For correspondence
Name: Kensuke Nishioka
Address: Graduate School of Materials Science, Nara Institute of Science and Technology 8916-5 Takayama, Ikoma, Nara 630-0192, Japan
Tel/Fax/E-mail: +81-743-72-6072 / +81-743-72-6079 / ni-kensu@ms.aist-nara.ac.jp

Evaluation of Temperature Characteristics of High Efficiency InGaP/InGaAs/Ge Triple-Junction Solar Cells under Concentration

Kensuke Nishioka[1], Tatsuya Takamoto[2], Takaaki Agui[2], Minoru Kaneiwa[2],
Yukiharu Uraoka[1] and Takashi Fuyuki[1]
[1]Graduate School of Materials Science, Nara Institute of Science and Technology
8916-5 Takayama, Ikoma, Nara 630-0101, Japan
[2]SHARP Corporation
282-1 Hajikami, Shinjo-cho, Kitakatsuragi-gun, Nara 639-2198, Japan

ABSTRACT

Temperature characteristics of the open-circuit voltage (V_{oc}) were investigated in the temperature range from 30°C to 240 °C for the InGaP/InGaAs/Ge triple-junction cells. Also, single-junction cells that had the similar structure to the subcells in the triple-junction cells were studied. In the high-temperature range (from 170°C to 240°C), the temperature coefficients of V_{oc} of the InGaP/InGaAs/Ge triple-junction solar cell (dV_{oc}/dT) were different from those in the low-temperature range (from 30°C to 100°C). This is because photo-voltage from the Ge subcell becomes almost 0 V in the high-temperature range. It was found that the open-circuit voltage of a Ge single-junction cell reduced to almost 0V temperatures over 120°C under 1 sun condition.

KEYWORDS: multi-junction solar cell, temperature coefficient, concentration, Fresnel lenses

1. INTRODUCTION

Multi-junction solar cells consisting of InGaP, (In)GaAs and Ge are known as super-high efficiency and are now used for space applications. The multi-junction cells lattice-matched to Ge substrates have been improved and the conversion efficiency has reached 31% (AM1.5G) by the lattice-matched configuration [1, 2].

Light concentration is one of the important issues for the development of an advanced PV system using high-efficiency solar cells. High-efficiency multi-junction cells under high-concentration have been investigated for terrestrial application [3, 4]. Also, for low-concentration operation, multi-junction cells have been investigated for space satellite use [5-7].

It is considered that the temperature of solar cells considerably rises under light concentrating operations. The solar cells installed in the probes for searching planets located in the short distance from the sun like Mercury and Venus need to operate under the environment of high temperature exceeding 200 ^{o}C. However, temperature characteristics of multi-junction solar cells under concentration have not been evaluated in detail. We evaluated temperature dependence of electrical characteristics of InGaP/InGaAs/Ge triple-junction solar cells under concentration.

2. EXPERIMENT

The light from the solar simulator (Light source: Xe lamp) was adjusted for 1 sun (AM 1.5G, 100 mW/cm^2), and was focused by a Fresnel lens. The concentration ratio was defined by dividing the short-circuit current (I_{sc}) under concentrated light by the I_{sc} under 1 sun illumination. The concentration ratio was varied from 1 sun to 14 suns. The cell was attached to the temperature control stage by solder with high-heat conductivity. The temperature dependences of cell characteristics were investigated in the temperature range from 30°C to 240°C.

Figure 1 shows a schematic illustration of the InGaP/InGaAs/Ge triple-junction cell evaluated in this study. The subcells (InGaP junction, InGaAs junction and Ge junction) were grown on a *p*-type Ge substrate using metal-organic chemical vapor deposition. An $In_{0.49}Ga_{0.51}P$ top subcell, an $In_{0.01}Ga_{0.99}As$ middle subcell, and a Ge bottom subcell are all lattice-matched. Both two tunneling junctions consist of a C-doped AlGaAs and a Si-doped InGaP layers. The cell size was 10 mm x 10 mm. The cell has an optimal electrode structure for 1 sun operation (Grid pitch of electrode: 1020 μ m). Then, the decrease in *FF* (fill factor) due to series resistance was observed under high concentration exceeding 10 suns.

