Fabrication and temperature dependence of a GaInP/GaAs/Ge tandem solar cell*

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Abstract: GaInP/GaAs/Ge tandem solar cells were fabricated by a MOCVD technique. The photoelectric properties of the solar cells were characterized by a current–voltage test method. The dependence of the solar cell's characteristics on temperature were investigated from 30 to 170 ℃ at intervals of 20 ℃. Test results indicated that with increasing temperature, J_{sc} of the cell increased slightly with a temperature coefficient of 9.8 (μA/cm^2)/℃. V_{oc} reduced sharply with a coefficient of –5.6 mV/℃. FF was reduced with a temperature coefficient of −0.00063/℃. Furthermore, the conversion efficiency decreased linearly with increasing temperature which decreased from 28% at 30 ℃ to 22.1% at 130 ℃. Also, detailed theoretical analyses for temperature characteristics of the solar cell were given.

Key words: GaInP/GaAs/Ge; tandem solar cells; temperature dependence; solar energy

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1. Introduction

To improve the solar energy conversion efficiency of photovoltaic (PV) cells and to reduce their cost for terrestrial applications are the two main aims of photovoltaic workers and researchers. Photovoltaic solar cells under concentration can achieve a higher efficiency and lower cost with less expensive concentrating mirrors or lenses[1]. Tandem solar cells including of GaInP, GaAs and Ge for terrestrial concentrator applications have attracted increasing attention in recent years for their very high conversion efficiencies. The higher efficiency[2] of 41.6% for GaInP/GaAs/Ge multijunction cells under the standard spectrum at 364 suns has been reported by King *et al.*[3].

It should be considered that the temperature of the solar cell will increase dramatically under light concentrating operations[4], which will significantly influence the performance of the cell. The conversion efficiency (η) and the open-circuit voltage (V_{oc}) of solar cells will decrease with increasing temperature[5,6]. Several researchers have studied the temperature dependence of many kinds of solar cells. In 1960, Wysocki *et al.*[7] first researched the temperature effects on the conversion efficiency of single junction solar cells. Then Fan[8] modeled the temperature coefficients for single-junction GaAs, Si and Ge solar cells. Furthermore, temperature coefficients of GaInP/GaAs dual-junction solar cells were theoretically simulated and also experimentally measured by Friedman[9] and Feteha *et al.*[10], respectively. Nishioka *et al.*[11] measured the temperature coefficients of V_{oc} for the GaInP/GaInAs/Ge triple-junction solar cell under different concentration ratios. They[12] evaluated the temperature dependence of the characteristics of InGaP/InGaAs/Ge triple-junction solar cells under concentration in the temperature range 30 to 120 ℃, but the temperature range was a little narrow. Therefore, it is meaningful to investigate the temperature characteristics for tandem solar cells in detail, and the temperature range should be wider because of the solar cells combining concentrating operations.

In this work, the GaInP/GaAs/Ge tandem solar cells were fabricated by a metal organic chemical vapor deposition (MOCVD) method. The photoelectric properties of the solar cells were characterized by a current–voltage (I–V) test method. The temperature dependence of the solar cell's characteristics were investigated in the temperature range 30 to 170 ℃. The temperature effects on V_{oc}, I_{sc} (short-circuit current), FF (fill factor) and η on the solar cell were described in detail.

2. Experimental

GaInP/GaAs/Ge triple-junction tandem solar cells (3 × 3 mm^2) were fabricated by a MOCVD technique. The main precursors used to form the lattice layers were trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl), arsine (AsH_3) and phosphine (PH_3). The growth temperature typically ranged from 600 to 700 ℃. Figure 1 shows the schematic illustration of the GaInP/GaAs/Ge tandem cell. The bottom Ge cell was formed by a thin diffused layer from the p-Ge substrate. The middle GaAs cell (4 μm) was connected to both the bottom Ge cell and the top GaInP cell (0.7 μm) with the tunnel junctions. A highly doped GaAs cap layer was fabricated on the top cell. For the purpose of electrical evaluation, Au/Ti was deposited on the GaAs cap layer using a photolithography technique.

