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Enhanced thermal radiation conversion in a GaSb/GaInAsSb tandem thermophotovoltaic cell

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ABSTRACT

Beyond the ideal detailed balance evaluation, layer-dependent thermal radiation conversion has been systematically investigated here for tandem device consisting of a GaSb top subcell and a 0.53 eV GaInAsSb bottom subcell. Relying on the experimentally-accessible material parameters, it is demonstrated here that tandem device in its N-on-P configuration displays a superior thermal conversion efficiency, and the proper doping profile should be controlled as $N_d = 7–9 \times 10^{17}\ cm^{-3}$ and $N_a = 5 \times 10^{17}\ cm^{-3}$ for GaSb subcell while $N_d = 6–7 \times 10^{17}\ cm^{-3}$ and $N_a = 3.5 \times 10^{17}\ cm^{-3}$ for 0.53 eV GaInAsSb subcell. Moreover, due to different subcell-limited performance outputs, the dependence of thermal conversion efficiency on radiator temperature shows a remarkable "*S*-shape" feature, and the open-circuit voltage of tandem cell can be up to 0.7–0.8 V for typical radiator temperatures. Finally, limited by the larger bandgap of GaSb material, superior thermal conversion efficiency can be always expected for tandem cell when comparing to GaSb cell, but only for radiator temperature larger than 1500 K when comparing to 0.53 eV GaInAsSb cell.

1. Introduction

On the way to implement a powerful thermophotovoltaic (TPV) system, high-efficient TPV cells are strongly desirable due to their fundamental role in determining system electricity power generation from infrared thermal radiation. Experimentally, on the basis of narrow bandgap semiconductors like Ge and Sb-containing alloys, various TPV single-junction cells have been demonstrated [1–6]. However, the direct application of these devices might be an inefficient choice once a broadband but economical radiator is used [7]. The underlying reason is that device can only be opaque for photon with energy higher than the bandgap (E_g) of host material, and even for these photons, the effective electricity power generated from TPV cell is only comparable to E_g, implying the excess energy of the absorbed photons being also wasted.

Considering these physical limitations, one attractive scheme is to develop tandem TPV cell, for which several subcells are stacked together from top to bottom in the order of reducing host E_g and the adjacent subcells are interconnected by a proper tunnel junction. Actually, the validity of this strategy has been well demonstrated in GaAs-based and silicon-based photovoltaic technology [8–10], but little has been so far acquired for the feasible TPV counterparts. Historically, based on InP and GaSb-based narrow-bandgap compounds, several prototype tandem devices have been experimentally shown by various groups [11–14]. For instance, Andreev et al. [14] has experimentally manufactured a tandem TPV device consisting of a GaSb top subcell and a GaInAsSb bottom subcell (E_g = 0.56 eV), reporting an open-circuit voltage as high as 0.61 V. Surprisingly, irrespective of these achievements, the topic became silent immediately after these demonstrations. Recently, following the detailed balance evaluation, the optimum bandgap combination has been theoretically predicted for possible tandem TPV applications [15,16]. For instance, relying on the experimentally-accessible Sb-containing alloys with lattice 6.1 Å, one of the authors [16] has systematically summarized the evolution of optimum combinations versus the variation of radiator temperature for both dual-junction and triple-junction tandem devices. However, deeper yet realistic studies [17] are still in the blank because of the extensive scarcity of optoelectronic data for the concerned alloys.

