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Front Surface Tandem Filters using Sapphire (Al_2O_3) Substrates for Spectral Control in Thermophotovoltaic Energy Conversion Systems

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FRONT SURFACE. TANDEM FILTERS USING SAPPHIRE (AL_2O_3) SUBSTRATES FOR SPECTRAL CONTROL IN THERMOPHOTOVOLTAIC ENERGY CONVERSION SYSTEMS

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ABSTRACT

Front surface filters provide an effective means of improving thermophotovoltaic (TPV) system efficiency through spectral control of incident radiant energy. A front surface filter reflects the below band gap photons that can not be converted by the TPV cell back towards the high temperature radiator and allows convertible above band gap photons to pass through the filter into the TPV cell for conversion to electricity. The best spectral control efficiency to date has been demonstrated by front surface, tandem filters that combine an interference filter and an InPAs layer (plasma filter) in series. The InPAs material is a highly doped, epitaxially grown layer on an InP substrate. These tandem filter designs have been fabricated with energy and angle weighted spectral efficiencies of 76% for TPV cells with a 2.08µm (0.6eV) band gap [1]. An alternative to the InPAs layer on an InP substrate is an Al_2O_3 (sapphire) substrate. The use of Al_2O_3 may increase transmission of above band gap photons, increase the mechanical strength of the tandem filter, and lower the cost of the tandem filter, all at the expense of lower spectral efficiency. This study presents design and fabrication results for front surface tandem filters that use an Al_2O_3 substrate for 2.08µm band gap TPV cells.

INTRODUCTION

Thermophotovoltaic (TPV) energy conversion systems provide direct conversion of above band gap radiant thermal energy to electricity. Spectral control is an important factor in achieving high conversion efficiency TPV systems [2]. The spectral control scheme must allow the passage of above band gap photons to the TPV cell for conversion and suppress or return below band gap photons to the heat source for recuperation. Spectral efficiency of the front surface filter is a function of the incident spectrum from a radiating surface for a given temperature and emittance as well as the spectral and incident angle performance of the filter. The spectrum from a blackbody radiator is broadband with the above band energy representing only a fraction of the total radiant energy depending on the band gap of the TPV cell and the temperature of the radiator. Achieving high spectral efficiency with a front surface filter requires a filter design with very high and broad below band gap reflection and high above band gap transmission. The filter must perform well over all incident angles from near normal to near grazing for flat plate radiator geometries. Angle and energy weighted spectral efficiencies [1] are used to compare filter performance.

The tandem front surface filter is an effective approach for achieving high spectral efficiency and above band gap transmission performance. The tandem filter consists of an interference filter in series with a plasma filter. The interference filter is a multi-layered stack of optical films of different refractive index. The plasma filter is a heavily doped semiconductor layer. The interference filter defines a sharp transition edge from highly transmitting to highly reflecting and provides high reflection from the band gap edge to about 6µm. The plasma filter provides high reflection from about 6µm to longer wavelengths. Figure 1 presents the architecture of a tandem filter as well as the spectral performance of the interference filter, the plasma filter and the tandem filter. Tandem filters have been fabricated with energy and angle weighted spectral efficiencies of 76% for 2.08µm TPV cells [1]. Figure 2 represents a plot of a 2.08µm tandem filter reflection overlaid on a normalized blackbody emission spectrum for a 950^{o}C radiator to show spectral dispersion of the incident energy in comparison to the performance of the tandem filter. Figure 3 presents a measured reflection for a typical tandem filter over a range of incident angles. In general, the reflection edge shifts towards shorter wavelengths with increased incidence angle. The transmission of the above band gap region remains relatively stable up to 60^{o} and increases significantly at near grazing angles.

