LM-04K011
February 12, 2004

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Abstract: The efficiency of thermophotovoltaic (TPV) energy conversion is dependent on efficient spectral control. An edge pass filter (short pass) in series with a highly doped, epitaxially grown layer has achieved the highest performance of TPV spectral control.

OCIS codes: (310.0310) Thin films; (310.1620) Coatings; (310.1860) Deposition and fabrication

1. Thermophotovoltaic Spectral Control

Spectral control is paramount to successful energy conversion using thermophotovoltaic (TPV) diodes. The useful radiant energy for conversion is a fraction (sometimes a small fraction) of the total radiant energy. For example, only about 26 percent of the radiant energy can be converted to electricity for a 950°C radiator temperature and a 0.52 eV band gap TPV diode. The remaining 74 percent of the radiant energy cannot be converted to electricity and will be lost if absorbed. Ideally, this useless energy should be reflected back to the radiator (recuperated) in order to maximize TPV efficiency.

Without spectral control, TPV energy conversion performance suffers dramatically. The net conversion efficiency for a 30% efficient TPV diode with no spectral control would be only 8 percent (0.30*0.26 = 0.078) for a 950°C radiator temperature. On the other hand, an 80 percent efficient, spectral control configuration would yield a net efficiency of 24 percent (0.30*0.80 = 0.24) for the same TPV diode.

2. Front Surface, Tandem Filters for TPV Spectral Control

Front surface, tandem filters consist of an edge pass filter (short pass) in series with a highly doped, epitaxially grown layer as shown in Fig. 1 [1-4]. For the edge pass filter, Sb_2Se_3 (n~3.4) is used as the high index of refraction material and YF_3 (n~1.5) is used as the low index of refraction material. The development of Sb_2Se_3 as the high index of refraction optical interference material has been a key program achievement that has enabled high TPV spectral control performance to be achieved. Sb_2Se_3 provides a high index of refraction with a very low extinction coefficient (<0.0001) from 0.85 µm to greater than 30 µm.

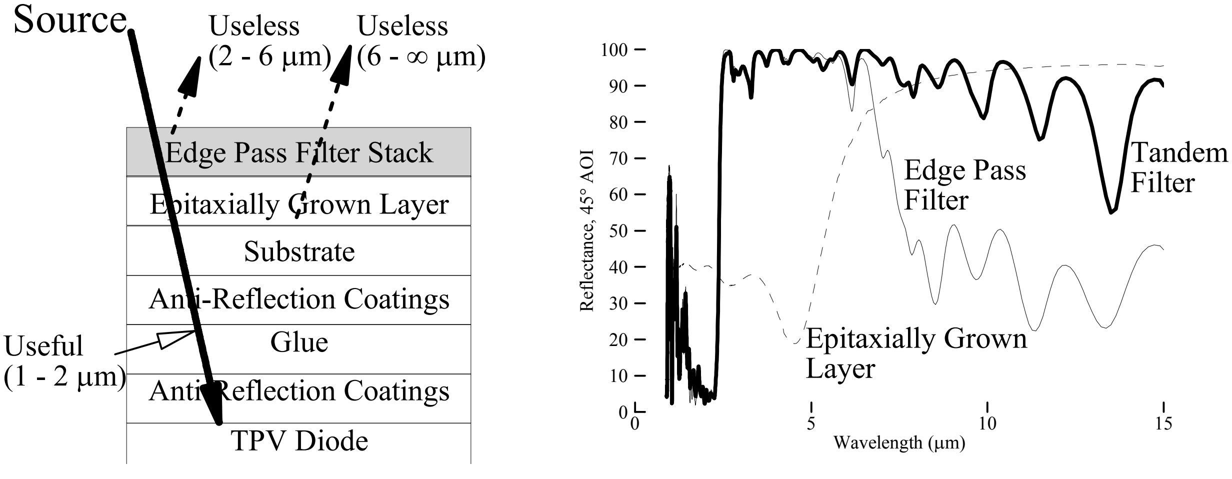


Fig. 1 Front Surface, Tandem Filter for TPV Spectral Control

These filters pass the majority of the useable photons with energies greater than the band gap of the TPV diode and reflect the unusable photons with energies less than the band gap. As a result, the spectral distribution of photons transmitted through the tandem filter to the TPV diode is skewed toward photons that can generate electricity as compared to the spectral distribution provided by an emitting surface.

