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SPECTRAL UTILIZATION IN THERMOPHOTOVOLTAIC DEVICES

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ABSTRACT

Multilayer assemblies of epitaxially-grown, III-V semiconductor materials are being investigated for use in thermophotovoltaic (TPV) energy conversion applications. It has been observed that thick, highly-doped semiconductor layers within cell architectures dominate the parasitic free-carrier absorption (FCA) of devices at wavelengths above the bandgap of the semiconductor material. In this work, the wavelength-dependent, free-carrier absorption of p- and n-type InGaAs layers grown epitaxially onto semi-insulating (SI) InP substrates has been measured and related to the total absorption of long-wavelength photons in thermophotovoltaic devices. The optical responses of the TPV cells are then used in the calculation of spectral utilization factors and device efficiencies.

INTRODUCTION

Thermophotovoltaic devices have received a great deal of attention due to their potential utility in space and other power generation applications. In contrast to silicon- and gallium arsenide-based photovoltaics (solar cells), material systems for TPV applications must be tailored to utilize the radiant spectrum from one of a limited number of blackbody-type radiators. Traditionally, front-surface spectral control elements, such as selective radiators and plasma or dielectric filters, have been employed to expose TPV devices only to the portion of a radiator's spectrum with energy greater than the cell bandgap. However, these types of bandpass front-surface spectral control methods generally result in systems that display lower output power densities.

An alternative approach is to design TPV cells that transmit all incident radiation, effectively utilize the portion of the incident light with energy above the bandgap and efficiently reflect lower-energy photons back to the radiator. The reflection of unabsorbed light is made possible by the use of back-surface reflectors (BSRs) and semi-insulating substrates. A thermophotovoltaic device that meets these criteria can display a high spectral utilization factor that is generally defined by the relationship:

$$F_u = \frac{\text{absorbed energy} > hc/\lambda_g \text{ in device}}{\text{total absorbed energy in device}} \quad (1)$$

In order to produce TPV devices with high spectral utilization factors, it is necessary to utilize materials that do not parasitically absorb long-wavelength, below-bandgap energy. As a result, InGaAs heterostructures grown epitaxially onto semi-insulating InP have emerged as useful material systems for the fabrication of low-bandgap TPV devices.¹ A gold BSR is employed for the reflection of low-energy radiation not absorbed in the device.² A schematic diagram of a typical TPV device architecture is shown in Figure 1.

0.1 μm	p+ InP Window
0.1 – 0.3 μm	p+ InGaAs Emitter
2 – 3 μm	n InGaAs Base
0.1 μm	n+ InP Back Surface Field
1 – 3 μm	n++ InGaAs Lateral Conduction Layer (LCL)
3 μm	InP _x As _{1-x} or In _x Ga _{1-x} As Graded Layers*
350 μm	Semi-insulating InP substrate
0.1 – 0.2 μm	Back-surface reflector (BSR)

Figure 1. Schematic, cross-sectional diagram depicting the layered architecture of a typical thermophotovoltaic device. (* For lattice-mismatched devices only.)

For architectures such as that shown in Figure 1, the p-doped emitter and window layers and the n-doped lateral conduction layer dominate parasitic absorption. Optically, it would be advantageous to incorporate only thin, lowly-doped layers into cell architectures. Unfortunately, this strategy results in electrical losses in the form of high series resistances. To combat this trade-off, it is important to understand the dependence of the total absorptance within TPV devices on each layer. This permits the accurate decoupling of the absorptances of the spectrally dominant layers within TPV cell architectures and enables the use of predictive capabilities that allow each layer to be grown at an optimum dopant density and thickness. Consequently, n- and p-type InGaAs layers of varying thickness and dopant density were grown epitaxially onto InP substrates in an effort to simulate the effects individual layers have on the total optical response of cells and to correlate these effects to optical response and device efficiency. In this work, these layers are characterized individually to determine their contribution to device absorptance and techniques employed to evaluate the spectral utilization factors and project device efficiencies are presented.

EXPERIMENTAL

Individual n- and p-type InGaAs layers were grown epitaxially onto semi-insulating InP substrates by organometallic vapor phase epitaxy (OMVPE). The precursor materials were trimethyl indium, trimethyl gallium, arsine and phosphine. Diethyl zinc and silane were employed for p- and n-type doping, respectively. Back-surface reflectors (BSRs) consisting of gold or gold on a thin MgF₂ layer were deposited by thermal evaporation.

Measurements of the optical responses of the individual layers and of complete grown structures were completed on a Nicolet 760 Fourier-transform infrared spectrophotometer fitted with in-compartment assemblies for independently measuring spectral reflectance at an incidence angle of 12° and total diffuse reflectance at normal incidence.

Measurements of sample dopant densities and electron mobilities were completed on a Lakeshore 7504 Hall Effect / Electronic Transport Measurement System capable of measuring carrier concentrations up to 10²⁰ cm⁻³ and sample resistances in excess of 10¹¹ Ω at room temperature and 77 K.

