Thermal stability analysis of concentrating single-junction silicon and SiC-based solar cells

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Concentrating photovoltaic systems have been used to deliver high electrical power in comparison to non-concentrated solar power systems. Concentrator solar cells provide the possibility of obtaining very competitive cost by substitution of high-band gap materials with silicon. Thus, an economic concentration of power incident on the photovoltaic cell is obtained due to higher thermal stability of materials with higher band gap. In this paper we have analyzed the operation characteristics as well as the thermal stability of silicon and SiC-based solar cells under illumination much higher than one sun. We have shown that the light intensity incident on a solar cell alters the solar cell performance parameters, including the short circuit current, the open circuit voltage, the fill factor, and the efficiency of solar cell due to variation in the device temperature. For this reason we have calculated the temperature-dependence of the material band gap to obtain the current density variation at the temperature range of 300^oK-1100^oK. Then, we have evaluated the temperature dependence of the open circuit and the fill factor, and finally, we have investigated the efficiency and the output power at different temperatures and intensities. It has been concluded that 3C-SiC shows considerable thermal stability for high-intensity, high temperature applications unlike single junction silicon solar cell. The maximum achievable efficiency for silicon-based solar cell decreases from 30% at 300^oK to ~1% at 1100^oK. 3C-SiC has good thermal stability and at the temperature near 700^oK its efficiency surpasses silicon. 6H-SiC as another polytypes of silicon that performs even better at temperatures beyond 1100^oK.

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1. Introduction

Solar cell is an optoelectronic device that can directly convert solar energy into electrical energy. In this field, study of the optoelectronic characteristics of a solar cell as a function of temperature is of great interest. Solar cells are usually operated under terrestrial condition and the operation temperature is typically below 350^oK [1]. Concentrating solar systems use mirrors or lenses to concentrate a large area of sunlight into a small area of solar panels to produce high power. In general, materials used to fabricate concentrators are less expensive than the photovoltaic materials. Concentrators take up most of the area of a concentrator system, and only a small amount of photovoltaic material is needed. One problem of the concentrator systems is the heating of the concentrator cell due to the losses of high energy photons in low band gap materials like silicon [2]. Also, the incident intensity variation on solar cell changes the operation temperature of the device, which in turn, changes the optoelectronic properties of the material, such as the carrier mobility and the optical band gap. Such changes generally affect the solar cell performance in a negative way [3]. Therefore, solar cells in concentrator systems need to have good thermal stability and they should have the ability of working at extreme temperatures specially without active cooling of the solar cells. Silicon solar cells are suitable candidates for terrestrial conditions, however, most of the energy loss in these solar cells is in the form of heat due to the loss of photons with energy exceeding the band gap [2, 4]. Solar cells made from wide band gap materials are more appropriate candidates for this kind of application. Silicon Carbide (SiC) has been recently given renewed attention as a potential material for high temperature applications. SiC is a wide-band gap semiconductor material with high breakdown electrical field, high saturated drift velocity of electrons and high thermal conductivity [5]. SiC polytypes have different band gap values such as 2.2eV for 3C-SiC and 3eV for 6H-SiC [6]. The performance of a solar cell is determined by the parameters such as the short circuit current density (J_{SC}), open circuit voltage (V_{OC}), fill factor (FF), and efficiency (η). However, for determining the solar cell performance, the effect of temperature on these parameters must also be studied.

A single junction solar cell has maximum efficiency at an energy gap of around 1.5eV [7]. Shockley and Quiesser showed that the maximum theoretical efficiency of a single junction solar cell is limited to 33% [8]. However, this limit decreases as the temperature increases.

This paper investigates the temperature dependency of the operation characteristics of silicon, 3C-SiC and 6H-SiC at the temperature range of 300^oK-1100^oK. It is shown that the use of high band gap materials such as 3C-SiC and 6H-SiC can reduce the cost per watt in concentrator systems. This analysis would be especially interesting when there is no active cooling of the solar cells in the concentrating system.

2. Theoretical basis

The temperature dependence of the energy band gap in a semiconductor is described by Varshni model [9]:

$$E_g(T) = E_g(0)-\alpha T^2/(T+\beta) \quad (1)$$

where $E_g(T)$ is the semiconductor band gap energy at temperature T, $E_g(0)$ is the band gap value at T=0°K and α and β are constants. The value of α, β and $E_g(0)$ for silicon and 3C-SiC are listed in table 1 [2, 10].