3. RESULT AND DISCUSSION

Figure 2 shows the temperature dependence of open-circuit voltage (V_{oc}) of the InGaP/InGaAs/Ge triple-junction solar cell. For all concentration ratios, V_{oc} decreased with increasing temperature. V_{oc} increased with increasing concentration ratio.

The current density-voltage (*J*-*V*) characteristic of solar cells is given by

$$J = J_0 \left\{ \exp\left(\frac{qV}{nkT} \right) - 1 \right\} - J_{sc}, \qquad (1)$$

where I_0, q, n, k and T are the saturation current, elementary charge, diode ideality factor, Boltzmann constant and absolute temperature, respectively.

From eq. (1), V_{oc} (J=0) is given by

$$V_{oc} = \frac{nkT}{q} \ln\left(\frac{J_{sc}}{J_0} + 1 \right). \qquad (2)$$

From eq. (2), it is considered that the temperature characteristic of the saturation current (J_0) remarkably influences the temperature characteristic of V_{oc}. The J_0 is given by

$$J_0 = q\left(\frac{D_e}{\tau_e}\right)^{1/2} \frac{n_i^2}{N_A}\left\{\frac{S_e(\tau_e / D_e)^{1/2}\cosh(x_p / \sqrt{D_e\tau_e}) + \sinh(x_p / \sqrt{D_e\tau_e})}{S_e(\tau_e / D_e)^{1/2}\sinh(x_p / \sqrt{D_e\tau_e}) + \cosh(x_p / \sqrt{D_e\tau_e})}\right\}$$

$$+ q\left(\frac{D_h}{\tau_h}\right)^{1/2} \frac{n_i^2}{N_D}\left\{\frac{S_h(\tau_h / D_h)^{1/2}\cosh(x_n / \sqrt{D_h\tau_h}) + \sinh(x_n / \sqrt{D_h\tau_h})}{S_h(\tau_h / D_h)^{1/2}\sinh(x_n / \sqrt{D_h\tau_h}) + \cosh(x_n / \sqrt{D_h\tau_h})}\right\}, \quad (3)$$

where n_i is the intrinsic carrier concentration, N_A and N_D are the acceptor and donor concentrations, S_h and S_e are the surface-recombination velocities in the *n*- and *p*-type materials, x_p and x_n are the thickness of the *p*- and *n*-type layers, D_e and D_h are the diffusion constants for electrons and holes, and τ_e and τ_h are lifetimes for electrons and holes, respectively. J_0 depends strongly on the T through its proportionality to the square of the n_i. The n_i is given by

$$n_i^{\,2} = 4M_c M_v (2\pi kT / h^2)^3 (m_e^{\,*} m_h^{\,*})^{3/2} \exp\left(-E_g / kT\right), \quad (4)$$

where M_c and M_v are the number of equivalent minima in the conduction and valence bands, h is Planck's constant, and m_e^* and m_h^* are the effective masses of the electrons and holes, and E_g is the band gap, respectively.

From equations (2), (3) and (4), it is found that the decrease in V_{oc} with increasing temperature arises mainly from changes in n_i. The value of J_0 increases exponentially with decreasing $1/T$, and V_{oc} decreases almost linearly with increasing T. Moreover, the V_{oc} increased with increasing concentration ratio. From eq. (2), V_{oc} will increase logarithmically with radiation intensity [8-11].

In the low-temperature range (from 30°C to 100°C) and the high-temperature range (from 170°C to 240°C), the temperature coefficients of V_{oc} (dV_{oc}/dT) were different. The bordering temperature (at which the temperature coefficient of V_{oc} changed) shifted to the higher temperature with increasing concentration ratio as shown in Fig. 2. The temperature coefficients of V_{oc} (dV_{oc}/dT) were estimated by linear regression, and the bordering temperature was estimated from the intersection of regression lines in the low- and high-temperature range. At 1 sun, the temperature coefficients of V_{oc} were estimated to be -0.0060 V/°C in the low-temperature range and -0.0048 V/°C in the high-temperature range, and the bordering temperature was 119.42°C. On the other hand, the bordering temperature increased to 160.33°C at 14 suns.