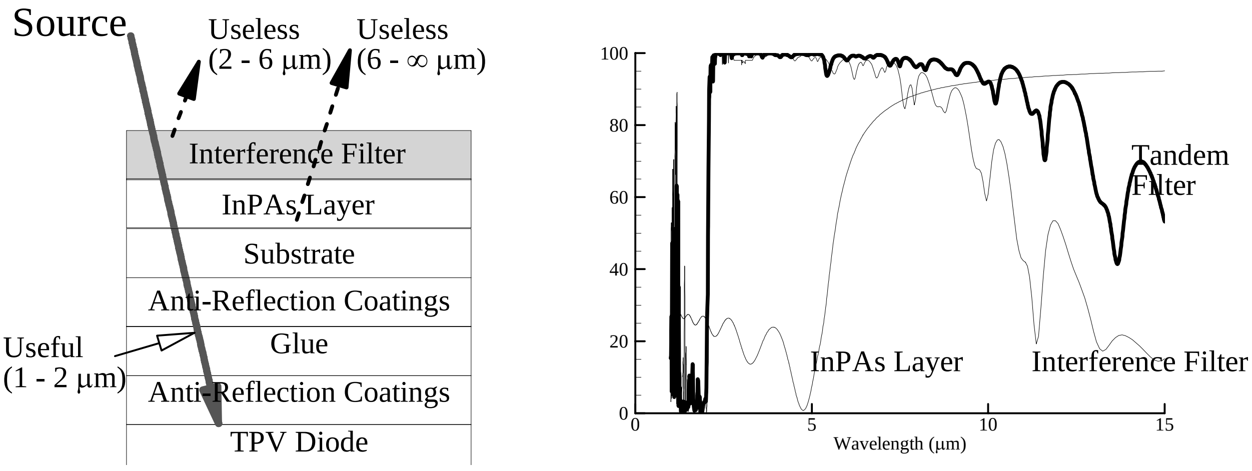
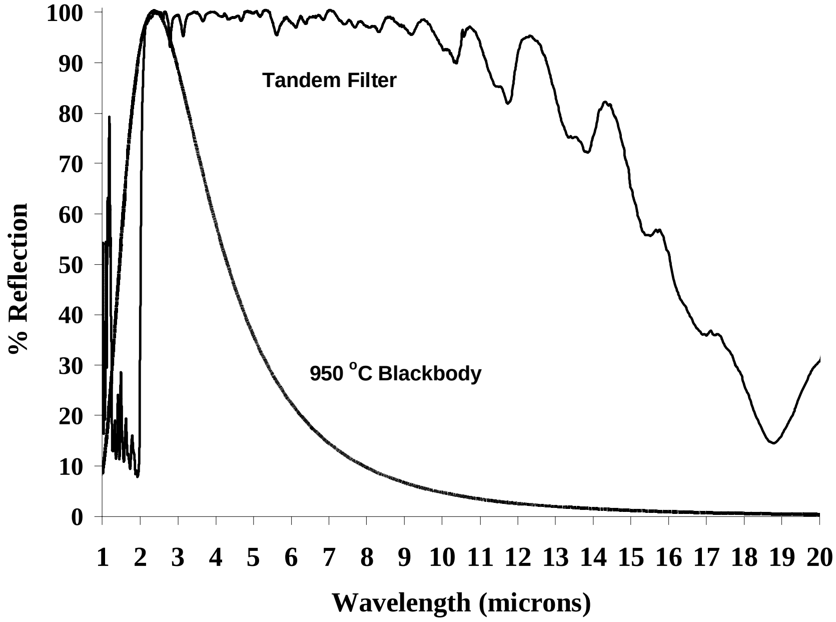


Figure 1 Tandem filter architecture with a plot of measured reflection for the plasma filter, the interference filter on a silicon substrate, and a tandem filter (interference filter in series with a plasma filter)



The transition edge of the filter is placed at the band gap of the TPV cell. High reflection of below band gap photons is needed to achieve high spectral efficiency.

Figure 2: Measured reflection of a 2.08µm front surface tandem filter is plotted along with a black body spectrum for 950 ^{o}C.

The pass band transmission degrades at near grazing angles.

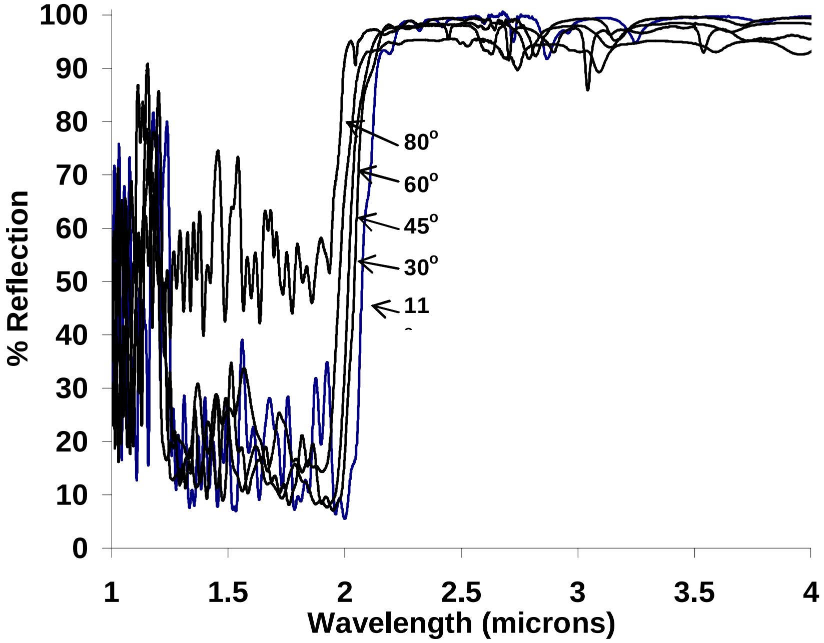


Figure 3: Measured reflection measurements of a 2.08µm front surface filter highlight the shift in the transition edge with angle of incidence (AOI).