I–V characteristics for solar cells were measured under the standard spectrum of AM1.5 with a Xe lamp as the test light

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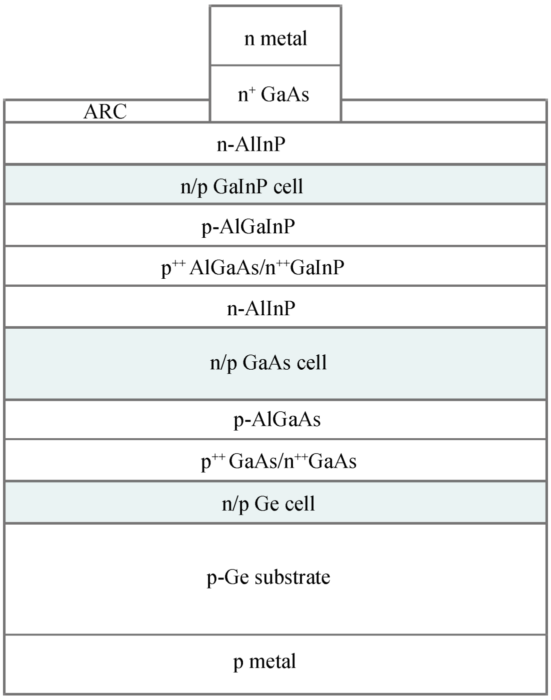

Fig. 1. Schematic illustration of the GaInP/GaAs/Ge tandem solar cell.

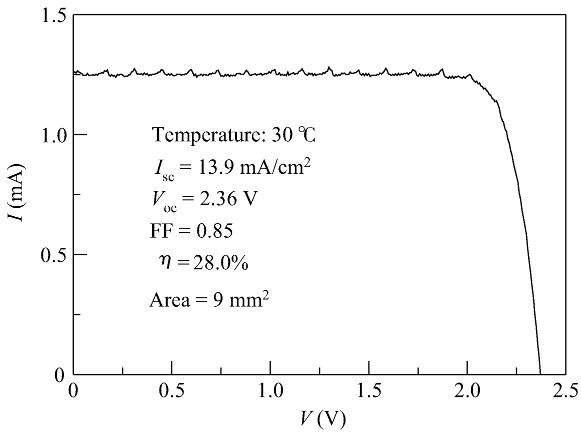

Fig. 2. I–V curve of the GaInP/GaAs/Ge tandem solar cell.

source. Temperature alteration of the fabricated solar cell was conducted using a stabilized hot copper block, to which the cell was attached using solder with a high heat conductivity, and the temperature was measured by a Pt-100 temperature sensor.

3. Results and discussions

The measured I–V curve of the GaInP/GaAs/Ge tandem solar cell under AM1.5 at room temperature (30 ℃) is shown in Fig. 2. As shown in the figure, the cell's conversion efficiency of 28.0% has been achieved (short-circuit current density J_{sc} $= 13.9$ mA/cm^2, $V_{oc} = 2.36$ V, FF $= 0.85$).

The tandem solar cell was heated by the stabilized hot copper block from 30 to 170 ℃ at intervals of 20 ℃. Figure 3 shows the temperature dependence of the cell's characteristics including J_{sc}, J_m, V_{oc}, V_m, FF and η for the GaInP/GaAs/Ge tandem solar cell, where J_m and V_m are the electrical parameters when the solar cell works at maximum output.

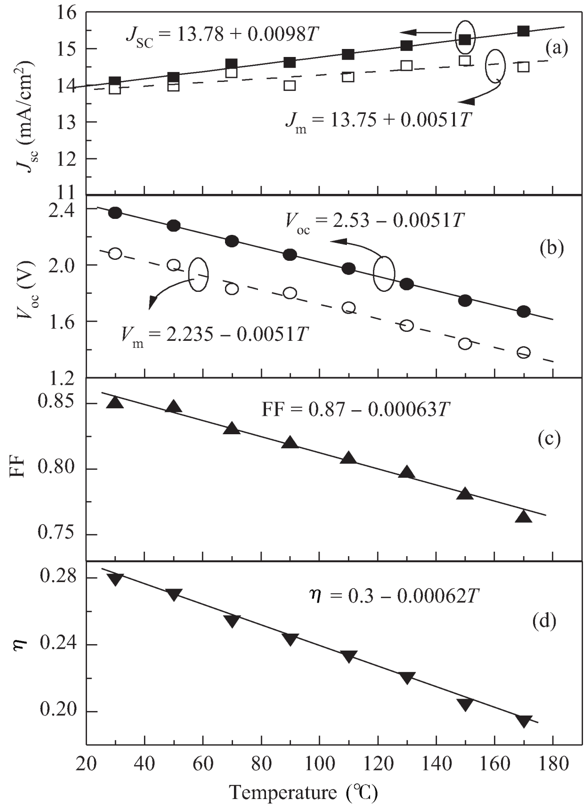

Fig. 3. Temperature dependence of the characteristics of the GaInP/GaAs/Ge tandem solar cell. (a) J_{sc}. (b) V_{oc}. (c) FF. (d) η.

