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Simulation of the extra-terrestrial and terrestrial performance of GaAs/Ge dual-junction solar cells

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Abstract

The performance of GaAs/Ge dual-junction solar cells is studied in extra-terrestrial and terrestrial conditions using the full simulation approach. Simulations consist of solar radiation modelling and the electronic transport modelling of each subcell. Simulation result shows that the efficiency of the solar cells in the extra-terrestrial condition is 31.91%, while in the terrestrial condition, the efficiency is 35.24%. Although the solar cell efficiency in the extra-terrestrial condition is lower, it produces more electricity because a larger amount of solar radiation illuminates the first subcell (GaAs). It is found that for an area of 1.0 m^2 of GaAs/Ge solar panel, about 419.2 watts of electric power are generated in the extra-terrestrial condition as compared to 314.34 watts in the terrestrial condition.

Keywords: Dual-junction solar cells; extra-terrestrial; GaAs/Ge; PC1D simulation; terrestrial.

1. Introduction

The use of earth orbiting satellite plays a vital technical role in assisting various modern human needs, such as data communication, spatial data information, military defense, and remote sensing. In modern agriculture, satellites have been used to map the area of cultivation, to monitor plant growth (Chen *et al.*, 2011; Onojeghuo *et al.,* 2018). This allows for the observation of variations in soil parameters (Anguela *et al.,* 2010) and deforestation rates (Achard *et al.,* 2010). Almost every aspect of modern life is affected by geosynchronous orbiting satellites. Therefore, sustainable development of satellite technology is necessary. One important aspect of this technology includes research on energy resources for satellites.

Satellites usually use solar cells as their primary source of energy. Solar cells for space application are mostly based on III-V based multijunction solar cells. The III-V based materials have been crucial in the development of many technological application such as in LEDs, solar cells and diodes (Lu *et al.,* 2013; Dimroth *et al.,* 2016; Mantarci & Kundakçi 2019). The multi-junction solar cells are mostly based on III-V group elements and are composed of several subcells to maximize the absorption of the solar radiation spectrum. These types of solar cells can reach up to 46% efficiency, as reported by Fraunhofer's group (Dimroth *et al.,* 2016). Some examples of MJSC systems are InGaP/GaAs (Singh & Sarkar, 2012), GaAs (Makableh *et al.,* 2014), GaInP/GaAs/Ge (Wu *et al.,* 2018). Alternatively, concentrators can be added to multiply the amount of incoming radiation to increase the efficiency of solar cells (Kinsey *et al.,* 2008; Fernández *et al.,* 2013).

The GaAs-based solar cells are more favorable than silicon-based for space vehicle applications because they are more efficient and have better material resistance to thermal and mechanical degradation that occurs in their environments (Polman *et al.,* 2016). Higher electron mobility and a saturation rate of GaAs materials allow solar cell efficiency to top the 25% limit.

Multi-junction solar cells use several subcells (or layers of solar cells) which are arranged sequentially in order to absorb solar energy in various spectrum ranges. The top layer absorbs radiation energy in the short wavelength's range, while the next layer absorbs radiation in the longer wavelengths (Sumaryada *et al.,* 2013; Sumaryada *et al.,* 2019). Fabrication of thin film multi-junction solar cell needs an advanced deposition technology such as a laser deposition technique (Mantarci *et al.,* 2017; Kokaj *et al.,* 2018). As a consequence, fabricating many junctions in solar cell is complicated, so its commercialization will take longer. In that situation, dual-junction solar cells can be a good choice due to their ability to absorb more spectral irradiance as compared to a single junction solar cell. The benefit is that they only consists of two subcells. In GaAs/Ge dual-junction solar cells (DJSC), the gallium-arsenide layer absorbs the solar radiation from 100 nm to 885.6 nm, while germanium absorbs from 100 nm to 1550 nm.