This paper describes the results of the design and fabrication of tandem filters using an Al_2O_3 substrate as an alternative to the InPAs layer component as shown in Figure 4. Al_2O_3 has an intrinsic *Raststrahlen* reflectance band shown in Figure 5 that can be used in series with an interference filter to provide the required, below band gap reflectance. The InPAs layer begins to strongly reflect at about 6.5µm while Al_2O_3 begins to reflect strongly at 12µm. In order to meet the high, below the band gap reflection requirement with a Al_2O_3 substrate instead of an InPAs layer, the interference filter portion of the tandem filter must be designed to provide high reflection from the band gap edge to about 12µm instead of 6.5µm.

In addition, an Al_2O_3 substrate will substantially increase the mechanical strength of a tandem filter. The elastic modulus of an Al_2O_3 is 415 GPa as compared to 61 GPa for InP, the substrate material used for the tandem filter with the InPAs layer. Furthermore, an Al_2O_3 substrate provides more flexibility for the geometry of a tandem filter and larger fabrication sizes. For now InP substrates used for the tandem filters with a the InPAs layer are only available in circular wafers with a 100 mm diameter. In contrast, Al_2O_3 substrates are available in several shapes to include 90 by 66 mm rectangles and 150 mm diameter circles. Finally, the cost of a tandem filter with an Al_2O_3 substrate may be an order of magnitude lower than a tandem filter with the InPAs layer.

