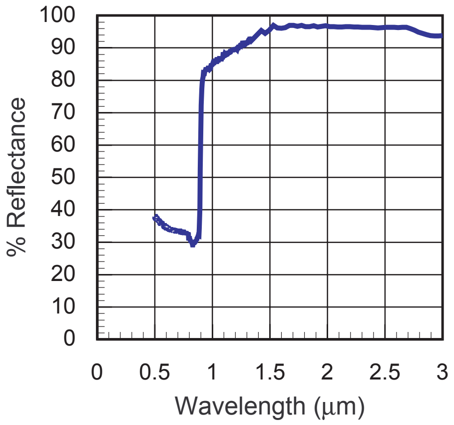
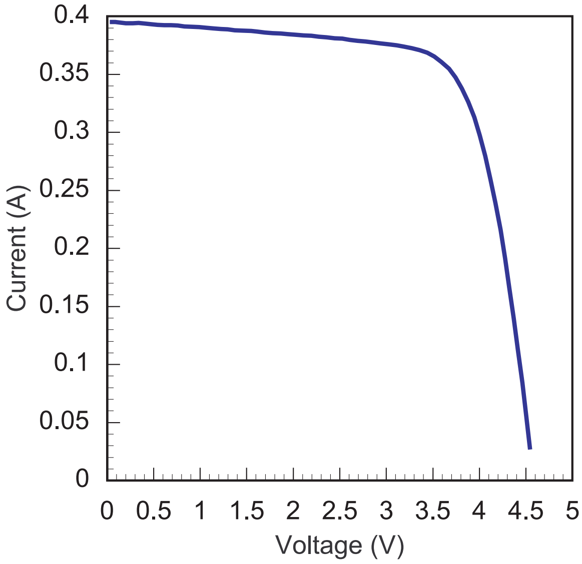


Figure 5: Reflectance curve for Au BSR on semi-insulating GaAs substrate.

A typical dish concentrator system may afford between a 400X and 2000X geometric concentration ratio. At a nominal direct-normal insolation of 0.08 watts/cm^2 and a concentration ratio of 2000X, there will be 65.6 watts/cm^2 of incident energy below the response range of the device. This BSR will do an effective job of removing most of this energy from the power conversion unit and reflecting it to an area where it may be usefully employed.

Figure 6 illustrates the current-voltage characteristics of a prototype GaAs MIM under an arbitrarily intense illumination from a flash simulator. Evidence of series resistance due to the non-optimized grid structure, as well as some shunting, is apparent in the fill-factor of 71.8%. A high-quality GaAs device may be expected to generate roughly 24 mA/cm^2 at 1 sun and 1000 watts/ m^2 and 19.2 mA/cm^2 at 800 watts/m^2. The individual cells in the 4-cell, 0.25-cm^2 MIM have an area of 0.0625 cm^2. Allowing for a 15% loss of active area associated with the grid structure and interconnects, the Isc of 0.395 A represents a current density within the active area of the component cells of 7.45 A/cm^2. This is what one would expect from a geometric concentration ratio of approximately 387X. The power output density of 5.2 watts/cm^2 would represent an efficiency of 16.8%. It should be stressed that no efficiency claim is made here. Rather, it is an indication of how this device would perform under these conditions were the current optimized. There is clearly room for improvement in the fill factors of these devices, and it is reasonable to expect real, measured, efficiencies to exceed 20% after further development.



Voc = 4.585 V
Isc = 0.3954 A
Fill Factor = 71.85%
Area = 0.25 cm^2

Vmax = 3.686 V
Imax = 0.3535 A
Pmax = 1.303 W

Figure 6: Current-voltage characteristics of a prototype 4-cell 0.25-cm^2 GaAs MIM under a flash simulator with arbitrary intensity.

MULTIJUNCTION APPROACHES

The real promise of this technology, however, will be realized with the use of advanced multi-junction devices. GaInP/GaAs, two-terminal, two-junction solar cells, invented and developed at the National Renewable Energy Laboratory, are being produced commercially by several manufacturers for space power applications. These devices have demonstrated efficiencies in excess of 30% under the direct-normal spectrum, although they have yet to be fully optimized for use in concentrator systems [5].