In order to investigate the difference of temperature coefficient in the V_{oc} for the triple-junction cells, the temperature characteristics of the single-junction solar cells consisting of InGaP, GaAs and Ge were evaluated. The structures (thickness of each layer, carrier concentration, and so forth) of the single-junction (InGaP, GaAs and Ge) solar cells have striking resemblances to those of each subcell in the InGaP/InGaAs/Ge triple-junction solar cell. The temperature dependence of V_{oc} for the InGaP single-junction solar cell, the GaAs single-junction solar cell and the Ge single-junction solar cell are shown in Figs. 3 (a), (b) and (c), respectively. In all cells, V_{oc} decreased with increasing temperature and increased with increasing concentration ratio. It was found that the V_{oc} of the Ge single-junction solar cell decreased close to 0 V in the temperature range over 120°C at 1 sun.

Figure 4 shows the temperature dependence of current-voltage (*I*-*V*) characteristics in the Ge single-junction cell under 1 sun operation. It was found that the Ge single-junction cell could not operate as a solar cell in the high temperature range over 120^{o}C under the 1 sun condition. However, the V_{oc} of the Ge single-junction cell increased with increasing concentration ratio and the temperature at which V_{oc} became 0 V rose as shown in Fig.3 (c).

Because the V_{oc} of the InGaP/InGaAs/Ge triple-junction solar cell is the sum of the photo-voltages of the top (InGaP), middle (InGaAs) and bottom (Ge) subcell, the temperature coefficient of V_{oc} for the triple-junction solar cell is simply the sum of the temperature coefficients of V_{oc} of the top, middle and bottom subcells. The temperature coefficients for all cells at various concentration ratios are summarized in Table 1. The sum total of the temperature coefficients of V_{oc} of the InGaP, GaAs and Ge single-junction cells agreed well with the temperature coefficient of V_{oc} of the InGaP/InGaAs/Ge triple-junction solar cell in the low-temperature range. Moreover, the sum total of the temperature coefficients of V_{oc} of the InGaP and GaAs single-junction cells agreed well with the temperature coefficients of V_{oc} of the triple-junction solar cell in the high-temperature range.

It is expected that the Ge junction (Ge subcell) is not able to contribute to the photo-voltage of the InGaP/InGaAs/Ge triple-junction solar cell in the high temperature range, and the sum total of the photo-voltages from only the InGaP and the InGaAs junctions dominate the V_{oc} of the triple-junction solar cell in the high-temperature range over 120°C under the 1 sun condition. The bordering temperature increased with increasing concentration ratio as shown in Fig. 2. Therefore, it is expected that the Ge junction can contribute to the V_{oc} of the triple-junction solar cell up to the higher temperature range with increasing concentration ratio.

Figure 5 shows the bordering temperature as a function of concentration ratio. We can predict the maximum temperature that the Ge junction can exert on the photo-voltage of the triple-junction solar cell at a certain concentration ratio. The bordering temperature shows the temperature over which an advantage of the triple-junction cells compared to the dual-junction cells is lost. For operating temperature over 200°C, concentration ratio of several hundred times is required to maintain the photo-voltage from the Ge junction.

The J_{sc} of the InGaP/InGaAs/Ge triple-junction cell evaluated in this study is limited by the top subcell (InGaP subcell) short-circuit currents. The temperature coefficient of J_{sc} in the triple-junction solar cell (dJ_{sc}/dT) is equal to the temperature coefficient of short-circuit current in the top subcell, and J_{sc} in the triple-junction solar cell increases linearly with increasing temperature [11]. The increase in J_{sc} with increasing temperature is less than the decrease of V_{oc}. The conversion efficiency of the triple-junction solar cell is greatly influenced by V_{oc} in the high temperature conditions. Therefore, the contribution of photo-voltage from bottom junction (Ge junction) is very important for the conversion efficiency of triple-junction solar cell. Then, it is considered that the development of triple-junction solar cell that has bottom subcell consisted of wider band gap materials than Ge is also effective for the high temperature operations.

