AlGaAs/GaAs tunnel junctions in a 4-J tandem solar cell*

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Abstract: The III–V compound tandem solar cell is a third-generation new style solar cell with ultra-high efficiency. The energy band gaps of the sub-cells in a GaInP/GaAs/InGaAs/Ge 4-J tandem solar cell are 1.8, 1.4, 1.0 and 0.7 eV, respectively. In order to match the currents between sub-cells, tunnel junctions are used to connect the sub-cells. The characteristics of the tunnel junction, the material used in the tunnel junction, the compensation of the tunnel junction to the overall cell's characteristics, the tunnel junction's influence on the current density of sub-cells and the efficiency increase are discussed in the paper. An AlGaAs/GaAs tunnel junction is selected to simulate the cell's overall characteristics by PC1D, current densities of 16.02, 17.12, 17.75 and 17.45 mA/cm^2 are observed, with a $V_{\rm oc}$ of 3.246 V, the energy conversion efficiency under AM0 is 33.9%.

Key words: III–V compound; tandem solar cell; tunnel junction; current match; energy conversion efficiency

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1. Introduction

III–V compound tandem solar cells are usually used as the energy sources on satellites and spacecrafts due to their ultra-high conversion efficiency, attributed to superior material characteristics, stability, radiation harness, miscibility and, most notably, the tenability of the band-gap energy. The S–W effect (illumination degenerate) that generally exists in crystal and amorphous Si tandem solar cells has a negative influence on the efficiency of Si cells. As III–V compound tandem solar cells have no S–W effect, conversion efficiency is improved significantly. Due to the miscibility of the III–V compound materials, chemical elements such as P and In can be doped into the III–V compound photovoltaic to improve the energy band gap and obtain a photovoltaic material whose band gap is suitable for the solar spectrum. This is of great significance for the selection of a proper sub-cell band gap[1]. The energy band gaps of sub-cells in a GaInP/GaAs/InGaAs/Ge 4-J tandem solar cell are 1.8, 1.4, 1.0 and 0.7 eV, respectively. Research shows that such band gap collocation has optimal spectrum efficiency and is expected to break the record efficiency and exceed 45%. At present, InGaP/InGaAs/Ge 3-J tandem solar cells can reach a conversion efficiency of 31.7% under one sun (AM1.5G) and even reach 39.2% under 200 suns[2, 3].

An InGaP/InGaAs/Ge 3-J tandem solar cell, with a first layer InGaP band gap of 1.8 eV and a second layer InGaAs band gap of 1.0 eV, has a wider gap, resulting in no less waste of the solar spectrum. Thus, it is feasible to add a GaAs layer of 1.4 eV between the first two layers[2]. A GaInP/GaAs/InGaAs/Ge 4-J tandem solar cell with this structure has better theoretical conversion efficiency than an InGaP/InGaAs/Ge 3-J tandem solar cell due to its improved use of the solar spectrum. However, the addition of a sub-cell creates a higher demand on the coordination between each sub-cell, the lattice match between different sub-cell materials, the current matching between sub-cells, the overall stability of the cells and the $V_{\rm oc}$. It is important to introduce heavily doped tunnel junctions in tandem solar cells for increasing sub-cell matching, thereby improving the overall characteristics and stability of the solar cells.

2. Material and characteristics of the tunnel junctions

For voltage addition from the stacked cells, a low-resistance, optically transparent interconnect must be made between the stacked cells[3]. For such interconnects, current must flow from an n-type semiconductor layer into a p-type semiconductor layer and tunnel junctions are the typical approach for joining the stacked solar cells. Such tunnel junctions should be able to operate up to 1000 suns, with current densities of about 20 A/cm^2. The most difficult connecting tunnel junction connects the top solar cell to the underlying solar cell and the connecting junction must be transparent to the wavelengths collected by the underlying cells. Doping levels approaching 10^{20} cm^{-3} on both sides of the junction are also required and the dopants should have low diffusion properties in order to minimize junction degradation[4]. The current density of the tunnel junction is given by the following equations[4].

$$\begin{aligned} J &= A\exp\left(-BE_{\rm b}^{3/2}/E_{\rm F}\right)\left(\overline{E}/2\right)D \\ &= A\exp\left(-BE_{\rm b}^{1/2}/qW\right)\left(\overline{E}/2\right)D. \end{aligned} \tag{1}$$

Here,

$$A = \frac{qm^*}{2\pi^2\hbar^3},\quad B = \frac{\pi(m^*)^{1/2}}{2^{3/2}q\hbar},$$

$$\overline{E} = \frac{2^{5/2}\hbar E_{\rm b}^{1/2}}{3\pi(m^*)^{1/2}W},\quad E_{\rm b} = qE_{\rm F}W,$$

