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External Quantum Efficiency of Quantum Well Solar Cells*

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Abstract: The external quantum efficiency of quantum well solar cells (QWSCs) is compared with the control cells without multi-quantum wells. The QWSCs extend the absorption spectrum from 870 to 1000nm. When the wavelength is below 680nm, the external quantum efficiency of the QWSCs is lower than that of the control cells, but when the wavelength is above 680nm, the external quantum efficiency of the QWSCs is higher than that of the control cells. The possible reasons for this phenomenon are discussed. Basing on the experimental data, the possibility of substituting the middle cells of conventional triple-junction solar cells with the QWSCs to improve their performance is also discussed.

Key words: solar cells; quantum wells; external quantum efficiency
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1　Introduction

For over a decade, quantum well solar cells (QWSCs) have been known to extend absorption spectrums and enhance output currents[1~6], but whether multi-quantum wells can increase the conversion efficiency of solar cells or not is still doubtful[7~9]. The reason is the decrease of the output voltage, which is attributed to increased recombination in the multi-quantum wells[10]. It seems that there still is a long way for the QWSCs to become an applicable type of solar cells.

However, if we combine the QWSCs with the challenges faced by GaInP/GaAs/Ge triple-junction solar cells (TJSCs), the current enhancement in the QWSCs may be helpful because the GaAs middle cell of the TJSCs has the lowest photocurrent, limiting the further improvement of the TJSCs[11~14]. To optimize the design of the TJSCs with the quantum well middle cells, an improvement in the spectral response (external quantum efficiency) of the QWSCs is important. In this paper, we report our experimental results for the spectral responses of the QWSCs and control cells. Based on the calculation from the experimental data, we find that substituting the middle GaAs cells of the TJSCs with the QWSCs is possible.

2　Experiment

Single junction QWSCs were made by an Emcore D180 low pressure metalorganic chemical vapor deposition (LP-MOCVD) system. A 2μm n-type GaAs base layer was grown on a Si-doped (100) GaAs substrate. TMGa, TMAl, TMIn, pure AsH_3, and pure PH_3 were used as precursors for material growth. The doping sources were SiH_4 and DEZn and the growth temperature was 580 to 680℃. Twenty periods of $GaAs_{0.95}P_{0.05}/In_{0.16}Ga_{0.84}As$ strain-balanced multi-quantum wells (the thickness of the GaAsP barrier layer and the InGaAs well layer is 41 and 7.1nm, respectively) were deposited on the base layer. The thickness of the p-type GaAs emitter layer was 0.45μm. The window layer was an AlGaAs film covered by an anti-reflection coating. The control GaAs cells were fabricated by the same process except the introduction of the multi-quantum wells. The samples were cut as 2cm × 2cm, and material quality was characterized by X-ray double crystal diffraction.

3　Results and discussion

Figure 1 is the X-ray double crystal diffraction rocking curve of the epitaxial layers in the QWSCs. The experimental curve agrees very well with the simulated one, and it is not easy to differentiate between them in Fig. 1. This indicates that the materials in the QWSCs have good crystal quality.

Figure 2 shows the spectral responses of the QWSCs and the control cells. The multi-quantum wells extend the solar cell's longest absorbable wavelength from 870 to 1000nm. In the extended 870 ~ 1000nm spectrum, the external quantum efficiency is much lower than the wavelength range below 870nm.

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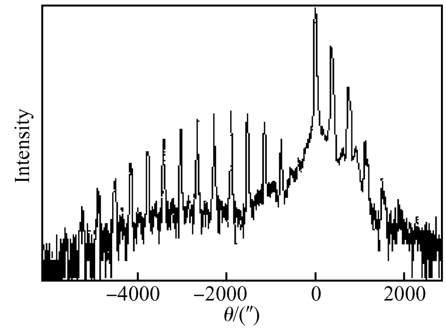

