High efficiency indium gallium arsenide photovoltaic devices for thermophotovoltaic power systems

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The development of indium gallium arsenide ($E_g = 0.75$ eV) photovoltaic devices for thermophotovoltaic power generation is described. A device designed for broadband response had an air mass zero efficiency of 11.2 % and an internal quantum yield of over 90% in the range of 800 to 1500 nm. Devices designed for narrow-band response have also been developed. Both structures are based on a n/p junction which also makes them applicable for integration into indium phosphide based, monolithic, tandem solar cells for solar photovoltaic applications.

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Research in thermophotovoltaic (TPV) power systems has persisted for many years, driven by high projected thermal to electric systems efficiencies.[1,2] Several variants of TPV systems have emerged with the principal difference being the method of thermal to radiant energy conversion. Common to all TPV systems designed for operation at moderate temperatures (<1500 K) is the need for a low band gap photovoltaic device. For TPV systems using blackbody (broadband) emitters, low band gap devices reduce the amount of infrared (IR) energy which needs to be recycled to the illumination source to achieve high system efficiency. Selective emitter (narrow-band) based systems require low band gap cells that match the emission band of the selective emitter.

Indium gallium arsenide ($In_{0.53}Ga_{0.47}As$) solar cells have been investigated by several research groups, primarily for use as the bottom cell in a tandem solar photovoltaic cell structure. Reported efficiencies have been as high as 5.5% under an InP filtered air mass zero (AM0) spectrum.[3-5] $In_{0.53}Ga_{0.47}As$ solar cells have also been developed for laser power conversion, with one sun AM0 efficiencies of 7.14%.[6] These devices have incorporated thick InP overlayers either as active devices or for the reduction of series resistance and for surface passivation. Thick window layers are not detrimental to selective emitter based TPV systems, because the window layer will not appreciably absorb the incident radiation. Blackbody based systems, on the other hand, are sensitive to window layer thickness since a significant portion of the radiated energy will be greater than the band gap of the InP window, at high emitter temperatures (~1500 K).

$In_{0.53}Ga_{0.47}As$, lattice matched to indium phosphide (InP), was grown in a horizontal low-pressure organometallic vapor phase epitaxy (OMVPE) reactor. The InP substrates were (100) oriented, Zn doped (4×10^{18} cm^{-3}), and were used as received from the vendor. The high-purity precursor materials were trimethylindium (TMIn), trimethylgallium (TMGa), diethylzinc (DEZn), arsine (100% AsH_3), phosphine (100% PH_3) and silane (100 ppm in H_2). Growth took place at 620 °C in a reaction chamber maintained at 190 Torr. Total carrier gas flow was 3.1 standard liters per minute (SLM) with a V/III ratio of 50. The InGaAs/InP lattice mismatch was 420 ppm (0.042%), as determined by x-ray rocking curve measurement.

For both types of $In_{0.53}Ga_{0.47}As$ devices ($E_g = 0.75$ eV, 1.653 μm), the structure is a n/p configuration with InP ($E_g = 1.35$ eV, 0.918 μm) front and rear window layers for surface passivation (Fig. 1). The principal difference between the cells is the thickness of the front InP window layer, with the broadband device having a thin window (0.05 μm) and the narrow-band device having a thick InP window layer (1.5 μm). Front contacts are nonalloyed gold/germanium with 5.5% grid shadowing. The rear contact is alloyed gold/zinc.[7] For the cells reported here, a single layer antireflection (AR) coating of SiO (800 Å) was deposited by resistive evaporation to minimize reflective losses for the AM0 spectrum. Ideal AR coatings would be optimized for the illumination source, i.e., selective emitter, etc. We have found that thick SiO films (>0.15 μm), optimized for long wavelength transmission, are unstable and spall after several days of exposure to air. We believe that this is due to stress in the as-deposited SiO or stress generated by the oxidation of SiO to SiO_2, or both, although stress measurements have not been per-

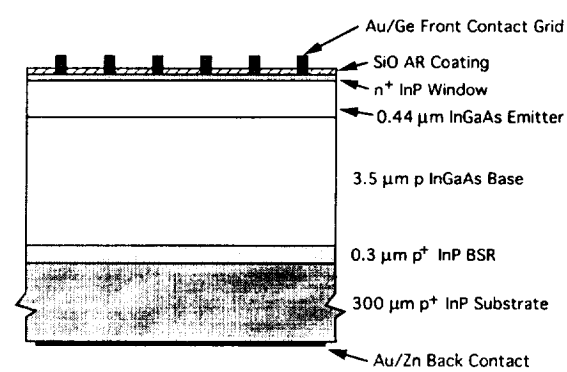

FIG. 1. InGaAs photovoltaic cell. The broadband design has a window layer of 0.05 μm. Narrow-band cells have 1.5-μm window layers.