Simulating the solar cell performance can be carried out using a variety of software such as PC1D (Basore & Clugston, 1996), SCAPS1D (Burgelman *et al.,* 2000) or GVPDM (MacKenzie *et al.,* 2016). These modelling software programs, generally use a simple physical model, such as a single diode model and the standard semiconductor's electronic transport equations. In this research, we simulate the performance of dual-junction GaAs/Ge solar cells in terrestrial and extra-terrestrial conditions using MATLAB and PC1D simulations. For simplicity, some assumptions and idealizations were made in this simulation including: (i) The effects of cosmic radiation on solar cell performance were disregarded; (ii) The temperature of the solar cells in the terrestrial condition was set to a standard condition of 300 K, while in the extra-terrestrial condition, it was assumed that the temperature in outer space is 276 K (3.0 ºC). Solar panels for satellites are typically designed to survive temperatures between -100º C to 125º C (Pisacane, 2005). By assuming that some temperature controller is used in the system, it is quite safe to assume that the average working temperature in the extra-terrestrial condition is 3.0 ºC; (iii) The series connection of subcells (identical current model) was used by enforcing the same value of current flows in each subcell; (iv) The tunnel junction between the two consecutive junctions (GaAs and Ge) was not taken into account; and, (v) The detailed structure, durability and the stability of each subcell under a realistic condition were not taken into account. Our simulation only gives a general idea of the performance of two mechanically-stacked semiconductor subcells. The performance of each subcell is independently investigated. The only connection between those subcells is the amount of radiation transmitted from the first to the second subcell, which is simulated using a simple Beer-Lambert's type equation that only requires the absorption coefficient data and the thickness of each subcell.

The electrical performance of GaAs/Ge in extra-terrestrial and terrestrial conditions will be presented in the results and discussions section. The performances discussed are the power production parameters: short-circuit current, open circuit voltage, fill factor, and the total efficiency of solar cells. The results are not intended to propose a precise design of GaAs/Ge solar cells which is ready for fabrication or commercialization. This paper only focused on simulating the performance of GaAs/Ge solar cells in idealized conditions.

2. Materials and methods

To begin the simulation, the incoming spectral irradiance on the surface of the first subcell was prepared by using the blackbody radiation model. The following equation was used (Sumaryada, *et al*., 2013):

$$I(\lambda)=\frac{2\pi hc^2}{\lambda^5\left(\exp\left(\frac{hc}{k_B\lambda T}\right)-1\right)}\,, \tag{1}$$

where $I(\lambda)$ is the spectral irradiance (W/m^2.nm), λ is the wavelength of electromagnetic radiation (light), and T is the temperature of the black body radiation (set at 5772 K). The values of other constants, h, k and c, are Planck constants (h = 6.626 x 10^{-34} J.s), the Boltzmann constant (k_B = 1.38 x 10^{-23} J/K) and the speed of light (2.998 x 10^8 m/s). The amount of radiation in earth's geosynchronous orbit is calculated using this relation:

$$I_{geo}(\lambda)=\left(\frac{R_S}{R_{SG}}\right)^2 I(\lambda)\,, \tag{2}$$

where R_{SG} is the distance between the center of the sun to the geosynchronous orbit of the earth, and R_S is the sun's radius (6.957 x 10^5 km). The R_{SG} can be calculated by subtracting the earth's average distance to the sun (149.6 x 10^6 km) with the radius of the earth's geosynchronous orbit (3.5786 x 10^4 km) and the earth's radius (6.371 x 10^3 km). For the terrestrial condition, the incoming radiation to the first subcell was taken from the AM1.5D spectrum data (ASTM-G173) with a total intensity value of 892 W/m^2. The absorption coefficient (α) of GaAs is calculated using the direct-bandgap model following this equation:

$$\alpha(h,\upsilon)=A\sqrt{h\upsilon-(E_G\mp\Delta)}(cm^{-1}). \tag{3}$$

As for Ge, the indirect-bandgap equation is calculated by Equation (4):

