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Efficiency improvement of single-junction InGaP solar cells fabricated by a novel micro-hole array surface texture process

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Abstract

In this study, single-junction InGaP solar cells fabricated by a novel micro-hole array surface texture process are presented. The characteristics of the single-junction InGaP solar cells with and without the micro-hole array surface texture are studied. An increase of 10.4% in short-circuit current is found when a single-junction InGaP solar cell is fabricated by the micro-hole array surface texture process. The conversion efficiency measured under one-sun air mass 1.5 global illumination at room temperature can also be improved from 13.8% to 15.9% when the size of the micro-holes is 5.3 μm and the period of micro-hole array is designed to 5 μm.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

III–V compound semiconductors are promising materials for achieving high reliability and high performance in optoelectronic devices. Wherever converting light into electronics or vice versa, they constantly present superior characteristics when compared to silicon-based materials. In solar cell applications, the conversion efficiency of GaAs solar cells either predicted by theoretical calculation or demonstrated by practical fabrication is found to be higher than that of silicon [1–6]. This is because GaAs solar cells can provide physically direct bandgap and lattice match properties; for example, a p^+–n GaAs solar cell with a base layer thickness of 3.3 μm can absorb 97% of the solar air mass 1.5 global illumination spectrum, and the generated carriers with high mobility ensure that they can reach the junction before any recombination process takes place. In addition, multi-junction tandem solar cells based on III–V compound semiconductors have received much attention because they can provide wide range absorption in the solar spectrum from visible to infrared then to generate high conversion efficiency [7–13]. Theoretical calculation has also shown that a conversion efficiency of 53.6% can be achieved by a four-junction III–V compound solar cell structure with careful material bandgap alignment [14]. Quite recently, combining lattice-match InGaP and GaAs p–n junctions with Ge bottom junction as triple-junction solar cells has been found to provide extremely high conversion efficiency [15].

To date, to obtain higher efficiency, the device structure design and novel materials, epitaxial layer quality improvement and device process of improving optical absorption properties are presented [16–19]. Some researchers have successfully enhanced the conversion efficiency by depositing nanoparticles on the surface of solar cells [20–23]. A surface texture process has widely been used in the fabrication of silicon-based solar cells for roughening the surface, leading to an increase of incident light intensity [24–26]. Although, the III–V compound solar cell structure seems to involve a complicated *in situ* epitaxial growth, further substantial works are required to produce high-efficient and low-cost III–V compound solar cells. To our knowledge, relevant works on the development of using the surface texture

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process in the fabrication of III–V compound solar cells are rare. Therefore, a novel process of micro-hole array surface texture technology is presented in the fabrication of single-junction InGaP solar cells in this study. Related characteristics of the single-junction InGaP solar cells with and without utilizing the micro-hole surface texture process technology are studied. It is found that the micro-hole surface texture improves the short-circuit current, hence further improving the conversion efficiency of the single-junction InGaP solar cell.

2. Cell fabrication and discussion

The single-junction p^+–n InGaP solar cell structures were grown by low-pressure (50 Torr) metal-organic chemical vapor deposition in a vertical reactor (Veeco D180). A Si-doped n-type GaAs substrate (1 0 0) off zero degree was used for the deposition. Trimethyl (TM-) sources of aluminum, gallium and indium were used for group-III precursors, while arsine and phosphine were used as the group-V reaction agents. Silane (SiH_4) and diethylzinc (DEZn) were used as the n-type and p-type dopant sources, respectively. The epitaxial growth rate for all phosphine based layers were kept at 1.8 μm h^{-1}, while the indium source was precisely controlled by an Epison controller system with monitoring the velocity of the gas mixture because TMIn is a powdery solid at room temperature. The V/III ratio was kept about 200 in a growth temperature range of 600–670 °C in this work. The uniformity of bulk layer thickness during the epitaxial growth was controlled to less than 0.4% standard deviation for a 3 inch wafer. The photoluminescence peak emission wavelength of InGaP was approximately 655 nm at room temperature, and the lattice mismatch between epitaxial InGaP and InAlP layers and GaAs substrate was less than 0.2%.

A schematic plot of the fabricated single-junction InGaP solar cells is shown in figure 1. The InGaP solar cell consists of an n^+-InAlP back-surface-field layer, an n-InGaP base layer, a p^+-InGaP emitter layer, a p^+-InAlP window layer and a p^+-GaAs contact layer to form Ohmic contact with an electrode. It is noteworthy that two single-junction InGaP solar cell structures with different p^+-InAlP window layer thicknesses were prepared in this study. With an aim of forming efficient micro-hole array surface texture, the thickness of the p^+-InAlP window layer in one of the single-junction InGaP solar cell structure was grown to 300 nm for the micro-hole array surface texture process, while another was 30 nm as typical design and reference for the standard process.