Figure 3(a) shows the temperature dependence of J_{sc} and J_m. We can see that there are slight increases in J_{sc} and J_m with increasing temperature. The temperature coefficients of J_{sc} and J_m of the tandem solar cell are 9.8 (μA/cm^2)/℃ and 5.1 (μA/cm^2)/℃ respectively, which is higher than the result of Nishioka *et al.*[12]. The J_{sc} of the solar cell mainly depends on the optical absorption edge (λ_0) which relies on the energy gap (E_g) of the semiconductor material[5]. Increasing temperature will make the solar cell material's E_g narrow down[13], which will widen the optical absorption edge slightly. Therefore, the more photon-generated carriers will be produced, which results in the increase of J_{sc}. It's worth noting that J_{sc} increases just slightly because of the little narrowed E_g with the increase in temperature of the solar cell.

Figure 3(b) shows the temperature dependence of V_{oc} and V_m. In the figure, with increasing temperature, V_{oc} of the solar cell decreases sharply, this will severely worsen the performance of the solar cell. According to the I–V characteristic of the solar cell, the current (J) in the cell can be described as[14]

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

where J_0, q, and k are the saturation dark current density, elementary charge, and Boltzmann constant, respectively.

J_0 is usually given by

$$J_0 = AT^{\gamma} \exp \left(-\frac{E_g}{kT} \right), \tag{2}$$

where A is the diode factor depending on the material, and γ is a constant between 2 to 4.

Generally, $V \geqslant 3kT/q$, then

$$J \approx J_{\mathrm{sc}} - J_0 \exp \frac{qV}{kT} = J_{\mathrm{sc}} - AT^{\gamma} \exp \frac{qV - E_{\mathrm{g}}}{kT}. \quad (3)$$

When the solar cell is in an open circuit state, $J = 0$. So J_{sc} is given by

$$J_{\mathrm{sc}} = AT^{\gamma} \exp \frac{qV_{\mathrm{oc}} - E_{\mathrm{g}}}{kT}. \quad (4)$$

Then V_{oc} is

$$V_{\mathrm{oc}} = \frac{E_{\mathrm{g}}}{q} + kT \ln \frac{J_{\mathrm{sc}}}{AT^{\gamma}}. \quad (5)$$

According to the slight temperature effects on E_{g}, the first term on the right-hand side of Eq. (5) is ignored. V_{oc}'s derivation on T is given by

$$\frac{\mathrm{d}V_{\mathrm{oc}}}{\mathrm{d}T} = -k\left(\gamma - \ln \frac{J_{\mathrm{sc}}}{AT^{\gamma}}\right), \quad (6)$$

where $\ln \frac{J_{\mathrm{sc}}}{AT^{\gamma}}$ is very small with varying temperature.

We can see from Eq. (6), V_{oc}'s derivation on T is negative as a constant. Therefore, with the increase of temperature, V_{oc} decreases as a linear variation.

In Fig. 3(b), V_{oc} and V_{m} depend linearly on temperature, which corresponds to the theoretical analysis. The temperature coefficients of V_{oc} and V_{m} are both −5.1 mV/℃, which are lower than the results of Nishioka *et al.*[12].