$$\alpha(h\upsilon)=\alpha_a(h\upsilon)+\alpha_e(h\upsilon)(cm^{-1}) \tag{4}$$

The optical band gap of the material, E_G is 1.42 *eV* for GaAs, and 0.67 *eV* for Ge (Basore & Clugston, 1996; Sumaryada *et al*., 2017) The α_a and α_e parameters are the absorption coefficient and photon emissions, respectively. The constant A is calculated using the Equation (5):

$$A=\frac{q^2X_{\upsilon c}^2}{\lambda\varepsilon_0 n\hbar^3}\left(\frac{2m_{hf}m_{ef}}{m_{hf}+m_{ef}}\right)^{3/2}(eV^{-1/2}m^{-1}), \tag{5}$$

where q is the electron charge, λ is the wavelength, ε_o is the permittivity of vacuum, n is the refractive index, $\hbar$ is $h/2\pi$, and m_{hf} and m_{ef} are the effective masses of holes and electrons. X_{vc} is a constant whose value is adjusted to the experimental data and has the same order as lattice constants (in Angstrom scale).

The power-producing simulations are carried out using a PC1D simulator to calculate the basic output of solar cells, such as the short-circuit current, I_{SC}, the open-circuit voltage, V_{OC}, and the maximum power produced by solar cells, P_{max}. The total efficiency of dual-junction solar cells GaAs/Ge can be calculated using a simple approach:

$$\eta = \frac{P_{out1} + P_{out2}}{I_0} \times 100\% \ , \tag{6}$$

where P_{out1} is the output power of the GaAs subcell, P_{out2} is the output power of the Ge subcell, and I_0 is the incoming solar power fall on the first subcell. The Fill Factor (FF) is defined as the ratio between the installed power produced by the solar cells ($P_{max} = P_{out1} + P_{out2}$) with the maximum power in theory ($FF = P_{max} / V_{OC} \cdot I_{SC}$). It represents the overall performance and the quality of particular solar cells.

3. Results and discussions

Simulation of the solar radiation spectrum at earth's geosynchronous orbit was carried out using the blackbody equation. It produced a continuous spectral irradiance. The total radiation intensity received at this extra-terrestrial position was 1313 W/m^2, and it was conducted by calculating the area under the curve (Figure 1). As a comparison, the amount of radiation intensity received in the terrestrial position (on the earth's surface) from AM1.5G (global) and AM1.5D (direct) data also given in Figure 1. For the AM1.5G spectrum, the total intensity was 993 W/m^2, while for AM1.5D, it was 892 W/m^2.

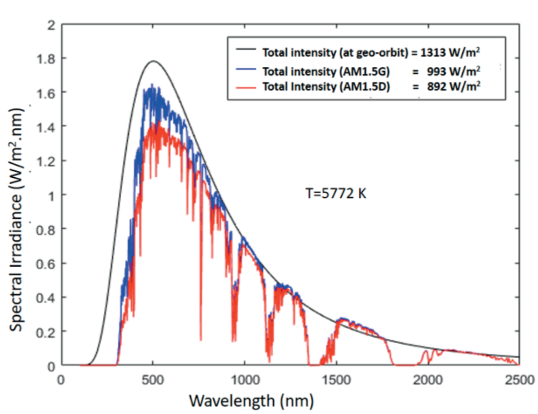

Fig. 1. The comparison between blackbody spectrum in geosynchronous orbit with terrestrial spectrums (AM1.5G & AM1.5D)

In this study, we used the experimental data of the absorption coefficient from the GaAs Handbook (Palik, 1985) to generate the absorption coefficient model using Equations (3) and (4). The absorption coefficient model (Figure 2) was then applied to the PC1D program to produce the electrical performance of solar cells, such as I_{SC}, V_{OC}, P_{out}, and the total efficiency. During the fitting process, the edge of the absorption coefficient data and the cutoff wavelength of each subcell (885.6 nm for GaAs, and 1550 nm for Germanium) had to be carefully taken into account, since they determine the amount of transmitted spectrum and intensity in each subcell.