In this work, taking two experimentally well-studied alloys, GaSb and $Ga_{0.84}In_{0.16}As_{0.14}Sb_{0.86}$, as subcell host material, we have theoretically investigated layer-dependent radiant thermal conversion in a GaSb/GaInAsSb tandem device. By systematically performing parametric simulations, we show here that tandem cell in its n-on-p configuration displays superior power output and the optimum "doping-pair" for subcells is $N_{d(a)} = 7(5) \times 10^{17}\ cm^{-3}$ for GaSb subcell while $N_{d(a)} = 7(3.5) \times 10^{17}\ cm^{-3}$ for GaInAsSb subcell. For p-on-n configuration, the corresponding optimum doping profile is $N_{d(a)} = 6(4) \times 10^{17}\ cm^{-3}$ for GaSb subcell while $N_{d(a)} = 4(3) \times 10^{17}\ cm^{-3}$ for

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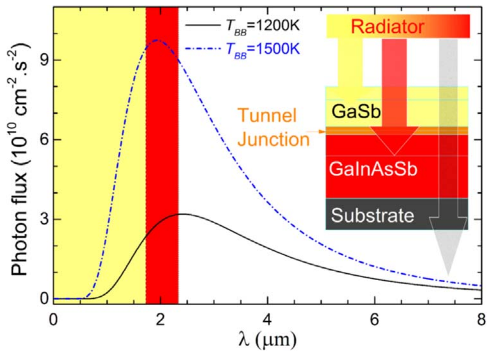

Fig. 1. Photon wavelength (λ)-dependent photon flux of blackbody-like radiator with two typical radiator temperatures, where the specific spectrum response region for GaSb subcell (yellow) and 0.53 eV GaInAsSb (red) is shown. In the inset, the specific structure of our concerned tandem device is schematically depicted. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

GaInAsSb subcell. With the increasing radiator temperature T_{BB}, an *S*-type response is generally observed for energy conversion efficiency η. Importantly, for the typical T_{BB}s, V_{OC} up to 0.70–0.80 V could be easily expected for tandem device, rendering fully the attractive properties of tandem device for TPV applications.

2. Model and equations

Our concerned device is schematically depicted in the inset of Fig. 1, where a GaInAsSb subcell and a GaSb subcell are interconnected via an ideal tunnel junction. Under thermal spectrum illumination, photon with energy E_{ph} larger than E_g of GaSb is mainly utilized by the top subcell while the rest flux might still be utilizable for the GaInAsSb bottom subcell once E_{ph} is higher than E_g of GaInAsSb alloy, i.e., E_g = 0.53 eV for the current investigation. Apparently, as shown in Fig. 1, tandem stack has extended spectrum absorption edge into that for bottom host material (vertical short-dotted line), improving thus the whole spectrum utilization comparing to top subcell alone. Besides, as marked by different colored block, great reduction of thermalization loss could be expected for bottom subcell since the high energy flux has been optically filtered by top subcell. Following these features, an enhanced TPV energy conversion should be naturally expected for tandem device once the same subcell working current is reached. However, in what way this realistic condition can be realized is still less known.

Here in order to concentrate on the thermal radiation conversion controlled by device active layers, we consider a naked tandem cell under the illumination of the assumed blackbody-like thermal spectrums. Thus, some favorable spectrum controls like anti-reflection coating and back surface reflector have been neglected in our calculations. Moreover, for the specific device evaluation, we have also neglected some realistic factors like series resistance and employed an ideal diode model to mimic the subcells. For these reasons, comparing to more rigorous device simulations, some numerical deviations should be expected for our results. For instance, by incorporating the series resistance, the current density-voltage characteristic deviates from that for ideal diode model, leading to the degradation of device efficiency. The higher radiator temperature is, the larger degradation might be expected due to a much higher working current. However, since the main physics on thermal radiation conversion has been well captured by ideal diode model, some beneficial guidelines can still be acquired. Starting from the ideal diode model, the working voltage-current density characteristic for tandem device could be written as

$$V = \frac{k_B T}{q} \sum_{i=1,2} \ln\left(\frac{J_{SC,i} + J_{0,i} - J}{J_{0,i}}\right) \quad (1)$$

