2018 IEEE International Conference on Semiconductor Electronics (ICSE)

Optimization of p-type Emitter Thickness for GaSb-Based Thermophotovoltaic Cells

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Abstract—**Thermophotovoltaic (TPV) cells that convert thermal heat directly into electricity are attracting attention as they potentially produce high output power densities. Owing to its capability to convert with a Carnot efficiency, an optimization of these cells is essential to further enhance their performance and efficiency. This paper focuses on the optimization of p-type emitter thickness of Gallium Antimonide (GaSb) based TPV cell using Silvaco TCAD simulation software. The simulation works in this paper were validated by having a good agreement with those from the experimental work in terms of the electrical characteristics and efficiency of the GaSb TPV cell. Further simulation was done with different p-type emitter thicknesses ranging from 0.15 µm to 1.20 µm. It was demonstrated that the open circuit voltage (V_{oc}) of the cell increases while the short-circuit current density (J_{sc}) decreases with increasing p-type emitter thickness. Since the rate of increasing V_{oc} is faster than that of decreasing J_{sc}, higher maximum power efficiency was obtained at an optimum thickness of 0.85 µm. It was found that, under AM1.5 illumination condition, an increment of power efficiency from 5.91 % to 6.63 % was achieved when increasing p-type emitter thickness from 0.15 µm to 0.85 µm.**

Keywords— emitter thickness; Gallium Antimonide; thermophotovoltaic

I. INTRODUCTION

Thermophotovoltaic (TPV) device can be utilized for clean energy conversion from thermal heat into electricity. Recently, the advances in semiconductor materials eventually broaden up the opportunity for the researchers to explore on the use of TPV cells in a wide range of applications. In principle, TPV cells could operate at their optimum efficiency in the condition where the TPV semiconductor energy bandgap spectrally matched to the blackbody spectrum generated by the heat source [1].

Since TPV cells are ideally designed to convert radiation heat from the infrared region, a semiconductor material with a higher cut-off wavelength which corresponds to a lower bandgap energy (typically <0.75 eV) is more desirable to be used as the material for the fabrication of TPV cells [2]. Therefore, research efforts have been focused on group III-V semiconductor materials as they have the possibility of growing lattice-matched compound with bandgap energies ranging from 0.53 to 0.73 eV [3].

The authors gratefully acknowledge the Tenaga Nasional Berhad (TNB) Seeding fund (Project code: U-TG-RD-18-04) and the UNITEN Internal Grant (J510050710) for the access to the simulation software.

At present, Gallium Antimonide (GaSb) material is often regarded as one of the most ideal choices for fabricating an infrared device. This is because of its low bandgap energy (~0.72 eV) which allows the material to absorb photons at longer wavelengths (up to 1720 nm) from the blackbody radiation spectrum. The conventional ways of fabricating GaSb cells are either by Zinc (Zn) diffusion [4] or epitaxial growth [5] method. Numerous researches [6, 7, 8] have been focusing on improving the GaSb cell performance by optimizing various parameters such as doping concentration, layer thickness, and operating temperature. This paper will only focus on the effect of p-type emitter layer thickness of GaSb TPV cells.

Most of the literatures reported that a thin layer of p-type emitter for their GaSb TPV cells was found to be optimum in producing good quantum efficiency. In these studies, the optimum emitter thickness was investigated based on the factors of internal quantum efficiency (IQE), external quantum efficiency (EQE), short-circuit current density (J_{sc}) and open-circuit voltage (V_{oc}). Table I shows the range of p-type emitter thickness studied in previous literatures, their optimum thicknesses as well as the factors they considered for the chosen optimum thicknesses.