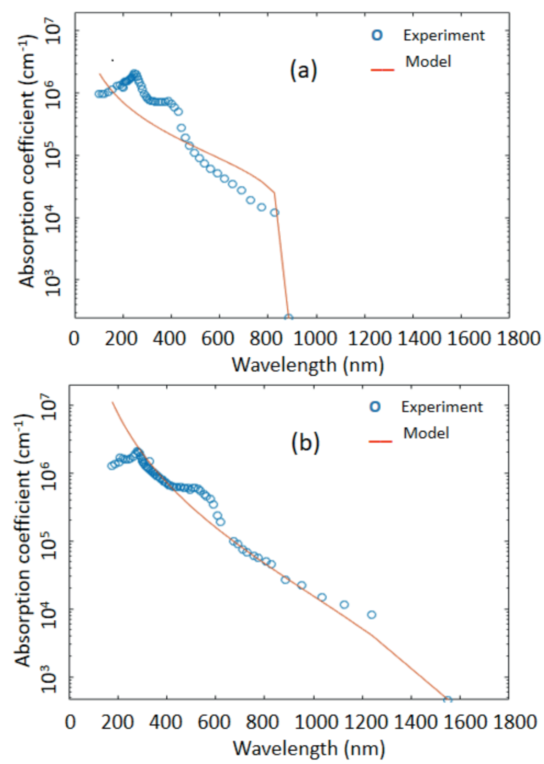

Fig. 2. The comparison between experimental data of absorption coefficient (Palik., 1985) with fitting (simulation) model for (a) GaAs and (b) Ge subcell.

The appropriate setting of physical parameters was made by utilizing the quick-batch menu on PC1D. By varying the doping, thickness, and junction depth, the set of parameters which maximizes the output power of GaAs/Ge DJSC could be determined (Table 1). Note that for the simplicity of the simulation, the surface area used was 1.0 cm^2. In the discussion of the results, the area is scaled up to 1.0 m^2. From those parameters, the schematic model of the optimized design of GaAs/Ge DJSC could be illustrated (Figure 3).

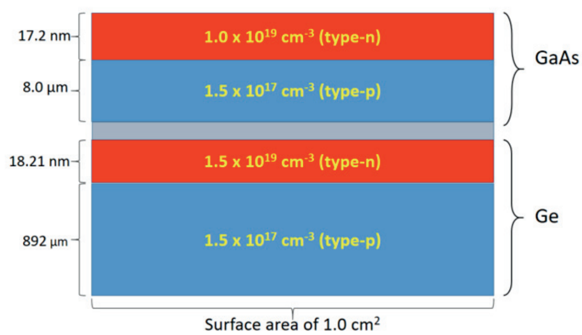

Fig. 3. The design of GaAs/Ge DJSC (not to scale) for geosynchronous orbiting satellite as optimized by PC1D program

The optimum performance of GaAs/Ge dual-junction solar cells in the geosynchronous orbit is shown in Table 2. A different simulation temperature was implied on each subcell (T = 353 K for GaAs and, T = 276 K for Ge). The first subcell was directly exposed to solar radiation, and it was assumed to have a higher temperature as compared to the second subcell located at the bottom of the solar cells.

from the first subcell to the second subcell dissipates and becomes a power loss in the form of heat. In this simulation, the first and second subcell were connected in a series so that the current values flow in both subcells had to supposedly be identical. However, it is difficult for the PC1D simulations to produce such an identical current. There is still 4.90 mA (or 12.6%) difference of I_{SC} between the first and second subcell.

The simulation's results for fill factor show that the first subcell has a better performance (86.75%) as compared to the second subcell (74.8%). It was confirmed by the current-voltage characteristic of solar cells (Figure 4). Here, the second subcell received a smaller current and voltage (34 mA and 0.99984 V) compare to GaAs (38.9 mA and 0.32158 V). The results for the fill factor, (V_{OC} and I_{SC}) and total efficiency are in reasonable agreement with the results of other GaAs/Ge and GaAs/Si DJSC (Bouzazi *et al.,* 2018; Khan & Khan, 2018).