where k_B is Boltzmann constant, T = 300 K is cell temperature, q is the elementary charge, V (J) is the working voltage (current density), and $J_{SC,i}$($J_{0,i}$) is the subcell short-circuit current density (dark current density) with subscript i = 1(2) for GaSb (GaInAsSb) subcell. Depending on the specific parameters for subcells, i.e., donor(acceptor) doping concentration N_d (N_a) and the width of quasi-neutral region of P(N)-type layer, the calculation of $J_{SC,i}$($J_{0,i}$) has been performed in the same procedure as previous works on single-junction device [18], where the blackbody-like thermal spectrum is assumed for radiator working at T_{BB} and the optical absorption coefficient of host materials are calculated from the analytical dielectric model [19,20], which agrees well with the experimentally reported data. Due to the subcell current-matching condition, the maximum working current density of tandem device $J_{max,\ t}$ is approximately taken as the smaller one for subcells, reading as

$$J_{\max,t} = \text{Min}\,[J_{\max,1}, J_{\max,2}] \quad (2)$$

Substituting the above result into Eq. (1), the maximum working voltage of tandem device $V_{max,\ t}$ can thus be determined, and energy conversion efficiency η for tandem device can be further determined as

$$\eta = \frac{V_{\max,t} J_{\max,t}}{\sigma T_{BB}^4} \quad (3)$$

with σ the well known Stefan-Boltzmann constant. Obviously, by defining the ratio between the product of $J_{max,\ t}$ and $V_{max,\ t}$ and that for J_{SC} and V_{OC} of tandem device as fill factor (FF), Eq. (3) has the same form as the general expression for η.

3. Results and discussions

Since the subcell can be generally fabricated in either N-on-P or P-on-N configuration, the resulting tandem device can also be designed as N-on-P or P-on-N configuration. Thus, to show the effect of configuration on thermal radiation conversion, both configurations are studied here.

3.1. N-on-P configuration

Prior to directly evaluate tandem cell, subcell optimization is firstly performed to search an optimum structure. To do this, by employing layer-dependent η as the standard of device evaluation, we initially calculate η as a function of the quasi-neutral region thickness of n-type and p-type layer for a given doping profile and thermal spectrum illumination. From this calculation, an optimum structure showing the maximum η could be easily traced in the layer-dependent iso-efficiency plot [21] due to the competition between thermal spectrum utilization and photo-generated carrier collection. Subsequently, the same calculation is reproduced by modifying the doping concentration in p-type layer from $N_a = 10^{17}\ \text{cm}^{-3}$ up to $2 \times 10^{18}\ \text{cm}^{-3}$. After completing these calculations, the specific dependence of optimum structure as well as its η on N_a in p-type layer is obtained. Finally, by further modifying N_d in n-type layer, reproducing above device simulations enables us to acquire an integrated picture on the layer-dependent thermal radiation conversion for a given spectrum illumination.

With T_{BB} = 1200 K, typical results for GaSb subcell are shown in Fig. 2, where η (symbols) of each doping profile-related optimum structure is plotted as a function of N_a for a series of N_d. It is easily seen that for a fixed N_d an optimum N_a showing the maximum η can be well traced. With the increasing N_d, this optimum N_a shifts from $3 \times 10^{17}\ \text{cm}^{-3}$ for $N_d = 10^{17}\ \text{cm}^{-3}$ up to $5 \times 10^{17}\ \text{cm}^{-3}$ for N_d in the range of 5–10 $\times 10^{17}\ \text{cm}^{-3}$. Subsequently, further improving N_d shifts again the optimum N_a towards a lower value. Interestingly, the increasing N_d improves initially the η-N_a spectra upward while shifts downwards again when N_d surpasses a critical value. Therefore, under a given spectrum illumination, there is an optimum "doping pair" for subcell to maximize the thermal power conversion. In the inset, this optimum N_d can be identified as $7 \times 10^{17}\ \text{cm}^{-3}$ by examining η-N_d spectrum with $N_a = 5 \times 10^{17}\ \text{cm}^{-3}$. Indeed, we have also performed the similar