The advantage of using a GaInP/GaAs tandem device for this application is not limited to increased efficiency, and hence, power density output. It also offers an advantage related to thermal management. The response range of the tandem device is the same as a single-junction GaAs device because GaAs is the bottom (low-bandgap) component of the tandem. The BSR on a tandem MIM will still reflect back out most of the light with a wavelength above 867 nm. This represents 41% of the incident spectrum. The enhanced efficiency over the remaining 59% of the spectrum means that there will be less energy converted to heat, reducing the load on the cooling system required for high intensity operation. Additionally, because the spectrum is split between the two component cells, the current density as a function of geometric concentration ratio is effectively halved.

Because I^2R power losses and thermal management are the key restraints to high-intensity operation, the tandem device may be expect to operate at significantly higher concentration ratios. Work is continuing on adding a third, and ultimately, a fourth junction to the GaInP/GaAs tandem cell. Efficiencies in excess of 44% have been projected for a three-junction device using a third junction with a bandgap of 1.10 eV. These efficiencies increase to over 50% when a low-bandgap (around 0.7 eV) fourth junction is added [5].

Although a 50%-efficient power conversion unit composed of ultra-efficient future PV devices would be clearly superior to the mechanical alternative, the 30%-efficient GaInP/GaAs devices that are entering production today would rival the output of the current Stirling engines being used in these systems, while offering a number of advantages. The primary advantage is the potential for high reliability and low maintenance costs that are characteristic of PV systems when compared to mechanical devices. Another advantage is the significantly reduced mass of the power conversion unit. This has implications for increasing the tracking reliability of the dish and reducing its costs. Added to these advantages is the fact that, in this configuration, fully 41% of the incident energy is still available for conversion by other means.

ECONOMIC CONSIDERATIONS

A study done by Research Triangle Institute (RTI) comparing the cost of energy produced by various concentrator systems identified a required price of $10/cm^2 for tandem-junction GaInP/GaAs devices grown on GaAs substrates [6]. This price includes the profit for the manufacturer. The MIM fabrication process is not significantly more complicated than that of a high-quality concentrator cell. There is, however, a requirement for an extra photolithographic step, as well as the deposition of an insulating layer. For this reason, we are conservatively using an estimated price of double that of a standard concentrator cell, or \$20/cm^2. A 30% efficient device operating at 1000X geometric concentration ratio with a direct-normal insolation of 800 watts/m^2 will have an output power density of 24 watts/cm^2. At a selling price of \$20/cm^2, this amounts to \$0.83/watt. This works out to \$20,750 for tandem PV devices with the potential to generate 25 kW of electricity. As a point of comparison, the price of a 25 kW Stirling-engine-based power conversion unit (PCU) is currently around \$180,000.

The Stirling engine's PCU includes an inverter and power conditioning, as well as any required cooling system. Still, it is clear that within the \$159,250 difference between the two approaches, adequate funds should be available to pay for these elements of a PV-based PCU. Even the most optimistic projections of future cost reductions for the Stirling-engine-based PCU has them priced at over \$30,000. It is clear that the dual-junction GaInP/GaAs tandem MIM approach would make PV competitive with these cost projections for Stirling engines. When weight, reliability, and maintenance considerations are factored into the calculations, PV offers a clearly superior conversion technology. Add to these considerations that 41% of the incident power is still available for co-generation in the PV approach and the PV-based PCU seems even more advantageous.

SUMMARY

Recent advances in high-efficiency III-V solar cells, particularly the GaInP/GaAs tandem cell, combined with a new device configuration developed for TPV applications, make PV a viable alternative to the Stirling-engine-based PCUs used in large dish concentrator systems. Potential advantages to using PV for this application include reduced price, reduced mass, reduced maintenance costs, increased reliability, and the ability to use 41% of the incident radiation for cogeneration purposes. The economics of this application, with its focus on efficiency, becomes a strong motivation for continued development of high-efficiency multijunction device technology.

Prototype monolithic interconnected modules, using GaAs device structures, have been fabricated and characterized. The performance of a back-surface reflector on a semi-insulating GaAs substrate has been investigated. Future work will include the fabrication of larger-area MIMs using GaInP/GaAs tandem devices and optimized grid structures, as well as on-sun testing of these devices using NREL's solar furnace.

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