Fig. 1　X-ray double crystal diffraction rocking curve of the QWSCs

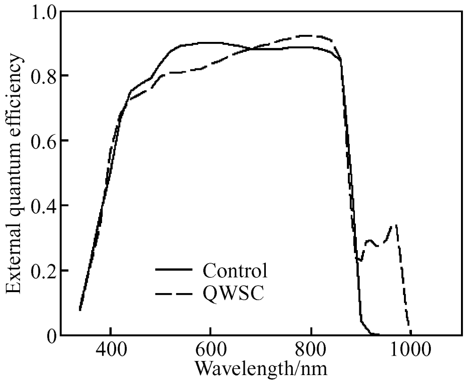

Fig. 2　External quantum efficiency of the QWSCs and the control cells

Previously, this was attributed to the recombination in the multi-quantum wells[2]. Besides the recombination in the wells, the photon transmission through the cells is also responsible for lower external quantum efficiency in the extended spectrum. Figure 3 shows the incident light reflection and transmission of the QWSCs. For photons with the wavelength above 870nm, the transmission rises rapidly with the wavelength. Thus, many photons in this range pass through the solar cells and are not absorbed by InGaAs well layers, which can absorb photons of the wavelength from 870 to 1000nm. This is because the total InGaAs well layers are not thick enough to absorb all photons in this range, leading to higher transmission. So we conclude that besides the recombination in the multi-quantum wells, the higher transmission of the photons is also responsible for the lower external quantum efficiency between 870 and 1000nm. Increasing the number of quantum wells or the width of the well layers may increase the light absorption, but it might not improve the external quantum efficiency in the extended spectrum because it will lead to the breaking of the strain balance of the multi-quantum wells and bring more defects into the epitaxial layers. Therefore, a suitable combination, including the number of quantum well periods and the width and the compositions of barriers and wells, is important to the external quantum efficiency.

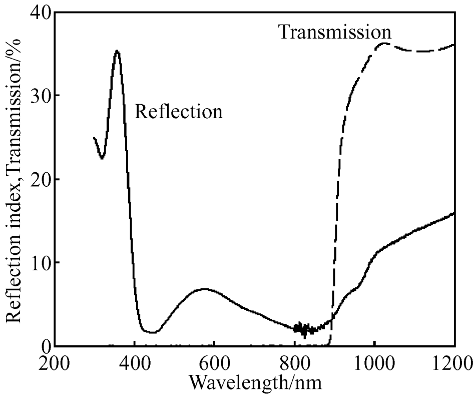

Fig. 3　Reflection and transmission of incident light on the surface of the QWSCs

Figure 2 shows that there exists a turning-point at about 680nm. At the wavelength of 420～680nm, the external quantum efficiency of the QWSCs is lower than that of the control cells, but in the range of 680～870nm the external quantum efficiency of the QWSCs is higher than that of the control cells. The lower external quantum efficiency of the QWSCs in the range of 420～680nm may be explained as follows: after the photons in this range are absorbed by the multi-quantum wells, some of the excited carriers lose part of their energies and drop down into the wells. These minority carriers have to surmount the GaAsP barriers in the intrinsic region and decrease the electron diffusion length in the emitter region. The mechanism of higher external quantum efficiency of the QWSCs in the range of 680～870nm is still not clear. Although this needs further investigation, it is verified that the multi-quantum wells can enhance the quantum efficiency in the wavelength range of 680～870nm, which is very useful in conventional TJSCs (the reason will be discussed later in this paper).

The existence of the turning-point can also be found in the work of Ekins-Daukes *et al*.[2]. The difference between Ekins-Daukes' results and ours is the position of the turning-point: 640nm in Ekins-Daukes' work and 680nm in ours. This might result from the difference in the composition of GaAsP barriers whose bandgap corresponds to the wavelength of the turning-point. In the samples made by Ekins-Daukes *et al*., the barrier layers are $GaAs_{0.939}P_{0.061}$, which has a larger bandgap than our samples with $GaAs_{0.95}P_{0.05}$ barriers, and this might lead to the shift of the turning-point.