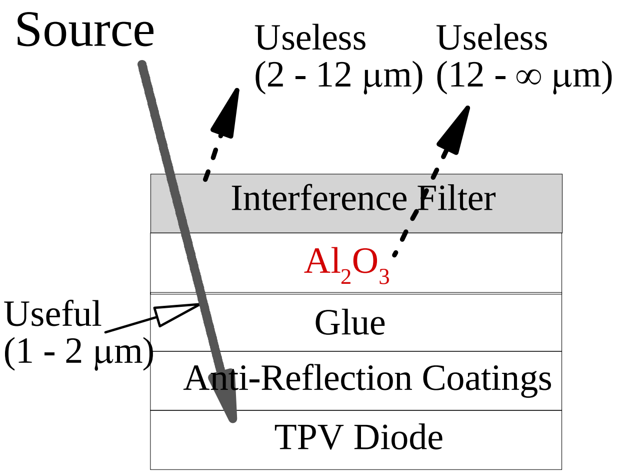


Figure 4 Tandem filter configuration with a Al_2O_3 substrate

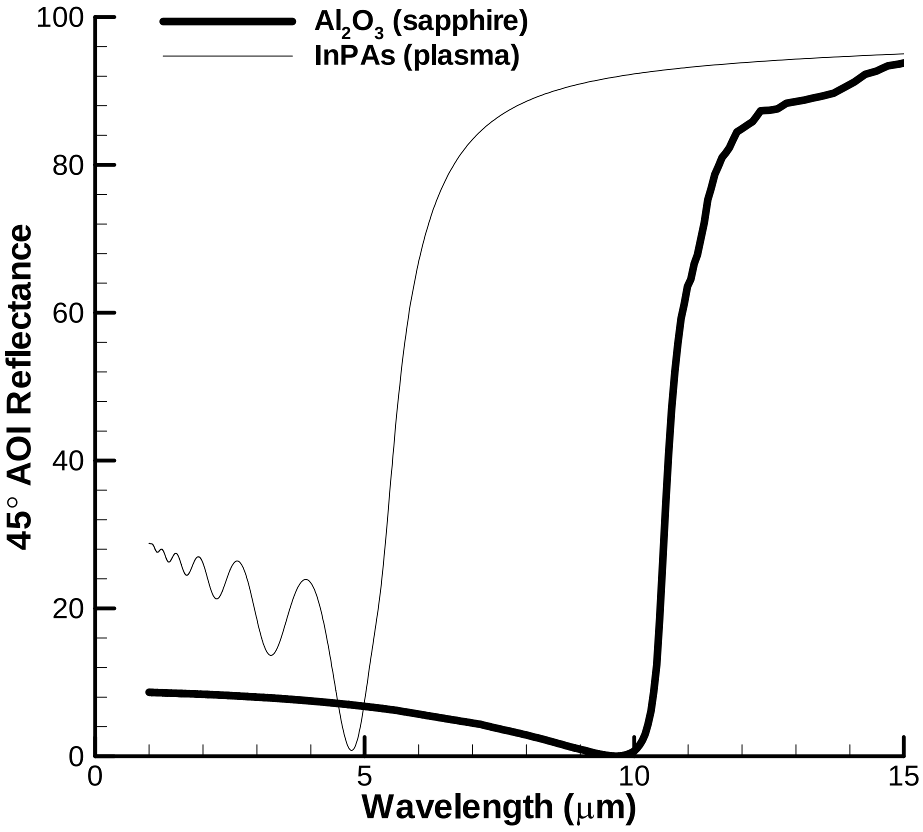


Figure 5 Plot of spectral reflectance for Al_2O_3 and the highly doped InPAs layer.

DESIGN DEVELOPMENT

The performance of tandem filters for TPV spectral control is quantified by two energy and angle weighted parameters, spectral efficiency and above band gap transmission [1]. In order to achieve maximum performance from a tandem filter design, these two parameters are combined into a common figure of merit for refinement optimization. Changing the relative refinement goals for each parameter changes the trade-off between the two parameters in the final design [3]. If the same starting design is refined against a matrix of different refinement goals for spectral efficiency and above band gap transmission, the result is a family of related designs. Performance for each design family is calculated by refining a previously developed design against different weights of the performance goals. In addition the complexity of the interference filter portion of the tandem filter is consistent for each design family. The results of this design method are shown in Figure 6 for a tandem filter with InPAs layer and an Al_2O_3 substrate. As shown, designs of tandem filter with an Al_2O_3 substrate yielded higher above band gap transmission but lower spectral efficiency as compared to tandem filters with the InPAs layer.