Even the low concentration ratio of 14 suns was confirmed to be effective for the increase in V_{oc} of the triple-junction solar cell at the high temperature. By using the light concentrating technique, it is possible to enhance the effect that the Ge junction exerts on the photo-voltage of the triple-junction solar cell in the high-temperature range.

4. CONCLUSION

In the high-temperature range (from 170°C to 240°C), the temperature coefficients of V_{oc} of the InGaP/InGaAs/Ge triple-junction solar cell were different from those in the low-temperature range (from 30°C to 100°C). This is because photo-voltage from the Ge subcell becomes almost 0 V in the high-temperature range. Because the Ge subcell could contribute to the V_{oc} of the triple-junction cell to the higher temperature with increasing concentration ratio, the bordering temperature at which the temperature coefficient of V_{oc} changed shifted to the higher temperature with increasing concentration ratio.

By using a light concentrating technique, it is possible to enhance the effect that the Ge junction exerts on the photo-voltage of the triple-junction solar cell in the high-temperature range. Moreover, by investigating the bordering temperature, we can predict the maximum temperature that the Ge junction can exert on the photo-voltage of the triple-junction solar cell at a certain concentration ratio. These results are very useful for the development of concentrator systems that demonstrate high efficiency in high-temperature conditions.

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Fig. 1. Schematic illustration of triple-junction solar cell.

Fig. 2. Temperature dependence of V_{oc} of triple-junction solar cell
(Solid lines and broken lines are the regression lines in the low- and high-temperature range, respectively).

Fig. 3. Temperature dependence of V_{oc} of (a) InGaP cell, (b) GaAs cell and (c) Ge cell.

Fig. 4. Temperature dependence of *I-V* characteristics of the Ge single-junction solar cell at 1 sun.

Fig. 5. The bordering temperature as a function of concentration ratio.

Table 1. Temperature coefficients of V_{oc} (dV_{oc}/dT)

	1sun (V/℃)	**7 suns (V/℃)**	**14 suns (V/℃)**
Triple-junction at low temperature	-0.0060	-0.0058	-0.0056
Triple-junction at high temperature	-0.0048	-0.0047	-0.0047
InGaP	-0.0025	-0.0024	-0.0023
GaAs	-0.0022	-0.0019	-0.0017
Ge	-0.0018	-0.0018	-0.0018
InGaP + GaAs + Ge	-0.0065	-0.0061	-0.0058
InGaP + GaAs	-0.0047	-0.0043	-0.0040