Considering the changes in the band gap energy, we have calculated the short circuit current density, open circuit voltage (V_{oc}), and conversion efficiency for this solar cell under AM0 spectrum.

Table 1. Energy gap parameters for silicon, 3C-SiC and 6H-SiC

material	$E_g(0)$ (eV)	$\alpha(eVK^{-1})10^{-4}$	β(K)
Silicon	1.155	7.02	1108
3C-SiC	2.2	6	1200
6H-SiC	3	6.5	1200

According to radiative balance, the incident intensity (I) and thermal radiation from the cell are related by:

$$\rho I = (\varepsilon_f + \varepsilon_r)\sigma T^4 \quad (2)$$

where ρ is the ratio of solar absorptivity, ε is thermal emissivity (f and r indicate the emissivity from the front and rear sides of the cell), σ is Stefan-Boltzmann constant and its value is 5.67×10^{-8} W/m^{2}K^4. Thus, temperature is obtained as:

$$T = \left[\left(\rho/\left(\left(\varepsilon_f + \varepsilon_r\right)\sigma\right)\right)I\right]^{0.25} = cI^{0.25} \quad (3)$$

We define the output power as a function of intensity as:

$$p = \left(\eta_{300k} + \frac{d\eta}{dT}\Delta T\right)I = \left(\eta_{300k} - 300\frac{d\eta}{dT} + c\frac{d\eta}{dT}I^{0.25}\right)I \quad (4)$$

where η_{300k} is the efficiency at 300°K.

3. Simulation results and discussion

In this work, we have evaluated three single junction solar cells based on silicon, 3C-SiC and 6H-SiC at different temperatures resulting from the intensity variation due to different concentrating ratios. Hence, our simulation consists both of temperature and intensity variations. First of all the current-voltage characteristics for each cell at temperatures of 300°K and 600°K have been calculated where the obtained results have been shown in Fig. 1. It is clear from these current-voltage characteristics that both current and voltage vary with temperature. The current density gradient in silicon is larger than 3C-SiC and 6H-SiC due to the larger band gap variation slope in silicon and this parameter increases the number of absorbed photons and consequently, enhances the photo-generation of electron-hole pairs in the solar cell. This phenomenon results in higher current density. The open circuit voltage decreases by increasing the cell temperature and the fill factor changes in line with the V_{oc}.

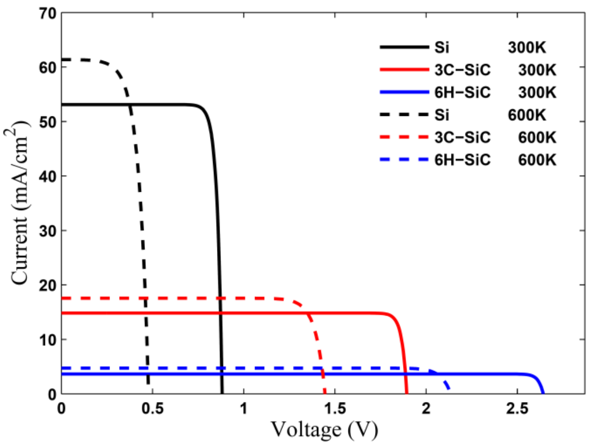

Fig. 1 Current-Voltage characteristics of Si, 3C-SiC and 6H-SiC solar cells at T=300°K and 600°K.

