The Effect of Illumination Intensity on the Performance of Germanium Based-Thermophotovoltaic Cell

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***Abstract*—The significance of optimizing power intensity in a thermophotovoltaic system had spurred the efforts on exploiting thermophotovoltaic cells which are typically installed near to the heat source. Germanium with 0.66 eV bandgap is recommended and extensively employed to harvest infrared radiation up to 1.8 µm. The integration of this material contributes to a cost-effective thermophotovoltaic system by capturing long wavelength under low blackbody temperature. Contrarily, the atmospheric perturbation between the heat source and the germanium thermophotovoltaic cells affects the intensity of incoming illumination, which alters the electrical performance of the cells. Nonetheless, the investigation of this issue is remained at the infancy stage and more characterization works are required to understand the influence of illumination intensity on the cell conversion efficiency. In this work, Silvaco TCAD software was used to characterize single Ge thermophotovoltaic cell under 2000 K blackbody radiation temperature by manipulating the illumination intensity. A conversion efficiency of 11.8 % was achieved under higher illumination intensity of 2000 K due to the increase in the maximum voltage from 0.19 V to 0.42 V when compared to AM 1.5 illumination condition. The success of this work will contribute to the incorporation of understanding the effect of incident illumination intensity on the performance of Ge cell.**

Keywords—TPV, Germanium cell, light intensity, Silvaco TCAD

I. Introduction

Thermophotovoltaic (TPV) is a device which converts thermal energy from combustion of fuels, waste heat, or nuclear energy into electricity. This device can be implemented in vast range of real-world applications such as vehicle, electrical generator, and aerospace applications. Moreover, the integration of TPV system in thermal power plant and metal-alloy industries is a wise yet viable choice to optimize and enhance the processes of many systems by recycling waste heat within the equipment. The main advantages of TPV system are mechanically stable without moving parts, noiseless, high reliability and large power density per unit area. Additionally, the operation of TPV cell close to the heat source maximizes the illumination of light intensity.

Germanium (Ge) is a semiconductor material with relatively cheaper price than other binary, tertiary or quaternary TPV materials [1]–[3]. The synthesis cost of Ge can be further reduced with hydrogenated amorphous silicon (a-Si:H) over flexible monocrystalline/c-Ge [4,5]. The Ge with typical bandgap of 0.66 eV is able to harvest heat from 1800 K heat source temperature with an efficiency of 25 %, assuming a blackbody energy of 10 W/cm^2 from 0.3 to 1.8 µm wavelengths [6]. Despite being a cost-effective TPV material, Ge shows several limitations such as low open circuit voltage (V_{oc}) [7] and high temperature coefficient [2]. Therefore, an effective cooling system is essential for Ge TPV cells.

Typical Ge solar cell has an V_{oc}, short circuit current (I_{sc}), fill factor (*FF*) and conversion efficiency (η) ranging between 0.203 to 0.26 V, 5 to 50.2 mA/cm^2, 45.7 to 70.68 %, and 5.25 to 8.2 %, respectively under AM 1.5 and AM 1.5 global (G) illuminating condition [1, 5, 8, 10, 11, 12, 13] Crystal quality and fabrication method play an important role in producing high Ge cell performance. Nowadays, approximately 95 % of Ge cell in the market are triple-junction solar cells [13], which are commonly used in concentrated solar cell applications. P. Sansoni et al [3] designed an elliptical optical cavity for combustion and tested with Ge TPV cell because Ge-based photodiode has lower cost in contrast to other compounds such as InAs or InGaAsSb. Under the concentration of 25 sun at AM 1.5 illuminating condition, an V_{oc}, I_{sc} and *FF* of 0.34V, 0.89 A/cm^2 and 68 % respectively were reported. V. P. Khvostikov et al [7] reported the utilization of back surface reflector with return efficiency of 90 % in Ge-based TPV cell to achive an η of 11.5 % under 2000 K blackbody temperature.

The output current density of typical concentrated solar cells is linearly increased with light intensity [3]. On the other hand, the effect of illumination intensity in TPV cells has not been precisely characterized. The amount of illumination intensity in a TPV system is primarily affected by the heat source temperature. The maximum illumination intensity is expected as the distance and contamination between the TPV cells and the blackbody source are reduced to nearly zero. To date, the investigation of the effect of incident illumination intensity by adjusting the distance between the heat source and the TPV cell is yet to be investigated.

The aim of this paper is to characterize the influence of illumination intensity on the performance of Ge TPV cell

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using TCAD Silvaco software. In this work, the characterization of Ge TPV cell under 2000 K heat source temperature and varying illumination intensity was conducted to acquire the most suitable illumination intensity that generates the highest *FF* and .