After epitaxy, the fabrication processes, including photo-lithography, chemical etching and metallization were used so as to fabricate the solar cell devices. In this study, back-side n-contact was formed by evaporating AuGe (250 Å)/Au (5000 Å), while the front p-contact consisted of evaporated Ti (250 Å)/Pt (250 Å)/Au (5000 Å). The shadow loss of the front strip contacts was 3.5%. An anti-reflective coating of SiO_2 film was evaporated to minimize the reflectivity. The area of the cells was 1 cm^2.

The micro-hole array surface texture was implemented after the front contact metal deposition and before the anti-reflection dielectric SiO_2 film coating. The patterns were formed photo-lithographically and etched by dipping into HCl solution (HCl:H_2O = 1:5) for 20 s, where the etching rate was precisely controlled to be 13–13.5 nm s^{-1} to prevent the exposure of the p^+-InGaP emitter layer. The size of micro-holes was designed to 5.3 μm in diameter, and the periods were varied from 5 to 10 and 15 μm, respectively in this study. A schematic plot and a scanning electron microscope (SEM) image of the micro-hole array with a period of 5 μm were shown in figure 2. The external quantum efficiency was measured at room temperature using homemade analysis systems.

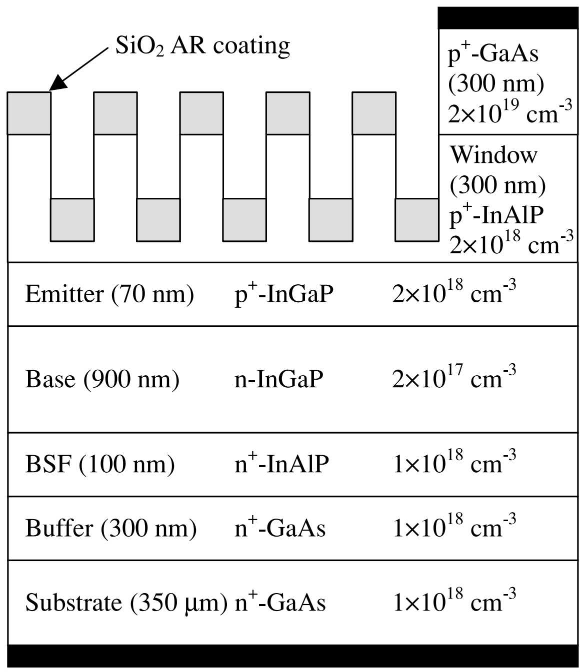

Figure 1. A schematic plot of the fabricated single-junction InGaP solar cells.

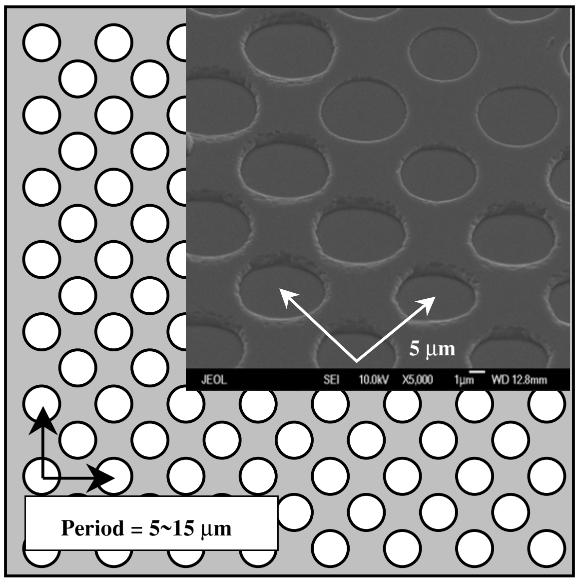

Figure 2. A schematic plot and a scanning electron microscope (SEM) image of the micro-hole array with a period of 5 μm.

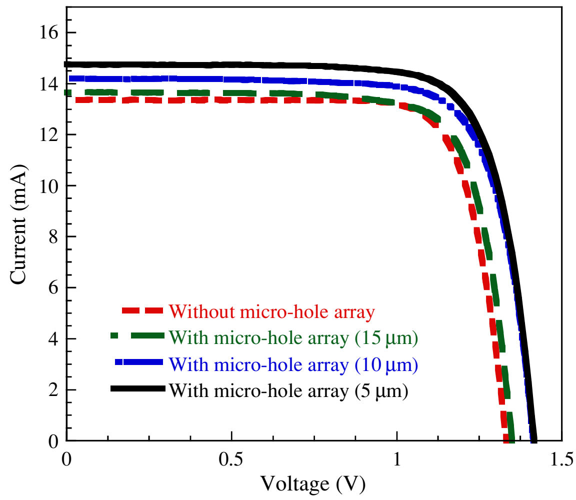

Figure 3. Photovoltaic *I–V* characteristics of the single-junction InGaP solar cells with and without utilizing micro-hole array surface texture.