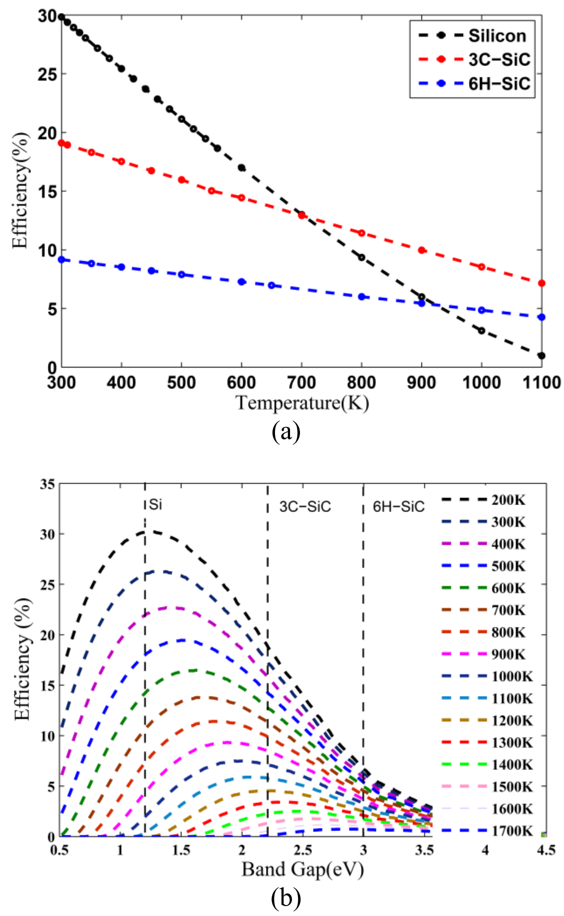

Fig. 2 (a) Efficiency vs temperature for Si, 3C-SiC and 6H-SiC based devices, and (b) Theoretical efficiency of solar cells as a function of band gap.

As the temperature of a solar cell rises, V_{oc} decreases while J_{sc} increases. The net result is a decrease in efficiency which is shown in Fig. 2(a) for the temperature range of 300 ^{o}K -1100^{o}K. The maximum achievable efficiency for silicon-based solar cell decreases from 30% at 300^{o}K to near 1% at 1100^{o}K. 3C-SiC has good thermal stability compared to silicon and at temperatures close to 700^{o}K its efficiency surpasses the silicon's efficiency. Although the efficiency of 6H-SiC is even lower at low temperatures, it shows higher thermal stability compared to silicon and 3C-SiC. We calculated the theoretical efficiency of solar cells as a function of band gap at the temperature range of 200^{o}K-1700^{o}K, with temperature steps of 100^{o}K. The results are shown in Fig. 2(b) where the band gap values of silicon, 3C-SiC, and 6H-SiC have been denoted by vertical dashed lines. It is obvious from this data that, silicon is appropriate for low temperature conditions while 3C-SiC and 6H-SiC can be operated at much higher temperatures more efficiently. Specifically, 3C-SiC and 6H-SiC show interesting properties for high intensity applications in solar panels under high concentration conditions. As it was mentioned before, light intensity alters all cell parameters and changes the solar cell temperature. The normalized generated power for different intensities for each solar cell is shown in Fig. 3 where the intensity has been determined by the number of suns. It can be seen that 3C-SiC and 6H-SiC produce higher output power at higher intensities as a result of good thermal stability compared to silicon. Hence, 3C-SiC and 6H-SiC are appropriate materials for high intensity conditions where efficient cell cooling is not carried out.

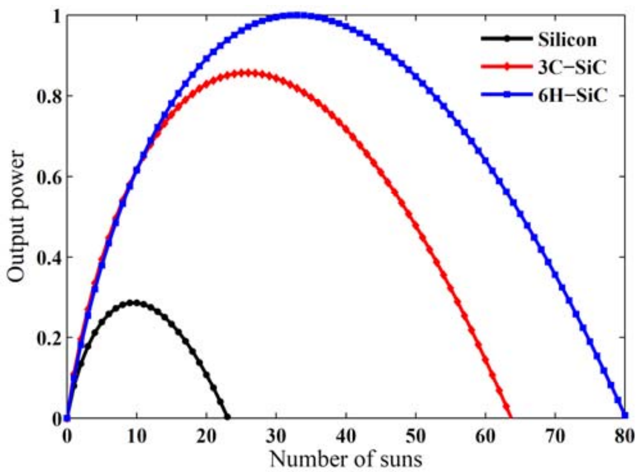

Fig. 3. Output power of Si, 3C-SiC, and 6H-SiC solar cells at different intensities.

4. Conclusions

In this paper, we evaluated single junction solar cells based on silicon, 3C-SiC and 6H-SiC for concentration applications. Our results consisted of efficiency versus temperature and normalized output power versus intensity characteristics of the above mentioned cells. Results showed that 3C-SiC is an appropriate candidate for high temperature operation while 6H-SiC performs better at even higher temperatures.

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