II. Experimental Details

The electrical behavior of Ge structure was obtained using TCAD Silvaco software. This software has the ability to predict the electrical behavior of TPV cell, analogous to a real cell. The software consists of a Virtual Wafer Fabrication package which includes ATLAS, BLAZE and DEV EDIT modules. These modules allow the users to develop a computer model of a TPV cell which is designed to absorb infrared radiation from an illuminated condition. In this study, the physical structure of Ge cell was designed using Dev Edit module, whereas the electrical characterization under 2000 K heat source temperature illumination spectrum with varying percentages of illumination intensity was conducted using ATLAS interface.

A. *Ge Structure*

Fig. 1 re-presents the schematic diagram of the Ge design as extracted from the TonyPlot. The Dev Edit was used to design a single-junction n-p Ge cell based on real fabrication work as reported in [12]. The real fabrication in [12] was done using low pressure metal-organic vapour-phase epitaxy (MOVPE) with isobutylgermane (IBuGe) as precursors. The thickness (doping) of n-emitter and p-base were fixed at 0.05 µm (2 $\times 10^{19}$ cm^{-3}) and 5 µm (2 $\times 10^{18}$ cm^{-3}), respectively. An n-InGaP window layer with thickness of 0.03 µm and doping of 2 $\times 10^{19}$ cm^{-3} was used to avoid high surface recombination rates and create Fermi level pinning. Next, an 0.3 µm thick, highly doped n-GaAs cap layer with 5 $\times 10^{18}$ cm^{-3} doping concentration was used to form an ohmic contact between the anode and the n-p junction. Finally, gold layer was formed to cover 15 % of the front-side and entire rear-side of the entire structure [2].

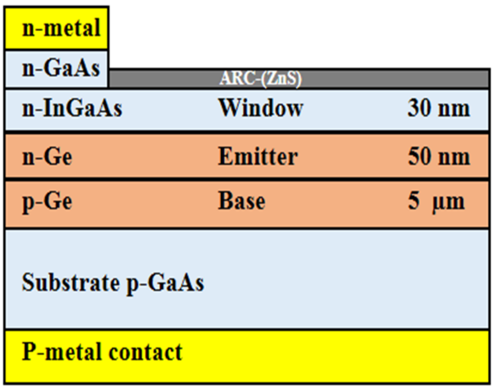

Fig. 1. Schematic diagram of Ge structure.

B. *Ge Parameters*

After the physical design of the single Ge structure was completed, the parameters of Ge, GaAs and InGaP layers were tabulated based on previous experimental and simulation works to validate the simulated results. The simulation results were conducted with different sets of Ge, GaAs, and InGaP parameters [4,11,15,16]. Table I shows the selected parameters used to simulate the Ge cell.

TABLE I. Selected Parameters of Ge, GaAs and InGaP Used in This Work

parameters	Ge		GaAs		InGaP	
	Value	ref	value	Ref	value	Ref
Band-gap (eV)	0.664	[4] [8] [11]	1.43	[16]	1.86	[15]
Permittivity	16	[17]	12.9		11.6	[14]
Affinity (eV)	4.13	[18]	4.07	[19] [14] [18]	4.16	[14]
Effective density of state (conduction band) N_c (cm^3)	1.04x10^{19}	[20]	4.7 x10^{17}	[15] [21] [19]	1.3x10^{20}	[14] [19]
Effective density of state (valance band) N_v (cm^3)	6 x10^{18}	[20]	7x10^{18}	[15] [19]	1.3x10^{19}	[14] [19]
Carrier lifetimes (s)	N=1x10^{-4} P=1x10^{-4}	[22]	N=2 x10^{-8} P=1 x10^{-9}	[14]	N=1 x10^{-9} P=1 x10^{-9}	[15] [14]
Mobility (cm^2/Vs)	N=3895 P=2505	[23]	N=8000 P=400	[19] [21] [14]	N=2500 P=141	[15] [14]

The N_c and N_v of Ge, GaAs and InGaP materials can be calculated using Equation (1) and Equation (2):

$$N_c = 2(\frac{2\pi m_e^* kT}{h^2})^{3/2} \quad (1)$$

$$N_v = 2(\frac{2\pi m_h^* kT}{h^2})^{3/2} \quad (2)$$

where k is Boltzmann's constant (1.38 $\times 10^{-23}$ J/K), h is Plank's constant (6.626 $\times 10^{-34}$ m^2 kg/s), m^*_e and m^*_h are electron and hole effective masses of the materials [24]. Based on the calculation, the N_c and N_v of Ge are ranging between 5.67 $\times 10^{17}$ to 5.08 $\times 10^{19}$ cm^3 and 2.24 $\times 10^{17}$ to 4.75 $\times 10^{18}$ cm^3, respectively. The selected values in Table II are within the calculated range which supports the legitimacy of the band diagram. Similar calculation was repeated to determine the range of the N_c and N_v of the InGaP window and GaAs cap layers to validate the selected values in Table II and generates the complete band diagram of the Ge structure.