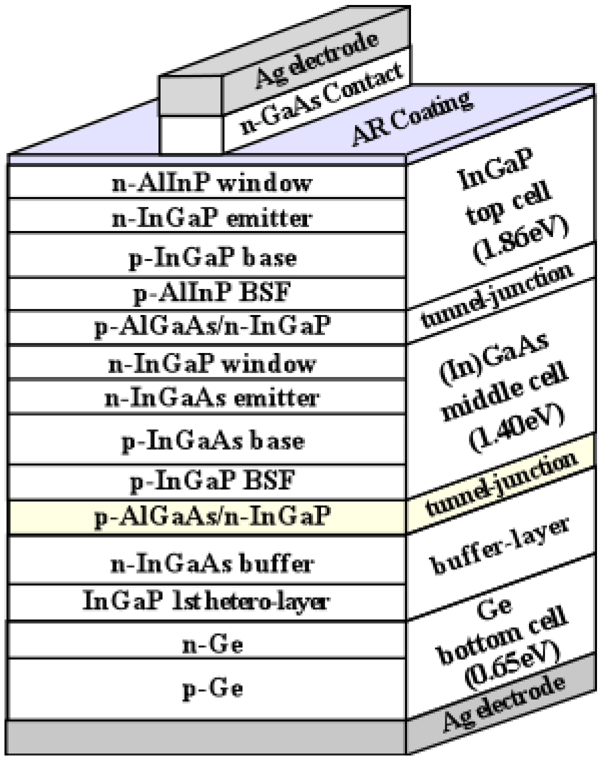

Fig. 1

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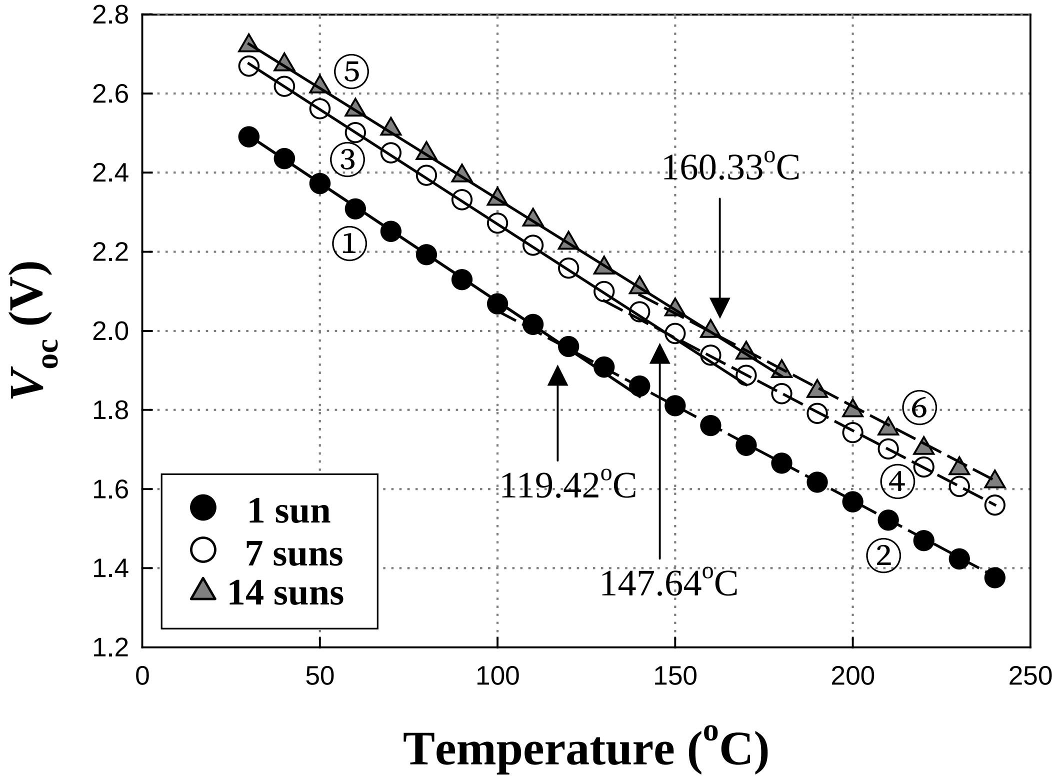

① 1 sun low-temperature: V_{oc}=2.6738-0.0060T(℃)
② 1 sun high-temperature: V_{oc}=2.5305-0.0048T(℃)
③ 7 suns low-temperature: V_{oc}=2.8497-0.0058T(℃)
④ 7 suns high-temperature: V_{oc}=2.6873-0.0047T(℃)
⑤ 14 suns low-temperature: V_{oc}=2.8932-0.0056T(℃)
⑥ 14 suns high-temperature: V_{oc}=2.7489-0.0047T(℃)

Fig. 2.