3. Merit functions: Spectral Efficiency ($\eta_{spectral}$) and Above Band Gap Transmission ($T_{<Eg}$)

For any energy conversion system, the efficiency of and the volume or mass associated with the conversion process are central. The merit functions for TPV spectral control, spectral efficiency and above band gap transmission, capture the spectral control performance that relates to the conversion efficiency and power density of a TPV energy conversion system. The spectral efficiency is the ratio of the above band gap power absorbed to the total power absorbed, and the above band gap transmission is the ratio of the above band gap power absorbed by the TPV diode to above band gap power available to be absorbed by the TPV diode (that is assuming a perfect anti-reflection coating on the TPV diode surface). Specifically, these merit functions are defined as follows:

$$\eta_{spectral} = \frac{\int_0^{\frac{\pi}{2}}\int_0^{\lambda_g} \varepsilon_{eff}(\lambda,\theta,T_{rad})\frac{T_{filter}(\lambda,\theta)}{1-R_{filter}(\lambda,\theta)}N(\lambda,T_{rad})\sin\theta\cos\theta d\lambda d\theta}{\int_0^{\frac{\pi}{2}}\int_0^{\infty}\varepsilon_{eff}(\lambda,\theta,T_{rad})N(\lambda,T_{rad})\sin\theta\cos\theta d\lambda d\theta} \qquad (1)$$

$$\mathrm{T}_{>\mathrm{Eg}} = \frac{\int_0^{\frac{\pi}{2}}\int_0^{\lambda_g} \varepsilon_{eff}(\lambda,\theta,T_{rad})\frac{T_{filter}(\lambda,\theta)}{1-R_{filter}(\lambda,\theta)}N(\lambda,T_{rad})\sin\theta\cos\theta d\lambda d\theta}{\int_0^{\frac{\pi}{2}}\int_0^{\lambda_g}\varepsilon_{rad}(\lambda,\theta,T_{rad})N(\lambda,T_{rad})\sin\theta\cos\theta d\lambda d\theta} \qquad (2)$$

Where:

$T_{filter}(\lambda,\theta)$ is the filter transmittance as a function of wavelength and angle of incidence,

$R_{filter}(\lambda,\theta)$ is the filter reflectance as a function of wavelength and angle of incidence,

λ is wavelength,

λ_g is the wavelength corresponding to the band gap (E_g) of the TPV diode,

$N(\lambda,T_{rad})$ is Planck's blackbody spectral distribution of emissive power as function of wavelength and temperature,

θ is the angle of incidence of incoming photons,

T_{rad} is the radiator temperature,

$\varepsilon_{rad}(\lambda,\theta,T_{rad})$ is the radiator emittance as a function of wavelength, angle and temperature,