TABLE I. TYPICAL FACTORS CONSIDERED IN CHOOSING THE OPTIMUM P-TYPE EMITTER THICKNESS

Range of emitter thickness studied (µm)	Optimum thickness (µm)	Factors considered	References
0.2 to 0.60	0.40	EQE and V_{oc}	[9]
0.0 to 0.40	0.23	J_{sc} and V_{oc}	[5]
0.05 to 0.30	0.18	IQE	[7]
0.05 to 0.10	0.05	IQE	[10]

However, to date, the relationship between the p-type emitter thicknesses of GaSb TPV cell and the maximum power efficiency was not fully elucidated. In this paper, a comprehensive study and detailed analysis were carried out for optimizing p-emitter thickness of GaSb cell. The objective of this work is to investigate the effect of p-emitter layer thickness of GaSb TPV cell on its maximum power efficiency using Silvaco TCAD software as a simulation tool.

II. METHOD OF SIMULATION

Silvaco TCAD software was used as a simulation tool due to its ability to predict the electrical behavior of

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specified semiconductor material. The software consists of a Virtual Wafer Fabrication package which includes ATLAS, BLAZE and Dev Edit modules that allow the user to easily optimize various of parameters on their semiconductor device prior to the fabrication process [11]. In this study, the GaSb TPV cell structure was modeled using Dev Edit interface and further analysis on its electrical characteristic with different p-type emitter layer thicknesses was performed using the ATLAS module.

A. The GaSb-based TPV Cell Structure

Fig. 1 shows the schematic diagram of the GaSb TPV cell constructed using Dev Edit interface. The structure modeled is mostly similar to that of the experimental work done in [4]. In their experiment, a Zn diffusion method was used to form the p-type emitter on the GaSb n-type substrate. Since a Zn diffusion depth of ~0.25 µm was achieved, a thickness of 0.25 µm p-type emitter was used in this simulation.

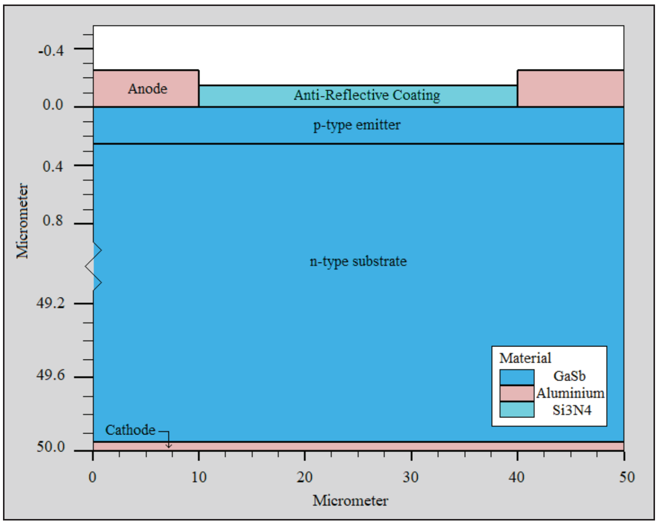

Fig. 1. Schematic diagram of GaSb TPV cell.

The doping concentrations of acceptors (p-type) and donors (n-type) used for our model structure were $2x10^{19}$ cm^{-3} and $3x10^{17}$ cm^{-3} respectively. Since the n-type layer was highly doped, the electric field was formed near the p-n junction. In this case, a thick n-type substrate would not be necessary as it doesn't cause significant difference in the simulation results. In this work, 50 µm of n-type substrate was used. Besides, a 0.15 µm thick Si_3N_4 anti-reflective coating was included in the structure which was similarly deposited to the experimental cell structure done in [4].

B. Material Parameters of GaSb for Simulation

Precise and reliable GaSb material parameters are needed to ensure the validity of the simulation results. Previous studies in [12] and [13] have successfully developed a reliable set of GaSb material parameters as an input for the semiconductor simulation software. In this work, a set of the GaSb material parameters were determined and the values were within the reported range by several literatures. Table II summarizes the material parameters of GaSb cell used in this simulation at an operating temperature of 300 K.