C. *Model Validation*

The simulation results were validated by having comparable electrical characteristics to the experimental results of the Ge photovoltaic cells in [12]. Newton mathematics method with models such as Shockley-Red Hall recombination, Auger recombination and radiative recombination were utilized to the simulation. The selection of these method and models enables the DeckBuild's Interface, whereby the validation analysis was performed under AM 1.5G illumination condition. An absolute η error of 0.08 % between the experimental and simulation was generated, with a minor deviation of 1.22 % for η (between the experimental η of 6.57 % and simulation η of 6.65 %).

D. *Characterization of Light Intensity in Ge TPV Cell*

Upon the completion of model validation, the illumination intensity analysis was performed on the similar structure. Initially, a blackbody source at 2000 K with 100 % illumination intensity was used as the radiation source for the Ge TPV cell. The illumination intensity was designed from 100 % (36.59 W/cm^2) down to 10 % (3.66 W/cm^2), with the intervals of 10 %. The cell temperature was maintained at 300 K, assuming an effective cooling system was deployed. A perfect filtration for wavelength longer than 1.8 µm was implemented in the simulation. The power density of 2000 K blackbody temperature decreases from 90.726 W/cm^2 to 36.592 W/cm^2 after using the filter.

III. Results and Discussion

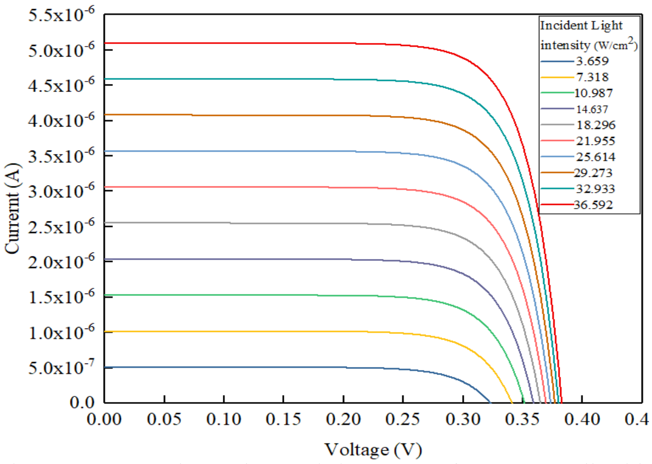

Fig. 2. Current-Voltage characteristic curves of Ge TPV cell with different illumination intensity under 2000 K heat condition.

Fig. 2 presents the electrical performance of Ge TPV cell as a function of different illumination intensity at 2000 K blackbody temperature. The J_{sc} and the V_{oc} increase proportionally to the increasing illumination intensity. This phenomenon was previously observed in numerous concentrated solar cells [3,9]. For instance, the V_{oc} of a triple-junction (GaInP/GaInAs/Ge) increases from 2.70 V to 3.28 V when the concentration of the suns is increased from 1 to 1000 at AM1.5G condition. The Ge in the bottom layer possesses an increment of 73 % in V_{oc} from 0.26 V to 0.45 V [25]. The enhancement of V_{oc} under the effect of high intensity has been comprehensively concluded from numerous works [9,28]. Based on [29,30], the TPV cells are installed in perpendicular position to the blackbody source with view factor of approximately one. The intensity of incoming illumination from the heat source is primarily dependent on two factors: the heat source temprature and the distance between TPV cells and heat source (D). An experimental work of GaSb TPV cell was studied by controlling D between 1.1 cm to 3.8 cm [29]. Based on the experimental findings, shorter D increases the J_{sc} but also decreases the V_{oc} under the effect of cell temperature.

As expressed in Equation (3), J_{sc} is proportional to both the external quantum efficiency (*EQE*) and light intensity. *EQE* presents the ability of cells to convert available photons into electricity. Since *EQE* was kept constant by sustaining the physical and optical parameters of Ge cell, the J_{sc} increases linearly with the increasing percentage of absorbed light intensity ($j_{y,Tbb}$), which is translated into direct growth of the power output. On the other hand, the slight increment in the V_{oc} is considered to be the main reason to improve Ge cell efficiency [9],[32]. The V_{oc} is improved either by increasing J_{sc} or decreasing dark current (J_o). Despite that TPV materials have high J_o, $j_{y,Tbb}$ is always larger than J_o. Therefore, higher V_{oc} is attained due to higher illumination intensity as shown in equation (3).