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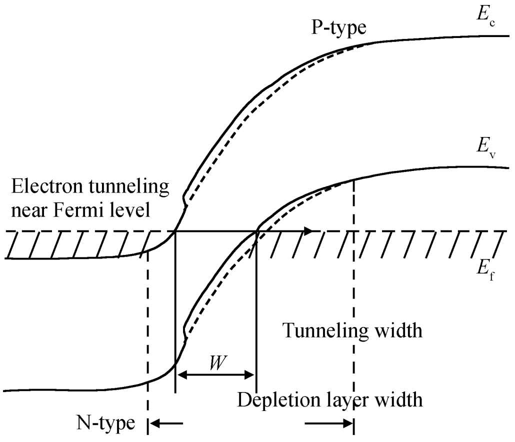

Fig. 1. Energy band diagram of the tunnel junction.

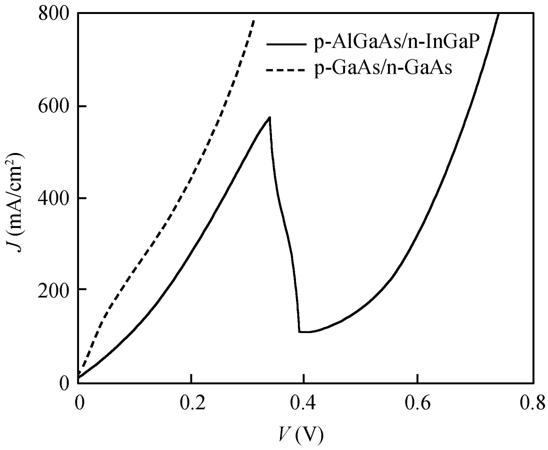

Fig. 2. J–V characteristic of p-AlGaAs/n-InGaP and p-GaAs/n-GaAs.

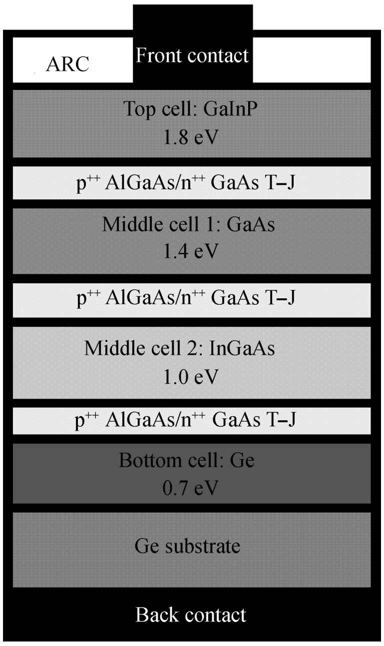

Fig. 3. Structure diagram of GaInP/GaAs/InGaAs/Ge 4-J tandem cell.

$$D = \int [F_C(E) - F_V(E)] \times [1 - \exp(-2E_s/E)]\, dE. \quad (2)$$

In these equations, m^* is the tunneling effective mass, W is the tunneling barrier width, E_F is the electric field in the tunneling region, E_b is the tunneling barrier height, $F_C()$, $F_V()$ are Fermi–Dirac functions for the conduction and valence bands, and $E_S = \min(E_1, E_2)$ with E_1 and E_2 being the energies measured from the band edges. The tunnel junction width W has an important effect on the T–J current density, as seen from Eq. (1).

Figure 1 shows the energy band diagram of the tunnel junction formed between a heavy doped n-type material and a p-type material, in which the donor doping concentration is $N_D = 3.6 \times 10^{19}$ cm^{-3}, and the acceptor doping concentration is $N_A = 1.8 \times 10^{20}$ cm^{-3}. According to the tunneling effect in quantum mechanics, the electron does not need extra energy for tunneling from the bottom of the conduction band to the top of the valence band. For the particular example in Fig. 1, the tunneling width is about 42% of the classically calculated depletion layer width. Also it is seen that the tunneling width is reduced when a conduction band offset exists[4]. This makes it easy for the tunneling effect and increases the tunnel junction current. In consideration of the lattice match with subcells, high specula permeability, low-resistance, heavily doped AlGaAs, InGaP, GaAs, etc are selected as tunnel junctions in III–V compound tandem solar cell[5].

Figure 2 shows the J–V characteristic of p-AlGaAs/n-InGaP and p-GaAs/n-GaAs in 3-J tandem solar cells InGaP/InGaAs/Ge. Estimated from the two curves, the resistances of the two tunnel junctions p-AlGaAs/n-InGaP and p-GaAs/n-GaAs are 1.2 mΩ and 0.8 mΩ, which are very low.