TABLE II. LIST OF GASB PHYSICAL PARAMETERS USED IN THIS WORK AND THEIR VALUES REPORTED IN OTHER LITERATURES

GaSb parameter	**Numerical value**	**Reference**	**Value used in this work**
Intrinsic carrier concentration	$1.7x10^{12}$ cm^{-3}	[12]	$1.4x10^{12}$ cm^{-3}
	$1.405x10^{12}$ cm^{-3}	[13]	
	$1.4x10^{12}$ cm^{-3}	[7], [14]	
Electrons density of states	$5.68x10^{18}$ cm^{-3}	[15]	$2.1\ x10^{17}$ cm^{-3}
	$2.1\ x10^{17}$ cm^{-3}	[16]	
Holes density of states	$2.95x10^{18}$ cm^{-3}	[15]	$1.8\ x10^{19}$ cm^{-3}
	$1.8\ x10^{19}$ cm^{-3}	[16]	
Shockley-Read-Hall lifetime electrons	$10\ x10^{-9}$ s	[12], [7], [13], [14]	$10\ x10^{-9}$ s
	$1\ x10^{-9}$ s	[15], [16]	
Shockley-Read-Hall lifetime holes	$600\ x10^{-9}$ s	[12], [7], [13], [14]	$600\ x10^{-9}$ s
	$1\ x10^{-9}$ s	[15], [16]	
Electrons mobility	6600 cm^2/Vs	[12], [7], [14]	6600 cm^2/Vs
	5650 cm^2/Vs	[13]	
Holes mobility	1250 cm^2/Vs	[12], [7], [14]	1250 cm^2/Vs
	875 cm^2/Vs	[13]	
Auger coefficient	$5\ x10^{-30}$ cm^6/s	[12], [7], [13], [14]	$5\ x10^{-30}$ cm^6/s
Permittivity	14.4	[15], [16]	14.4
Affinity	4.06 eV	[15], [16]	4.06 eV

Another important parameter that shall be considered is the absorption coefficient ($\propto$) of the GaSb material. The $\propto$ determines the percentage of absorbance and the penetration depth of the photons at a particular wavelength in the material. In Silvaco, the absorption coefficient of a semiconductor material is given by equation (1) where λ is the wavelength of the incoming photon and k is the imaginary part of the optical index of refraction for GaSb material.

$$\propto = \frac{4\pi}{\lambda} k \qquad (1)$$

From this equation, it can be clearly seen that the k values are needed as an input parameter to Silvaco simulation. Therefore, the k values used in this work was obtained from a study reported in [17].

C. Model Validation

In order to increase the accuracy of the simulation results, several physical models were used and the Newton numerical solution method was utilized. The physical models used were the Shockley-Red-Hall (SRH) recombination, Auger (AUGER) recombination as well as optical recombination (OPTR) models. More detailed information about these physical models can be found in [11]. The performance analysis was carried out under a standard irradiance spectrum with an air mass of 1.5 (AM1.5) illumination condition. The simulation results obtained in this work were compared to the experimental work done in [4] for validation purposes.

TABLE III. COMPARISON OF PERFORMANCE PARAMETERS

Performance Parameter	**Experiment [4]**	**JX Crystal Inc (JXC) [4]**	**Present work**
J_{sc} (mA/cm^2)	29.0	32.3	26.76
V_{oc} (V)	0.281	0.326	0.316
Efficiency, η (%)	3.90	5.50	6.19

Table III shows the performance comparison between the experimental work done in [4] and the present work. The performance parameters were extracted when the p-type emitter thickness of GaSb TPV cell was at 0.25 µm. It can be seen that the J_{sc}, V_{oc} and η of the proposed model are comparable to those of both experimental work and JXC's GaSb cell, thus confirms the validity of the present work. Since the GaSb model structure was created in Dev Edit interface, the model developed follows an epitaxially grown fabrication's steps. Hence, the simulated results in the present work indicates a smaller J_{sc} value compared to others and a slight increment in η can be observed. As claimed in [5], epitaxially-grown GaSb cells produced better performance than the Zn-diffused GaSb cells.