Table 1. The optimum PC1D's physical parameters for each subcell under extra-terrestrial conditions (earth's geosynchronous orbit)

Subcell	Temperature (Kelvin)	Area (cm^2)	p-type (cm^{-3})	n-type (cm^{-3})	Background thickness p-type (µm)	The junction depth of n-type (nm)
GaAs	353	1.0	1.5×10^{17}	1×10^{19}	8	17.2
Ge	276	1.0	1.5×10^{17}	1.5×10^{19}	892	18.21

Table 2. The output of solar cells in extra-terrestrial condition (panel area of 1.0 cm^2)

Subcell	V_{OC} (Volt)	*Isc* (A)	P_{max} (Watt)	Fill Factor (%)	Incoming radiation power 100-2500 nm (Watt)	Relative efficiency
GaAs	0.99984	-0.0389	0.03374	86.75	0.1313	25.70%
Ge	0.32158	-0.0340	0.00818	74.8	0.0432	18.93%

From Table 2, it can be observed that V_{OC}, P_{out}, and the relative efficiency of the first subcell (25.70%) is higher than the second subcell (18.93%). This result is expected because the radiation energy that arrives at 1.0 m^2 of the second layer (432 Watts) is smaller than in the first layer (1313 Watts). The amount of radiation transmitted

The maximum efficiency of GaAs/Ge DJSC in extra-terrestrial condition can be calculated using a similar method as in Equation (6). It can be expressed as

$$\eta_{extra-terrestrial} = \frac{(0.03374+0.00818)}{0.1313}\times100\% \\ =31.93\% \tag{7}$$

As an illustration, if we were to scale up the surface area of GaAs/Ge DJSC to 1.0 m^2, the solar panel would receive radiation power of 1313 Watts and convert it into 419.2 Watts of electrical power.

For a terrestrial condition, the output performance of GaAs/Ge solar cells is shown in Table 3. By using the same PC1D's physical parameters as seen in Table 1 (except the temperature of the whole subcells are set to 300 K), some interesting features showed up in the terrestrial simulation. Even though the electric power generated by the first layer has a higher relative efficiency (29.82%) than in the extra-terrestrial conditions (25.70%), the total electricity produced in 1.0 m^2 is much smaller (266 Watts). This finding is natural since the amount of radiation energy arrived at one square meter of the first subcell under the terrestrial condition was smaller (892 Watts) than in extra-terrestrial conditions (1313 Watts). On the other hand, the relative efficiency of the second subcell in the terrestrial condition was smaller (15.74%) than the extra-terrestrial one (18.93%). These data were confirmed by the result from the fill factor (70.57 % in terrestrial and 74.8 in extra-terrestrial condition). Another research study on GaAs/Ge DJSC (Bouzazi *et al.,* 2018) has reported 81.3% of the fill factor, 29.89% solar cell efficiency, 29.70 mA of I_{SC}, and 1.238 Volt of $V_{OC.}$ An interesting finding in this study is that the first subcell performs better in the terrestrial condition. This is in contrast to the second subcell which performs better in the extra-terrestrial condition. A higher operating temperature applied to the first subcell in the extra-terrestrial condition slightly downgrades the electrical performance of GaAs, which is reflected by a lower fill factor and relative efficiency.

The maximum efficiency of solar cells in terrestrial condition can be calculated using the relation:

$$\eta_{terrestrial} = \frac{(0.0266 + 0.004832)}{0.892} \times 100\%$$

$$= 35.24\% \tag{8}$$

As an illustration, for 1.0 m^2 of GaAs/Ge DJSC in terrestrial condition, the solar panel would receive radiation power of 892 Watts, which would be converted to 314.34 Watts of electrical power.