3. Structure of the 4-J tandem solar cells and the tunnel junction's characteristics

The introduction of a GaAs sub-cell of 1.4 eV makes better use of the solar spectrum a leads to better efficiency for the GaInP/GaAs/InGaAs/Ge 4-J tandem solar cell. However, it puts forward a high request on the cell structure. There should be a tunnel junction between every two sub-cells, four in total. According to research on GaInP/GaAs/InGaAs 3-J tandem solar cells, solar cells with p^{++} AlGaAs/n^{++} GaAs as tunnel junctions have higher V_{oc} and η than cells with p^{++} AlGaAs/n^{++} GaAs as T–Js[6]. So p^{++} AlGaAs/n^{++} GaAs tunnel junctions are employed in the 4-J tandem solar cells in this paper.

Figure 3 shows the overall structural diagram of a GaInP/GaAs/InGaAs/Ge 4-J tandem cell. In consideration of the short diffusion length of the minority carrier and the overall stability of the cell, the thickness of each sub-cell should be small or recombination should occur before the carriers reach the contact, so that the current density of each sub-cell will be severely reduced. For this, the thickness of each sub-cell thin film is set as GaInP 2 μm, GaAs 3 μm, InGaAs 4 μm, Ge 5 μm. Each sub-cell consists of two parts, an n-type emitter and a p-type absorber, to form a p–n junction inside the cell to collect electrons and holes. The thickness of the tunnel junction is set to be 30 nm, so that the tunnel junction can

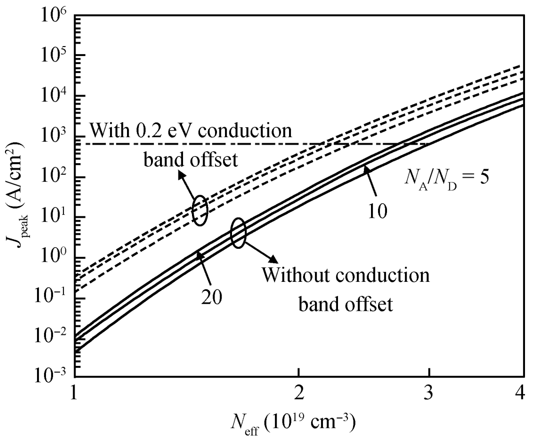

Fig. 4. Relation curve between J_{peak} and N_{eff} in the AlGaAs/GaAs tunnel junction.

lattice match to the up and down layers, and create good light permeability[7–9]. For better matching and transmission of the current in sub-cells, each tunnel junction must be a heavily doped p–n junction and the doping concentration should be over 10^{19} cm^{-3}. The doping level at two sides of the junction even reaches 10^{20} cm^{-3}. So the resistance of the tunnel junction can be low enough to further reduce the V_{oc} loss on it[10].

Here we use the PC1D solar cell simulation program developed by UNSW to analyze the relationship between the peak tunneling current J_{peak} and the effect doping concentration[11] N_{eff} $[N_A N_D/(N_A + N_D)]$, the following curves are observed.

As can be seen from Fig. 4, the maximum peak tunneling current of AlGaAs/GaAs T–J is 637 A/cm^2, the relevant effective doping concentration[12] is between 2.5 × 10^{19} and 3.0 × 10^{19} cm^{-3}. Here, the conduction offset has two effects: reducing the tunneling barrier and reducing the tunneling width, as shown in Eq. (1), both effects can make the tunneling current increase. So, the conduction offset caused by the tunnel junction's heavy doping has a direct influence on the tunneling current, which is realized by reducing the tunneling barrier and tunneling width[13–15]. Based on this, the doping concentration of the AlGaAs/GaAs tunnel junction is set as 3.0 × 10^{19} cm^{-3}, as heavy as possible to reduce the resistance, increase the tunneling current and thus reduce voltage loss.

4. Simulation and analysis of the overall cell

The tunnel junction's material, construction, doping and characteristics, the photoelectric characteristic, light permeability, peak tunneling current characteristics and the influence on the sub-cells are discussed above. Further research on the tunnel junction's influence on the whole cell is made below. On the whole cell's characteristics, PC1D is used to simulate the J–V curves of the cell. The parameters used in the simulation are shown in Table 1.

Table 1. Main parameters used in the process of tandem solar cell simulation.

Parameter	Value
Front surface area	4 cm^2
Front surface texture depth	3 μm
Exterior front reflectance	10%
Emitter contact	1 $\mu\Omega$
Base contact	15 mΩ
Internal conductor	0.3 S
Thickness of GaInP	2 μm
Thickness of GaAs	3 μm
Thickness of InGaAs	4 μm
Thickness of Ge	5 μm
Thickness of AlGaAs/GaAs	30 nm
N_{eff} of AlGaAs/GaAs	3.0 × 10^{19} cm^{-3}
Refractive index	3.81
n-concentration	2.87 × 10^{20} cm^{-3}
p-concentration	1.51 × 10^{16} cm^{-3}
Front-surface recom.	1 × 10^6 cm/s
Back-surface recom.	1 × 10^5 cm/s
Bulk recom.	7.208 μs