RESULTS

n-InGaAs Layers

Because of its thickness and dopant density, the lateral conduction layer contributes to optical losses significantly more than other n-type layers in TPV cells. In order to evaluate the degree of parasitic absorption in the lateral conduction layer, a series of n-In_{0.53}Ga_{0.47}As layers were grown epitaxially onto semi-insulating InP. Physical and spectral properties of these layers are summarized in Table 2. Reflectance as a function of wavelength was measured for the samples in order to determine the energy-weighted parasitic absorptance exhibited by each as shown in Figure 3.

Table 1. Physical Properties of n-In_{0.53}Ga_{0.47}As layers on InP.

Sample	Carrier Density (x10 ¹⁷ cm ⁻³)	Carrier Mobility (cm ² /Vs)	Thickness (μm)	% Power Absorbed (PA) λ > 2 μm*	
				1750°F Radiator	2250°F Radiator
1	279	1636	2.35	26.9	27.3
2	120	2029	2.67	16.1	14.6
3	84.8	2337	2.50	11.6	10.2
4	9.45	3949	2.95	2.8	2.5
5	287	1586	0.81	9.5	9.3

*2 μm corresponds to a bandgap of approximately 0.6 eV.

Free-carrier absorption in thick, highly-doped n-In_{0.53}Ga_{0.47}As can constitute a considerable loss in TPV devices. However, as the dopant density is decreased, the free-carrier absorption decreases in magnitude and shifts to higher wavelengths where less energy is available from a blackbody radiator.

Figure 2. Reflectance vs. Wavelength for a series of $n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ layers grown epitaxially onto InP. Free-carrier absorption bands can be seen at 7, 10, 12.5 and 7 in Samples 1, 2, 3 and 5, respectively. Absorption in the InP substrate is seen in Sample 4 because the lowly-doped LCL does not exhibit plasma reflectance at these wavelengths.

Plasma reflection in highly n-doped layers results in the reflection of low-energy photons (approaching 98% reflectance for Sample 1). With decreasing dopant density, the plasma reflection is attenuated and the resonance absorption band broadens. Note that layers doped below $\sim 3 \times 10^{18} \text{ cm}^{-3}$ exhibit no free carrier absorption band and reveal the absorption characteristics of the InP substrate that were previously masked by the plasma reflection (Sample 4 in Figure 2).

The importance of layer thickness is evident upon comparison of the reflectances of Samples 1 and 5. Although doped at comparable levels, the plasma absorption is greatly attenuated in Sample 5 which is $\sim 1/3$ as thick as Sample 1. This behavior is expected from the exponential dependence of absorption on thickness. Also, although each of the layers were grown as the $n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ ($\lambda_g = 1.70 \text{ } \mu\text{m}$) composition, the Burstein-Moss shift decreases the bandgap with increasing dopant density.

p-InGaAs Layers

The second major source of optical loss within TPV devices is absorption by p-type layers. Here, the emitter dominates the other p-type layers in the device due to its dopant density and its thickness. In order to evaluate the emitter's contribution to the spectral utilization, a series of $p\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ layers were grown epitaxially onto semi-insulating InP. Additionally, an InP layer was grown to quantitate the parasitic absorption in the top window layer. The pertinent properties of these layers are summarized in Table 3. Reflectance vs. wavelength data acquired for the four samples is shown in Figure 3.

Table 2. Physical Properties of $p\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ layers on InP.

Sample	Carrier Density ($\times 10^{19} \text{ cm}^{-3}$)	Carrier Mobility (cm^2/Vs)	Thickness (μm)	% Power Absorbed (PA) $\lambda > 2 \text{ } \mu\text{m}^*$	
				1750°F Radiator	2250°F Radiator
6	1.2	70	0.6	28.2	26.8
7	1.2	70	0.3	22.2	20.7
8	1.2	70	0.1	8.9	8.0
p+ InP	0.2	81	0.1	7.1	6.7

Although p-type layers do not display resonance absorption bands such as those caused by free-carriers in n-type materials, broadband absorption in p-type materials is equally detrimental to device efficiency. This fact is evident through comparison of the percent power absorbed in the various layers listed in Tables 2 and 3. In fact, p-type materials that are 10% as thick as comparably doped n-type

Figure 3. Reflectance vs. Wavelength for a series of p-In_{0.53}Ga_{0.47}As layers grown epitaxially onto InP.

materials (i.e. Samples 2 and 7) display higher energy-weighted parasitic absorptances. This observation is in agreement with previously published results that have shown that p-type layers display ~17 times the absorptance of comparable n-type layers.⁴

The reflectances of Sample 8 and the p+ InP approach the reflectance of the gold BSR (~98%) and the loss due to parasitic absorption in these layers can be considered negligible.

In order to relate the behavior of these layers to that of TPV devices, complete architectures with various combinations of p-doped emitters and windows and n-doped lateral conduction layers were grown and characterized. This strategy allows the determination of spectral utilization factors and device efficiencies and aids in the identification of the layers that contribute most to optical losses.

TPV Cell Architectures

The physical characteristics of two similar architectures grown at two different bandgaps (0.6 eV and 0.74 eV) are provided in Table 1. Absorptances as a function of wavelength for the four structures are shown in Figure 4 with the normalized spectral emission of a 1750°F blackbody radiator.