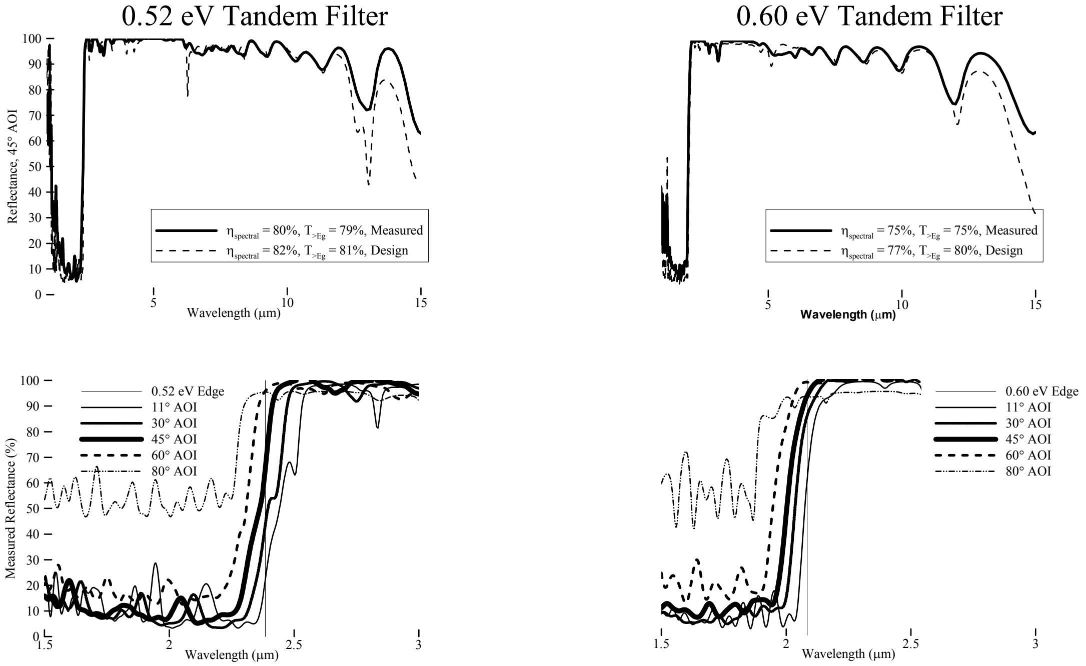
$\varepsilon_{eff}(\lambda,\theta,T_{rad})$ is the effective cavity emittance for infinite, parallel plates as follows:

$$\varepsilon_{eff}(\lambda,\theta,T_{rad}) = \frac{1}{\frac{1}{\varepsilon_{rad}(\lambda,\theta,T_{rad})}+\frac{1}{1-R_{filter}(\lambda,\theta)}-1} \qquad (3)$$

These merit functions are aggregate, energy weighted measures of TPV spectral performance and have been shown to correlate with the independently measured efficiency and power density of a combined TPV diode and spectral control configuration. The performance as captured in the merit functions is dependent on the available energy with wavelength, according to Plank's blackbody distribution, and angle of incidence (AOI). As a result, reflectance at a wavelength of 3 μm and 45° AOI is much more important than performance at a wavelength of 15 μm and an AOI of 80°. Spectrally, about 96% of the available energy is between 1.25-13.5 μm for a radiator temperature of 950°C. Directionally, the available energy is uniformly distributed about a peak at 45° incident angle.

4. Results

The current performance of TPV front surface, tandem filters for 0.52 and 0.60 eV TPV diodes is summarized in Fig. 2. The FT-IR spectrometer results compare well with the design results as assessed by OptiLayer™. Specifically, the measured results show excellent reflectance in the rejection band, minimal edge shift with angle of incidence, and sharp edge slopes. All these features yield a filter with an incident angle and energy weighted, spectral efficiency of 75-80 percent while transmitting 75-79 percent of the available, useful energy.



(a) (b)

Fig. 2. TPV Front Surface, Tandem Filter Performance, (a) Comparison of Design and Measured Performance for 45° Angle of Incidence (AOI) with Calculated Merit Functions (assuming $T_{radiator}$ = 950°C, T_{diode} = 50°C, and $\varepsilon_{radiator}$ = 1), (b) Measured Angle of Incidence Performance

5. Conclusions

Front surface, tandem filters have achieved the highest spectral efficiency and represent the best prospect for even higher spectral efficiency for TPV energy conversion systems. Specifically, improvements in the physical vapor deposition process, identification of other materials with a high index of refraction and a low absorption coefficient, and more efficient edge filter designs could provide higher TPV spectral performance.

6. References

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