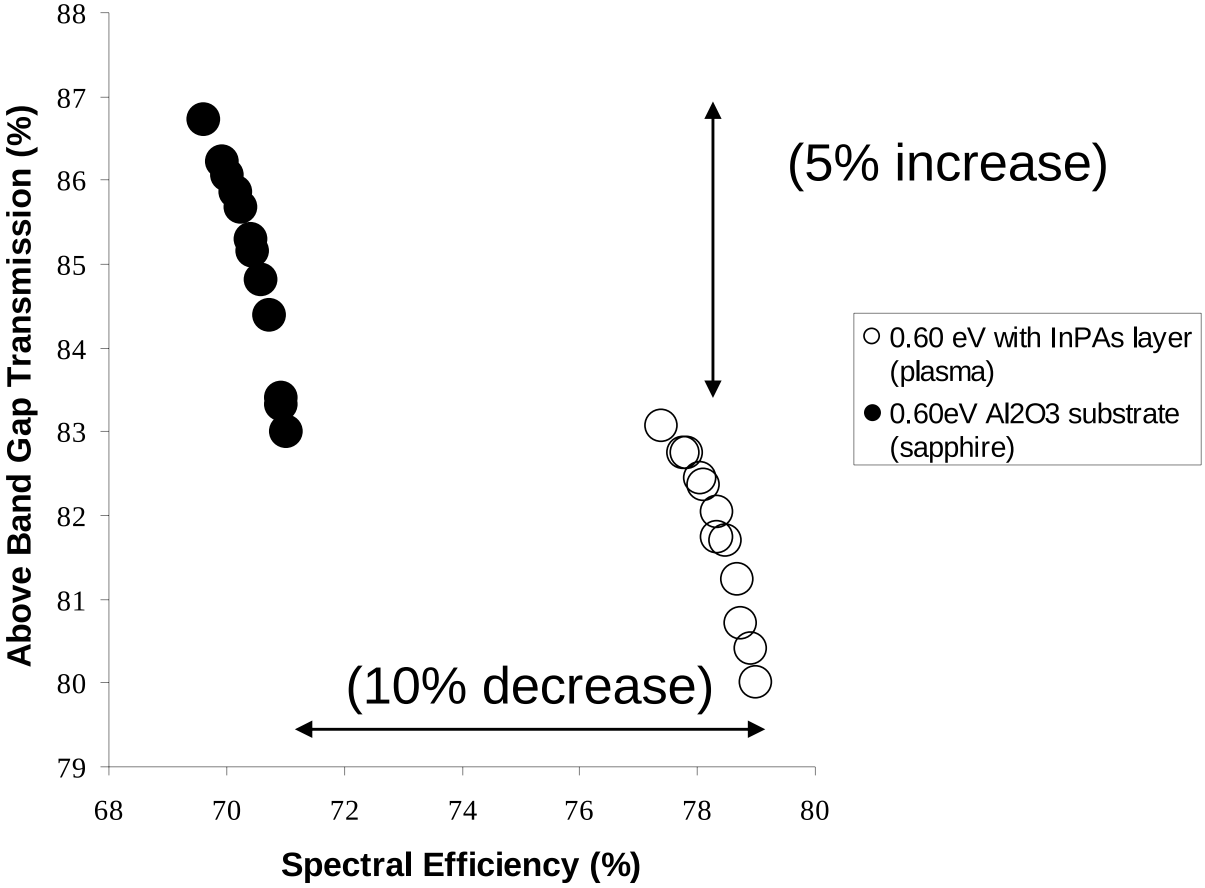


Figure 6 Comparison of above band gap transmission and spectral efficiency to illustrate the performance trade-off between Al_2O_3 and the highly doped InPAs layer tandem filters as well as between above band gap transmission and spectral efficiency

FILTER FABRICATION

Tandem filters using an Al_2O_3 substrates were successfully fabricated. Figure 7 presents an overlay of measured and design spectral reflectance at 45° angle of incidence for a 2.08µm tandem filter using an Al_2O_3 substrate.

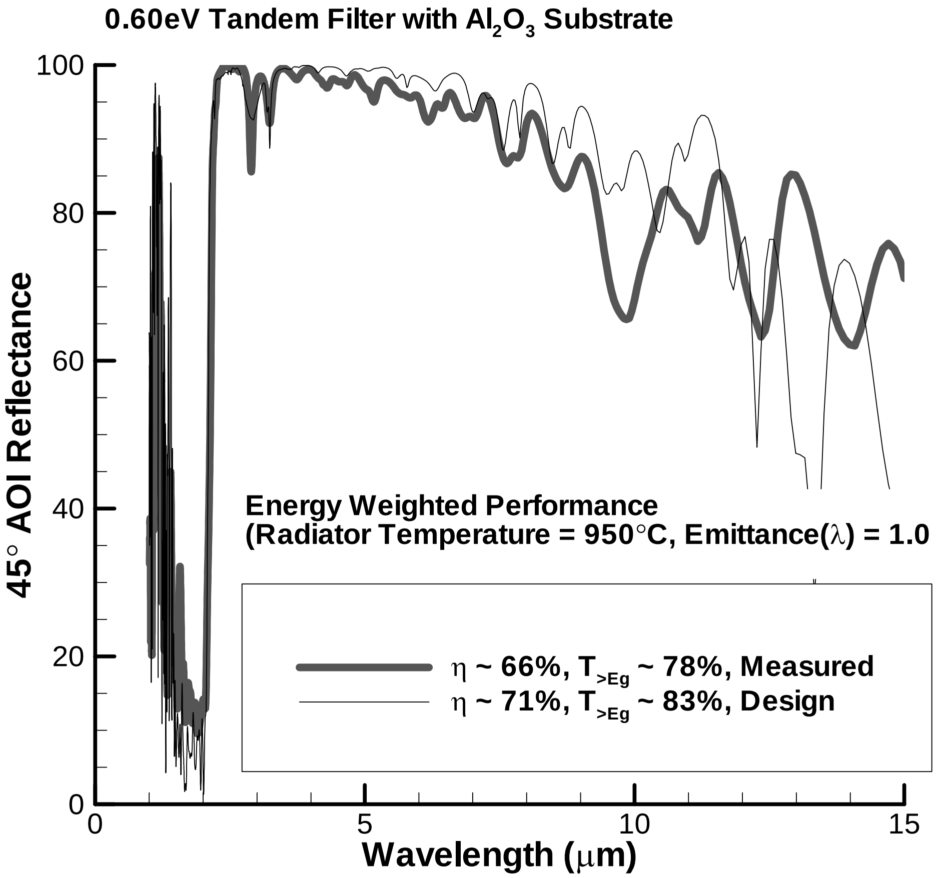


Figure 7 Comparison of Design and Fabricated Filter Performance

CONCLUSIONS

Tandem filters using an Al_2O_3 substrate have been demonstrated for 2.08μm band gap TPV cells. The spectral efficiency performance is lower (~10%) but above band gap transmission performance is slightly higher (~5%) as compared to a tandem filter using a highly doped, epitaxially grown layer of InPAs.

In addition, the tandem filters using an Al_2O_3 substrate provide the following advantages over tandem filters using an InPAs layer:

- Higher mechanical strength,
- Larger fabrication size and more geometry options,
- Lower cost.

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