Table 1 lists the short-circuit current density J_{SC}, the open-circuit voltage V_{OC}, the fill factors and the conversion efficiency (AM0) of the QWSCs and the

Table 1 Comparison between the QWSCs and the control cells

Sample	J_{SC} /(mA/cm^2)	V_{OC} /V	FF /%	AM0 efficiency /%
QWSC	32.93	0.952	0.7655	17.74
Control cell	32.09	1.03	0.82	19.15

control cells. The short-circuit current density of the QWSC is higher than that of the control cell due to the extended absorption spectrum. The open-circuit voltage of the QWSCs is less than that of the control cells, which is usually attributed to increased recombination in the multi-quantum wells. However, the reduction in the open-circuit voltage of the QWSC is different from a conventional solar cell. From Fig. 2, using the formula $\lambda = 1239.8/E_G$ (where E_G is the bandgap, and λ is the wavelength), we calculate the bandgap of GaAs in the control cells to be 1.42eV, and the bandgap of the InGaAs well layers in the QWSCs to be 1.27eV. Usually, if the bandgap of the materials decreases from 1.42 to 1.27eV, the reduction of the open-circuit voltage is approximately 0.15V (1.42 to 1.27). While in the QWSCs, it causes a reduction of only 0.078V.

The reduction in the open-circuit voltage of the QWSC brings a lower fill factor. Due to the decreases of the fill factor and the open-circuit voltage, the samples of the QWSCs have a lower conversion efficiency than the control cells although the short-circuit current increases. Some optimization may be possible through adjusting the composition of the GaAsP barrier layers.

Although the conversion efficiency of the QWSC samples is lower than that of the control cells, their current enhancement, especially under truncated spectra, makes the QWSC a good candidate for the middle cell of triple-junction GaInP/GaAs/Ge solar cells (TJSCs). In TJSCs, the bottom Ge cell has a photocurrent much higher than the top cell and the middle cell, and the overall current of the TJSCs is limited by the middle GaAs cell. In order to increase the conversion efficiency of the TJSCs, it is important to improve the current match of the three subcells. Usually, the way to improve the performance of the TJSCs is to increase the bandgap of the GalnP top cell or reduce its thickness to allow more photons to pass through the top cell and hit the middle cell[15]. Another way is to decrease the bandgap of the middle cell, but this is limited by the balance between the bandgap of the materials and the lattice constant. Therefore, using the current-enhanced QWSCs as the middle cell may be a way to improve the performance of the TJSCs.

Table 2 Short-circuit current densities of the control cells and the QWSCs under different truncated spectra

AM0 spectrum/nm	640～1000	660～1000	680～1000	700～1000
Control's J_{sc}/(mA/cm^2)	16.87	15.39	13.89	12.47
QWSC's J_{sc}/(mA/cm^2)	18.43	16.99	15.52	14.24
Increase of J_{SC}/%	9.25	10.40	11.74	14.19

To check the possibility of improving the performance of the TJSCs by substituting the middle cell with the QWSC, based on the data in Fig. 2, we calculate the short-circuit current density J_{SC} of the control GaAs cells and the QWSCs under different truncated AM0 spectra. The reason of carrying out the calculation under the truncated spectra is that, in conventional TJSCs, the absorption spectrum of the middle cell is about 650～900nm[15]. The calculated results are shown in Table 2. Under these truncated spectra, J_{SC} of the QWSCs is higher than that of the control cells, and the current enhancement rises as the bottom wavelength of the truncated spectra increases. This indicates the possibility of substituting the middle cell with the QWSC.

4 Conclusion

Solar cells with multi-quantum wells have been demonstrated to have a short-circuit current higher than the control cells. The spectral response of the QWSCs has a turning-point whose position might be dependent on the composition of the barrier layers. The QWSCs have higher external quantum efficiencies than the control cells above the turning-point, but lower external quantum efficiencies below the turning point, although the detailed mechanism needs further investigation. The higher short-circuit currents of the QWSCs under different truncated spectra indicate that the QWSCs are possible candidates for the middle cell of conventional TJSCs.

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量子阱太阳能电池的外量子效率*

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摘要： 通过实验比较了砷化镓量子阱太阳能电池与不含量子阱结构的普通砷化镓太阳能电池的外量子效率.结果表明,量子阱太阳能电池吸收光子的波长从 870nm 扩展到了 1000nm.当波长小于 680nm 时,量子阱太阳能电池的外量子效率低于普通太阳能电池;而当波长大于于 680nm 时,量子阱太阳能电池的外量子效率高于普通太阳能电池.对这个现象给出了解释,并对用量子阱太阳能电池代替三结电池的中间子电池的可能性进行了讨论.

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