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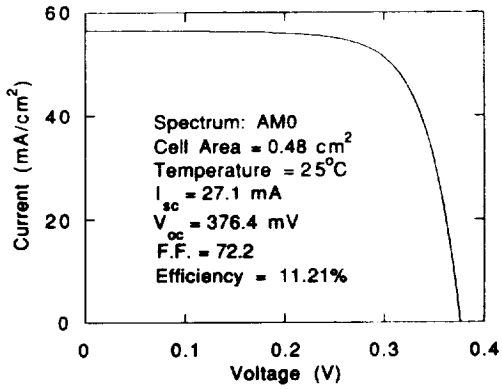

FIG. 2. I-V curve of broadband InGaAs photovoltaic cell.

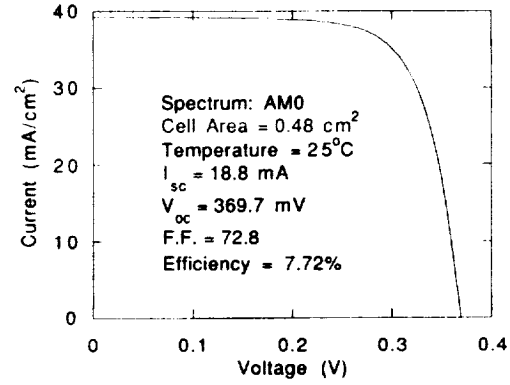

FIG. 4. I-V curve of narrow-band InGaAs photovoltaic cell.

formed. Ta_2O_5 is now being used for the IR optimized AR coating.

Current-voltage (I-V) and quantum yield measurements for both cell structures are shown in Figs. 2–5. The broadband cell demonstrated on AM0 efficiency of 11.2%, which is the highest reported to date. The accuracy of these measurements has been confirmed through use of the NASA High Altitude Solar Cell Calibration facility. Quantum yield, as used here, is defined a the number of collected carriers per photon entering the InP window layer. The quantum yield data are in general agreement with the literature data which indicates that the n/p collection efficiency is higher than for the p/n configuration.[3,4] We believe that the difference in minority carrier diffusion length between n-type and p-type $In_{0.53}Ga_{0.47}As$ is responsible for the higher collection efficiency measured in n/p devices. The narrow-band cells internal quantum yield (Fig. 5) is lower than the broadband cell data (Fig. 3) for wavelengths longer than the InP band gap. This may be due to lattice mismatching, although x-ray measurements have not been performed on this material.

Room-temperature I_{sc} vs V_{oc} and dark diode measurements for both cells indicate that they are diffusion limited with $n \sim 1.0$ and exhibit reverse saturation current densities (J_{01}) of $\sim 4\times10^{-8}$ A/cm^2. The broadband cell shows some losses due to series resistance which must be reduced for the high-intensity operation predicted for TPV operation. Optimization of emitter doping levels and thicknesses as well as the thickness of the InP window layer is underway to reduce this loss mechanism.

In summary, we have demonstrated the highest AM0 efficiency of any $In_{0.53}Ga_{0.47}As$ device reported (11.2%). Using measured cell parameters, we estimate the efficiency of both the broadband and the narrow-band devices under 1500 K blackbody and selective emitter illumination, to be over 25%. Optimization of material properties, AR coatings, and grid design increases the estimated efficiencies to well over 30%.

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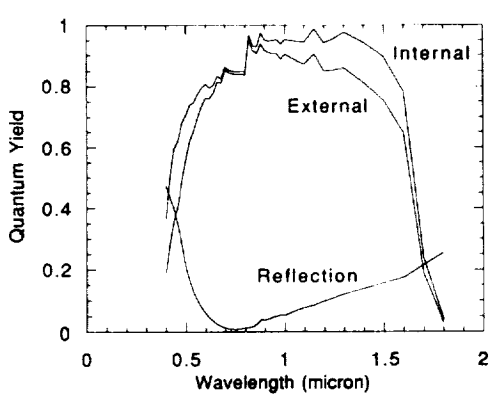

FIG. 3. Quantum yield of broadband InGaAs photovoltaic cell. The reflection data were taken from a cell without front contacts, AR coated at the same time as the reported cell. This was done to eliminate reflection measurement errors due to metallization.

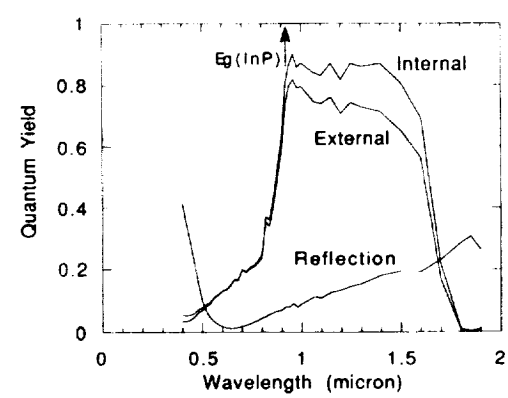

FIG. 5. Quantum yield of narrow-band InGaAs photovoltaic cell. The reduction in short wavelength response due to the thick InP overlayer is clearly visible.

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