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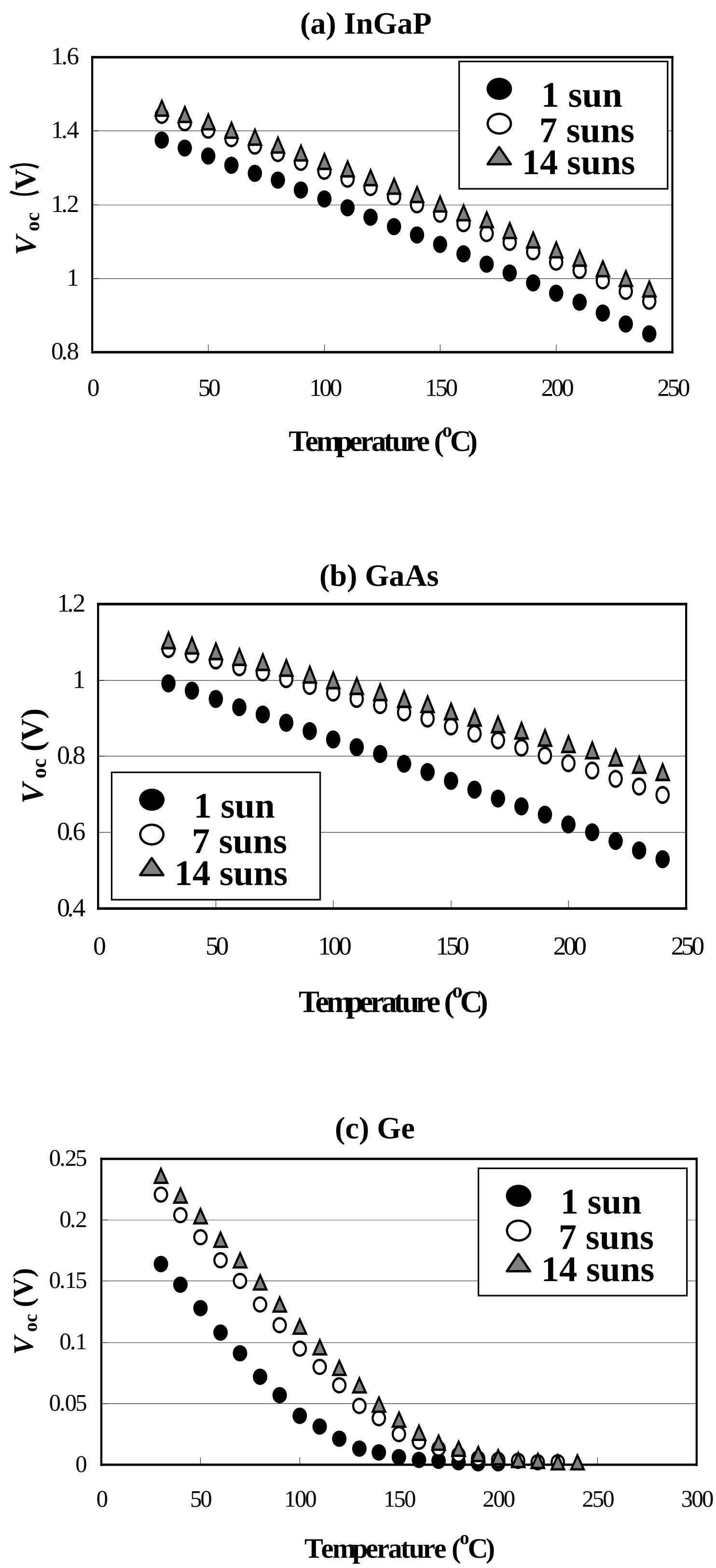