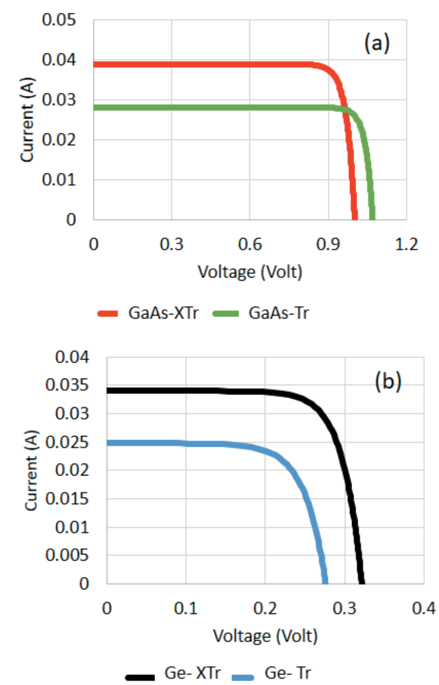

Fig. 4. The voltage-current curve of (a) GaAs subcell in extra-terrestrial (XTr) and terrestrial (Tr) conditions and (b) Ge subcell in extra-terrestrial (XTr) and terrestrial (Tr) conditions

Table 3. The output of solar cells in terrestrial condition (panel area of 1.0 cm^2)

Subcell	V_{OC} (Volt)	I_{sc} (A)	P_{max} (Watt)	Fill Factor (%)	Incoming radiation power 100-2500 nm (Watt)	Relative efficiency
GaAs	1.069	-0.0280	0.0266	88.87	0.0892	29.82%
Ge	0.2761	-0.0248	0.004832	70.57	0.0307	15.74%

A comparison of the electrical performance (current-voltage curves) of each subcell in both exposure conditions is shown in Figure 4. For GaAs, the open circuit voltage (V_{OC}) in extra-terrestrial conditions was smaller than in the terrestrial condition. The opposite occurred in the Ge subcell. The difference in the amount of radiation received by the first subcell in extra- and terrestrial conditions greatly determined the overall electrical performance of GaAs/Ge DJSC.

4. Conclusion

The performance of the GaAs/Ge dual-junction solar cells in extra-terrestrial conditions (geosynchronous satellites application) shows a slightly lower efficiency as compared to the terrestrial application. The temperature differences in the first and second subcell could be the cause of more dissipation of current and energy, which eventually decreases the total efficiency of the solar cells in the extra-terrestrial condition. However, the total electricity produced by one square meter of solar cells in extra-terrestrial conditions is still bigger than in terrestrial conditions. This is due to the far greater incoming solar radiation received by the first subcell in the earth's geosynchronous orbit.

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محاكاة أداء الخلايا الشمسية ثنائية الوصلات من النوع GaAs/Ge في محيط الأرض وخارجها

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الملخص

تمت دراسة أداء الخلايا الشمسية ثنائية الوصلات من النوع GaAs/Ge في محيط الأرض وخارج نطاقها باستخدام نهج محاكاة كاملة. تتكون طرق المحاكاة من نمذجة الإشعاع الشمسي ونمذجة النقل الإلكتروني لكل خلية فرعية. وأظهرت نتائج المحاكاة أن كفاءة الخلايا الشمسية خارج نطاق الأرض هي 31.91%، بينما في محيط الأرض هي 35.24%. بالرغم من أن كفاءة الخلايا الشمسية خارج نطاق الأرض أقل، إلا أنها تنتج المزيد من الكهرباء بسبب وجود كمية أكبر من الإشعاع الشمسي التي تضيء الخلية الفرعية الأولية (GaAs). وقد تبين أنه بالنسبة لمساحة تبلغ 1.0 متر مربع من الألواح الشمسية من النوع GaAs /Ge، يتم توليد حوالي 419.2 واط من الطاقة الكهربائية خارج نطاق الأرض مقارنةً بـ 314.34 واط في محيط الأرض.