$$J_{sc} = -e\int_{V_g}^{\infty} dj_{y,Tbb}(hw) = -e\, j_{y,Tbb} \quad (3)$$

$$V_{oc} = \frac{kT_{cell}}{e}\ln\left(\frac{J_{sc}}{J_o}+1\right) \quad (4)$$

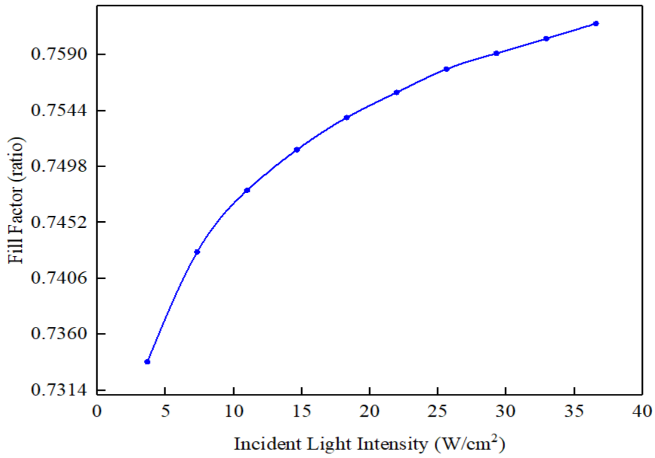

Fig. 3. Fill factor of the Ge TPV cell versus incident light intensity at 2000 K heat source temperature.

Fig. 3 illustrates the effect of increasing the percentage of intensity on the *FF*. Briefly, the *FF* increases as the illumination intensity of the blackbody increases. In [31], the author discussed on the improvement of V_{oc} with higher *FF* values and vice versa. However, the V_{oc} is not the only factor which increases the *FF*. Indeed, maximum voltage (V_m) also acts significantly to improve the *FF*. Equation (5) represents a better insight to investigate the relationship between *FF* and illumination intensity. As shown in Fig. 3, the *FF* is growing as the illumination intensity increases due to low resistance losses for blackbody temperature lower or equal to 2000 K. Moreover, higher cell efficiency is achieved with higher *FF*.

$$FF = \frac{V_m * J_m}{V_{oc} * J_{sc}} \quad (5)$$

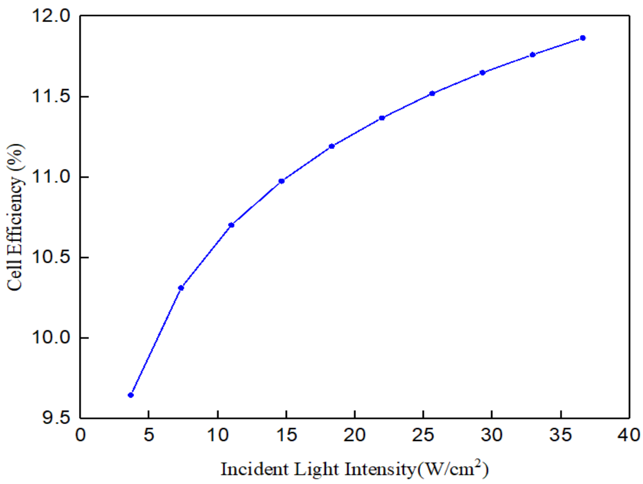

Fig. 4. Conversion efficiency of the Ge TPV cell versus incident illumination intensity at 2000 K heat source temperature.

Fig. 4 shows the effect of increasing the percentage of intensity on the Ge cell efficiency. Based on Fig. 2, a linear increase in the light intensity is neutralized by a linear increase in the J_{sc}. On the other hand, the cell efficiency grows with the intensity by the logarithmic increase in the V_m. According to Fig. 4, the $\boldsymbol{\eta}$ is increasing in faster manner for lower illumination intensity between 3.7 to 20 W/cm^2. This is attributed to small resistance losses under lower illumination intensity. The η is proportional to the *FF* ratio under the effect of resistance losses as shown in Equation (5), where P_{in} is the incident power of the Ge cell. The maximum *FF* and η achieved under 2000 K blackbody with 100 % intensity condition. These results did not consider the effect of ambient temperature on the TPV Ge cell. In real testing condition both *FF* and η are expected to decay as cell temperature increases.

IV. CONCLUSION

In conclusion, a Ge TPV cell was successfully modelled with TCAD Silvaco software. The V_{oc} and I_{sc} of Ge TPV cell increase proportionally with the linear increment of light intensity under 2000 K. Aside from V_{oc}, the V_m is also increased with higher light intensity. The V_m is limited by the series resistance. For blackbody temperature of 2000 K, both η and *FF* are gradually increased with high incident illumination intensity 22 to 36.6 W/cm^2 under the effect of larger series resistance. In summary, further research on improving the effect of light intensity in Ge TPV cell under high blackbody temperature will help to provide a concrete idea to researcher and manufacturer on the development of Ge TPV system.

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