D. Optimization of p-type Emitter Thickness of GaSb TPV Cell

The validation result shows a close agreement between experimental work and present work, thus validates the set of parameters used in the simulation. Further optimization of the p-type emitter thickness was carried out using thicknesses ranging from 0.15 µm to 1.20 µm. The electrical characteristics and performance of the modeled structure were analyzed for each thickness. The doping concentrations, n-type substrate thickness as well as the physical parameters remained constant throughout the optimization.

III. RESULTS AND DISCUSSIONS

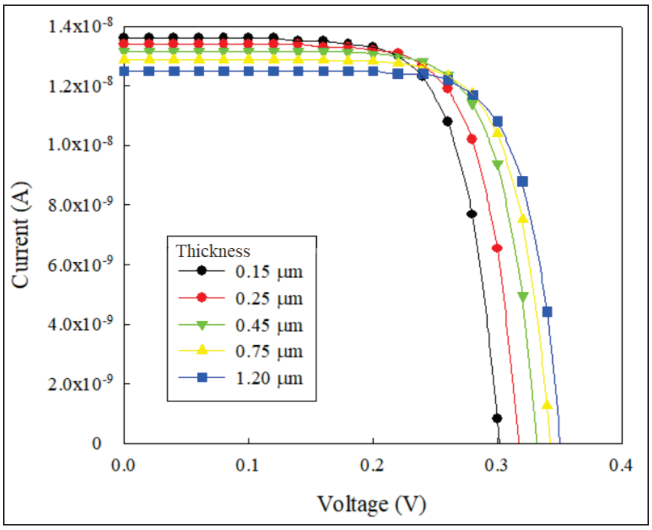

Fig. 2. Current-Voltage characteristic for different p-type emitter GaSb thickness.

Fig. 2 shows the current-voltage characteristic at different p-type emitter GaSb layer thicknesses. The graph clearly shows that increasing the p-type emitter thickness would greatly increase the V_{oc} but slightly reduce the short circuit current of the GaSb TPV cell. These results are similar to those reported by [12] and [14]. Both claimed that the increase in V_{oc} correlates to the decreasing dark current in the GaSb cell. The dark current is commonly defined as the sum of diffusion current defects and generation-recombination current occurs in the depletion region of the p-n junction. As stated in [9], a thick emitters are advantageous as they decrease the dark current in the device due to the influence of the infinite surface recombination at the interface.

In terms of the photocurrent, increasing the thickness of cell layer could intentionally cause an increase in series resistance at the p-n junction interface thus decreasing the short circuit current [18]. Another reason is, thicker p-type emitter layer tends to reduce the spectral response due to higher free-carrier absorption. Additionally, the increase in sensitivity of the front surface minority carrier recombination by thickening the layer would also contribute to the lower I_{sc} generated [19]. Therefore, it is clear that the variation of p-type emitter thickness could affect many crucial parameters which determine the device performance.

To date, most of the optimization of p-type emitter thickness based upon the factors of IQE and EQE. These research studies claimed that thinning of the p-type emitter thickness tends to enhance the quantum efficiency of the device [14, 15, 16]. However, the quantum efficiency only relates to the photocurrent generation by the TPV cell. As per definition, it is the ratio of the number of carriers collected by the TPV cell to the number of photons of a given energy incident on the cell. While the quantum efficiency of the TPV cell is important, thinning the p-type emitter layer would eventually decrease the V_{oc} of the device which contributes to lower power output. Hence, the optimization of p-type emitter of GaSb layer thickness should not be done solely based on either the quantum efficiency or V_{oc}. The optimization should instead consider the overall maximum power output or the overall efficiency.