Table 1. Characteristics of the single-junction InGaP solar cell with and without micro-hole array surface texture. The size of the micro-holes is 5.3 μm, and the periods are designed to 15, 10 and 5 μm, respectively.

Micro-hole array	V_{oc} (V)	I_{sc} (mA)	FF (%)	η (%)
Without	1.33	13.38	78.0	13.88
15 μm	1.35	13.66	76.8	14.16
10 μm	1.41	14.20	75.8	15.23
5 μm	1.42	14.77	75.8	15.91

To investigate the effect of micro-hole array surface texture on the single-junction InGaP solar cell, the photovoltaic *I–V* characteristics were measured under air mass 1.5 global illumination and room temperature conditions by a class-A solar simulator with a xenon flash tube according to IEC 904–9. Figure 3 shows the photovoltaic *I–V* characteristics of the single-junction InGaP solar cells with and without utilizing micro-hole array surface texture. The specific measured device parameters are summarized in table 1. As a reference for comparison, a short-circuit current (I_{sc}) of 13.38 mA, an open-circuit voltage (V_{oc}) of 1.33 V and a conversion efficiency (η) of 13.88% are obtained in the single-junction InGaP solar cell fabricated by the standard process of without micro-hole array surface texture.

It is found that the performance is improved when the micro-hole array surface texture process is utilized for the fabrication of single-junction InGaP solar cells. It yields a 2.1%, 6.1% and 10.4% increase of I_{sc} when the periods of micro-hole array are 15, 10 and 5 μm, respectively. In the mean time, η increases accordingly when the period of micro-hole array becomes smaller. It means that the micro-hole array surface texture becomes more efficient when the density of micro-holes increases. The increase of I_{sc} leads to a 2.0%, 9.7% and 14.6% increase of η for the single-junction InGaP solar cells fabricated by the micro-hole array surface texture process with periods of 15, 10 and 5 μm, respectively. A highest η of 15.91% can be obtained when the period of micro-hole array is 5 μm.

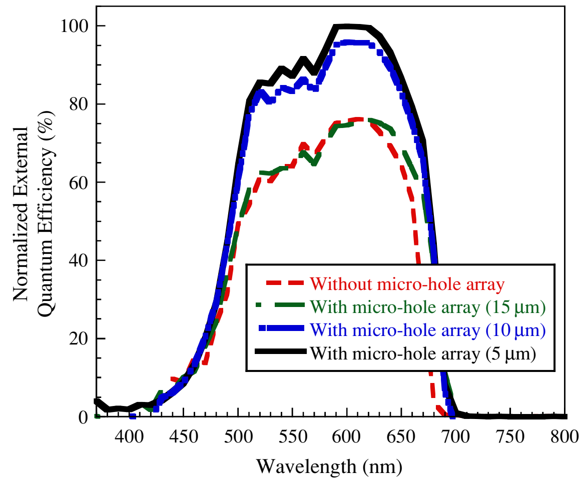

Figure 4. Normalized external quantum efficiency of the fabricated single-junction InGaP solar cell with and without utilizing micro-hole array surface texture.

This enhancement indicates that the absorption intensity of incident light in the p^+–n InGaP junction is enhanced. The loss of the incident light can be reduced, and more carriers are generated resulting in an increase of photocurrent accordingly. It is suggested that the micro-hole array surface texture provides a better light trapping effect and create an efficient light scattering into the p^+–n InGaP junction. As shown in figure 4, an increase in the quantum efficiency in the single-junction InGaP solar cells fabricated by the micro-hole array surface texture process is evident. Especially, the response in a spectrum range of 500–700 nm can be largely enhanced when the periodicity of the micro-hole array decreases.

3. Conclusion

In summary, current–voltage characteristics of the single-junction InGaP solar cells fabricated by a novel micro-hole array surface texture process were investigated. As compared to the standard process, both the external quantum efficiency and short-circuit current were found to be increased when the single-junction InGaP solar cell was fabricated by the micro-hole array surface texture process. We suggested that the micro-hole array surface texture could provide an efficient light trapping and scattering effect to the p^+–n InGaP junction. An increase in short-circuit current of 10.4% and an increase in conversion efficiency of 14.6% were achieved in the single-junction InGaP solar cell when the period of micro-hole array is designed to 5 μm.

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