Fig. 3

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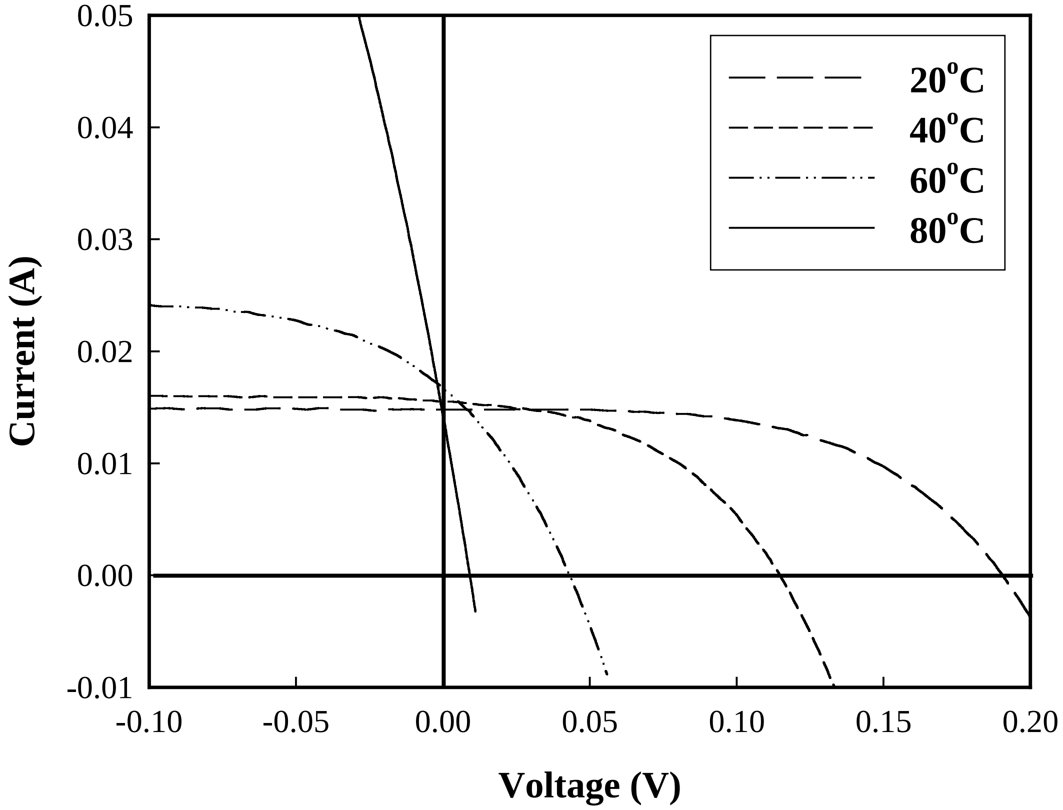

Fig. 4

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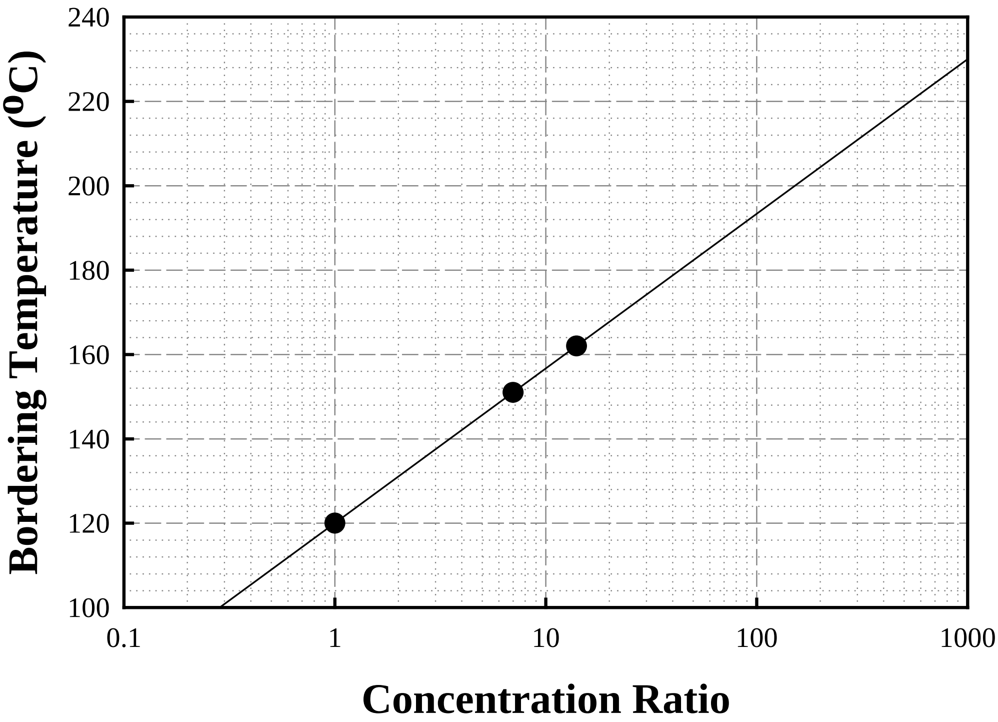

Fig. 5

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