Figure 3(c) shows the temperature dependence of FF. We know that the solar cell's fill factor FF is given by

$$\mathrm{FF} = \frac{V_{\mathrm{m}} J_{\mathrm{m}}}{V_{\mathrm{oc}} J_{\mathrm{sc}}}. \quad (7)$$

Therefore, Equation (7)'s derivation on T is

$$\frac{1}{\mathrm{FF}} \frac{\mathrm{dFF}}{\mathrm{d}T} = \frac{1}{V_{\mathrm{m}}} \frac{\mathrm{d}V_{\mathrm{m}}}{\mathrm{d}T} + \frac{1}{J_{\mathrm{m}}} \frac{\mathrm{d}J_{\mathrm{m}}}{\mathrm{d}T} - \frac{1}{V_{\mathrm{oc}}} \frac{\mathrm{d}V_{\mathrm{oc}}}{\mathrm{d}T} - \frac{1}{J_{\mathrm{sc}}} \frac{\mathrm{d}J_{\mathrm{sc}}}{\mathrm{d}T}. \quad (8)$$

From Figs. 3(a) and 3(b) we know that the $\frac{\mathrm{d}J_{\mathrm{m}}}{\mathrm{d}T}$ and $\frac{\mathrm{d}J_{\mathrm{sc}}}{\mathrm{d}T}$ are very small, so their effects on Eq. (8) are ignored. $\frac{\mathrm{d}V_{\mathrm{m}}}{\mathrm{d}T}$ and $\frac{\mathrm{d}V_{\mathrm{oc}}}{\mathrm{d}T}$ are equal, therefore Equation (8) can be derived as

$$\frac{1}{\mathrm{FF}} \frac{\mathrm{dFF}}{\mathrm{d}T} = \left(\frac{1}{V_{\mathrm{m}}} - \frac{1}{V_{\mathrm{oc}}}\right) \frac{\mathrm{d}V_{\mathrm{oc}}}{\mathrm{d}T}. \quad (9)$$

We can see from Eq. (9) that the temperature dependence of FF mainly comes from the temperature dependence of V_{oc}. The temperature has less effect on FF when FF is large or V_{oc} is nearing V_{m}. In Fig. 3(c), the FF of the cell approximately decreased linearly with an increasing temperature of −0.00063 /℃ in keeping with the result of Nishioka *et al.*[12].

Figure 3(d) shows the temperature dependence of conversion efficiency η. From the analyses above, with increasing temperature, V_{oc} decreases remarkably and FF decreases slightly. Although J_{sc} increases little with the increasing temperature, the conversion efficiency of the GaInP/GaAs/Ge tandem solar cell decreases as shown in Fig. 3(d). We can see that with the increase of temperature, η decreases linearly which decreases slower than the results of Nishioka *et al.*[12].

Table 1. Performance of the GaInP/GaAs/Ge solar cell at 30 and 130 ℃.

Parameter	30 ℃	130 ℃	Variation
J_{sc} (mA/cm^2)	13.9	15.07	+8.41%
V_{oc} (V)	2.36	1.86	−22.5%
FF	0.85	0.797	−6.24%
η (%)	28	22.1	−21.1%

For detailed investigation for the effects of higher temperature on the GaInP/GaAs/Ge tandem solar cell, the performances of the cell at 30 and 130 ℃ are compared in Table 1. As shown in Table 1, with the temperature increasing from 30 to 130 ℃, J_{sc} increases from 13.9 to 15.07 mA/cm^2 with the growth rate approaching to 8.41%. However, V_{oc}, FF and η decrease with the rate of −22.5%, −6.24% and −21.1%, respectively. We can see that with the temperature increasing, the performance of V_{oc} and η worsen significantly, which will shorten the solar cell's lifetime. The degradation of the cell's performance induced by temperature implies that additional efforts should be made for the concentrated photovoltaic technique, such as cooling operations.

4. Conclusion

GaInP/GaAs/Ge tandem solar cells were fabricated by an MOCVD technique. The photoelectric properties of the solar cells were characterized by an I–V test method. The temperature dependences of the solar cell's characteristics were investigated from 30 to 170 ℃ at intervals of 20 ℃.

Results indicated that with increasing temperature, J_{sc} and J_{m} of the cell increased slightly with the coefficients of 9.8 (μA/cm^2)/℃ and 5.1 (μA/cm^2)/℃, respectively. While, V_{oc} and V_{m} reduced sharply with a coefficient of −5.6 mV/℃. FF also decreased by −0.00063/℃. Furthermore, the conversion efficiency η decreased linearly from 28% at 30 ℃ to 22.1% at 130 ℃ with increasing temperature. Meanwhile, the theoretical analyses for temperature characteristics of the solar cell were given. These results can be used for the design of concentrator solar cell systems and in research of lifetime and reliability of the tandem solar cells.

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