Free-carrier absorption in the highly-doped LCL's is responsible for the peaks at 5.9 μm in Cells 445 and 446. Plasma reflectance from the LCLs and reflectance from the BSRs are responsible for optical interference that results in the periodicity of the response of these cells in the 5 μm to 10 μm range. That is, multiple reflections within the device provide many opportunities for radiation to be parasitically absorbed by the LCL and compositionally-graded layers. Cells 145 and 467 possess LCL's doped approximately an order of magnitude lower and do not display this effect.

Small differences in the absorptance characteristics in the 2 μm to 5 μm range are primarily due to absorption by the p-type emitter and top window layers. These layers also contribute to the gradual increase in absorptance observed for Cells 145 and 467 at long wavelengths. Although it displays a similar profile at short wavelengths, the absorptance of Cell 446 is ~12% higher than that of the other architectures because of optical losses in the graded layers of this device.

Table 3. Physical Characteristics of Thermophotovoltaic Cell Architectures

TPV Cell	Bandgap (eV/ μm)	Emitter Thickness (μm)	Emitter Dopant Density ($\times 10^{19}\text{cm}^{-3}$)	LCL Thickness(μm)	LCL Dopant Density ($\times 10^{18}\text{cm}^{-3}$)
445	0.74/1.69	0.1	1.0	1.0	20
467	0.74/1.69	0.1	1.2	0.15	2.0
446	0.6/2.25	0.3	1.0	1.0	20
145	0.6/2.25	0.3	1.2	0.15	2.0

Figure 4. Absorbance vs. Wavelength for four thermophotovoltaic cell architectures. The overlay is the normalized emission of a 1750° F blackbody radiator.

Thus, when designing TPV devices, the optical properties of the cells can be approximated by measuring the degree of parasitic absorbance in individual layers of the architecture. Successful implementation of this strategy allows the accurate prediction of the optical losses associated with various TPV cell architectures and results in the development of more efficient devices.

Spectral Utilization and Device Efficiency

In order to evaluate the spectral utilization of TPV cells, it is necessary to characterize the infrared reflectance of architectures such as that shown in Figure 1. Since the gold BSR prevents infrared transmittance through the rear of the device, long-wavelength absorbance can be determined with the following relationship:

$$\alpha(\lambda) = 1 - \rho(\lambda) \quad \text{for } \tau(\lambda) = 0 \quad (2)$$

The spectral utilization factor can then be evaluated from the measured reflectance as follows:

$$F_u = \frac{\int_0^{\lambda_g} [1 - \rho(\lambda)] N_{ph}(\lambda) d\lambda}{\int_0^{\infty} [1 - \rho(\lambda)] N_{ph}(\lambda) d\lambda} \quad (3)$$

where λ is the wavelength and N_{ph} is the energy flux given by:

$$N_{ph}(\lambda) = \frac{2\pi h c^2}{\lambda^5 [\exp(hc/\lambda kT) - 1]} \quad (4)$$

Spectral utilization is the single most important factor controlling TPV device efficiency. Efficiency can be approximated through knowledge of the voltage factor (V_{oc}/E_g), the energy-weighted quantum efficiency (QE), the fill factor (FF), the over-excitation factor (F_o) and the spectral utilization factor (F_u) as follows:⁵

$$\eta = \frac{V_{oc}}{E_g} \cdot \overline{QE} \cdot FF \cdot F_o \cdot F_u \quad (5)$$

Typical experimentally-determined values for these parameters measured on fully-processed TPV devices are:

$$\frac{V_{oc}}{E_g} = 0.55, \quad \overline{QE} = 0.7, \quad FF = 0.7, \quad F_0 = 0.8$$

Using these values, the influence of the spectral utilization factors associated with different TPV cell architectures can be quantified. Table 5 lists the calculated spectral utilization factors and device efficiencies from the reflectance measurements on the TPV cell architectures shown in Figure 4.

Table 4. Spectral Utilization Factors and Corresponding Device Efficiencies

TPV Cell	Bandgap (eV/ μ m)	1750°F Blackbody			2250°F Blackbody		
		F_U	PA (%)	η (%)	F_U	PA (%)	η (%)
445	0.74/1.69	0.40	12.3	8.6	0.63	11.5	13.6
467	0.74/1.69	0.65	4.4	14.0	0.69	4.1	14.9
446	0.6/2.25	0.55	27.8	11.9	0.83	27.1	17.9
145	0.6/2.25	0.85	6.0	18.3	0.92	5.5	19.8

By systematically characterizing the optical losses associated with individual layers, it is possible to design cells that exhibit high spectral utilization factors and device efficiencies.

CONCLUSIONS

Measurements of the reflectances of individual p- and n-type layers that comprise TPV cells have revealed that parasitic absorptance within the thickest, most highly-doped layers determines the overall optical responses of devices. Systematic study of the optical losses associated with these layers has resulted in the design of TPV architectures that display spectral utilization factors in excess of 0.8 and parasitic absorption within devices has been reduced to the point that efficiencies of 20% are attainable with a 1750°F blackbody radiator.

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