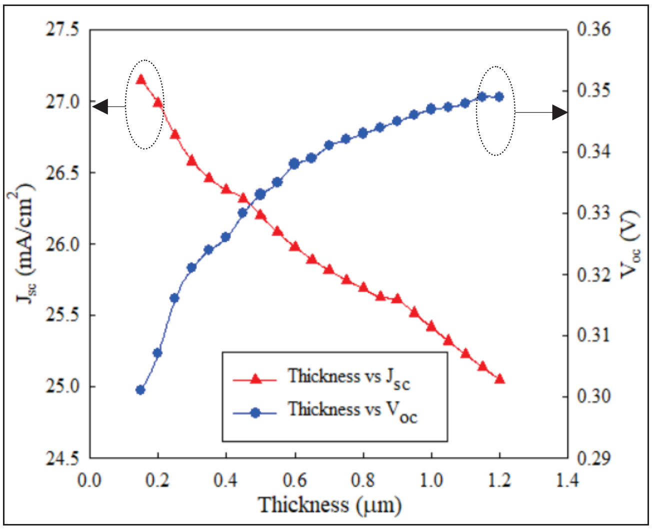

Fig. 3. Effect of p-type emitter thickness on V_{oc} and J_{sc}.

Fig. 3 illustrates the rate of increasing V_{oc} and the rate of decreasing J_{sc} while increasing the p-type emitter thicknesses ranging from 0.15 µm to 1.20 µm. It can be observed that the decreasing rate of J_{sc} was almost constant throughout the range of thicknesses. Whereas, the increasing rate of V_{oc} was higher at the beginning and start to slow down for thicknesses ≥ 0.80 µm. Since the rate of increasing V_{oc} is faster than that of decreasing J_{sc}, the maximum power efficiency would also be increased.

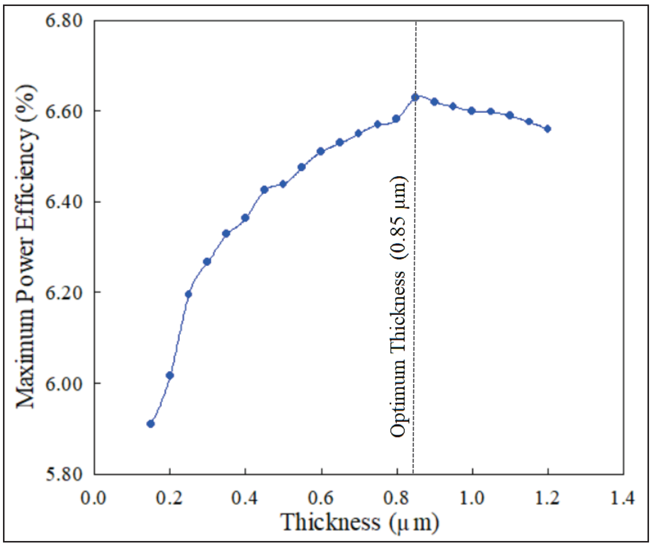

Fig. 4. Effect of p-type emitter thickness on the maximum power efficiency.

Fig. 4 shows the impact of varying the p-type emitter thickness on the maximum power efficiency of the GaSb TPV cell. As can be seen, an increment in power efficiency from 5.91 % to 6.63 % was achieved when the p-type emitter thicknesses were increases from 0.15 µm to 0.85 µm. In this work, the optimal thickness of the p-type emitter was found to be at 0.85 µm, with a maximum power efficiency of 6.63%. This is the optimum thickness where the highest maximum power output can be obtained.

IV. CONCLUSION

The effect of p-type emitter thickness on maximum power efficiency was investigated and presented in this paper. The simulated J_{sc} and V_{oc} values were in a good agreement with those obtained from experimental work and JX Crystal Inc, hence validates the set of parameters used for the GaSb model. A range of p-type emitter thicknesses from 0.15 µm to 1.20 µm were used to analyze the electrical characteristic and performance of the modeled structure. The result shows an increment in maximum power efficiency from 5.91% to 6.63% that is 1% increase in efficiency when the p-type emitter layer thickness increases to 0.85um. It was found that increasing the p-type emitter thickness would eventually increase the V_{oc} of the cell, hence improving the overall power efficiency of the GaSb TPV cell. Instead of considering quantum efficiency as a factor for optimizing the p-type emitter thickness, the results of this work clearly demonstrated that the overall power efficiency is the most suitable performance parameter for the optimization study.

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