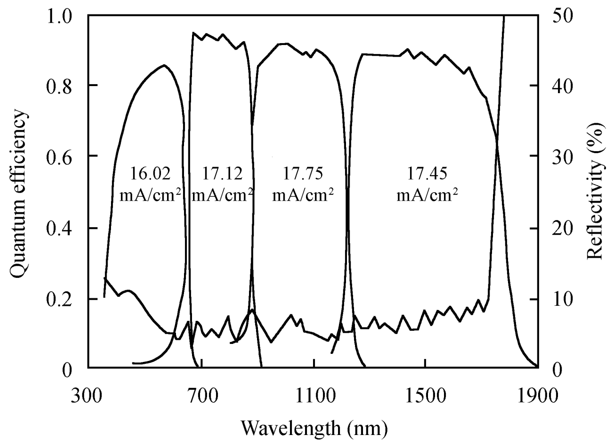

Fig. 5. External quantum efficiency and reflectivity of the 4-J GaInP/GaAs/InGaAs/Ge tandem solar cell.

Table 1 shows the main parameters used in the simulation, other parameters are set as default. Because of the heavy doping of the tunnel junction, defects caused by the heterojunction between tunnel junction and sub-cell are neglected. The resistance of the tunnel junction is also neglected. The curves and parameters are observed under condition of AM0G, 135.3 mW/cm^2, temperature of 28 ℃.

The current density of each sub-cell shown in Fig. 5 is 16.02, 17.12, 17.75, and 17.45 mA/cm^2, as a result of the heavily doped tunnel junctions, the current matching of each sub-cell is clear to see.

As shown in Fig. 5, each sub-cell's EQE has reached the optimal value of 90%, while the reflectance drops below 10% with the incident light wavelength under 1700 nm. Figure 6 show the optimal I–V curves with FF of 0.842, efficiency of 33.9%, higher than the efficiency of 3-J cells mentioned above.

5. Results and discussions

The N_{eff} of the tunnel junction is set as high as 3.0 × 10^{19} cm^{-3} either in p-AlGaAs or n-GaAs layer to cause a large peak current in the tunnel junction and thus ensure a low electronic resistance and high transmission coefficient in the junction, which will ensure current matching between the cell layers and improve the overall cell stability. The top sub-cell

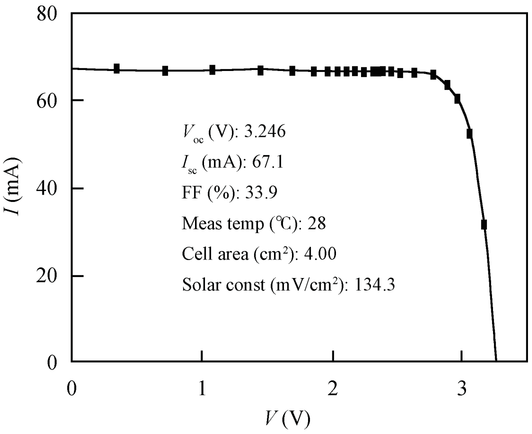

Fig. 6. $I-V$ characteristic of 4-J tandem solar cell.

should be as thin as 2 μm, which is shorter than the diffusion length of the excited charge carrier. To ensure that the charge carrier is collected by the electric field, the thin top cell is thin enough to be transparent to the cells below and presents a low resistance. The high $N_{\rm eff}$ can also cause a large surface recombination, which improves the current matching. To sum up, as a result of the high $N_{\rm eff}$, thin layer thickness, long carrier diffusion length and high surface recombination, the overall characteristic of the cell turn out to be better than estimated.

6. Conclusions

Each sub-cell's band gap of the GaInP/GaAs/InGaAs/Ge 4-J tandem solar cell is 1.8, 1.4, 1.0, 0.7 eV. The heavily doped AlGaAs/GaAs is selected as tunnel junction with doping concentration of 3.0×10^{19} cm^{-3}, the width of the tunnel junction is selected as 30 nm. The thickness of each sub-cell is, respectively, 2, 3, 4, and 5 μm from top to bottom. As shown in the paper, the conduction band offset caused by the heavily doped tunnel junctions increases the tunneling current and reduce the tunneling resistance through reducing the tunnel barrier and tunneling width, thus reducing the voltage drop on the junction. From a simulation of the cell with PC1D, the $V_{\rm oc}$ of 3.246 V, conversion efficiency of 33.9%, each sub-cell's current density of 16.02, 17.12, 17.75, and 17.45 mA/cm^2 are observed. But the $V_{\rm oc}$ and conversion efficiency are not markedly higher than those found in InGaP/InGaAs/Ge 3-J tandem solar cells. The reason may be the neglect of the defect density on the interface. Further studies will be made on this issue.

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