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RESEARCH ARTICLE

Novel Anti-Reflection Technology for GaAs Single-Junction Solar Cells Using Surface Patterning and Au Nanoparticles

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Single-junction GaAs solar cell structures were grown by low-pressure MOCVD on GaAs (100) substrates. Micro-rod arrays with diameters of 2 μm, 5 μm, and 10 μm were fabricated on the surfaces of the GaAs solar cells via photolithography and wet chemical etching. The patterned surfaces were coated with Au nanoparticles using an Au colloidal solution. Characteristics of the GaAs solar cells with and without the micro-rod arrays and Au nanoparticles were investigated. The short-circuit current density of the GaAs solar cell with 2 μm rod arrays and Au nanoparticles increased up to 34.9% compared to that of the reference cell without micro-rod arrays and Au nanoparticles. The conversion efficiency of the GaAs solar cell that was coated with Au nanoparticles on the patterned surface with micro-rod arrays can be improved from 14.1% to 19.9% under 1 sun AM 1.5G illumination. These results show that micro-rod arrays and Au nanoparticle coating can be applied together in surface patterning to achieve a novel cost-effective anti-reflection technology.

Keywords: GaAs, Single-Junction, Solar Cells, Photovoltaic, Surface Patterning, Micro-Rod, Au Nanoparticles, Conversion Efficiency, Light Absorption, Anti-Reflection, MOCVD.

1. INTRODUCTION

Solar cells based on III–V compound semiconductors can achieve high conversion efficiency because of the bandgap tunability by the elemental compositions, the direct bandgap property, and the smaller efficiency degradation by heat.[1] Recently, an over 40% efficiency of InGaP/GaAs/Ge triple-junction solar cells has been achieved using tandem structures and concentration technologies.[2–3] The high refractive index of the III–V compound semiconductor materials, however, causes more than a 30% incident light to be reflected from the surface of the solar cells. MgF_2/ZnS anti-reflection coatings (ARCs) can be used to prevent the reflection, but they can peel off easily because of their poor adhesion properties. In addition, the cost of the ARC deposition process in a high-vacuum condition is very high.[4]

For this reason, surface patterning technologies such as pyramidal texturing, micro-array patterning, and nanopatterning have been studied for cost-effective ARC of Si solar cells.[5–8] When the surface of the solar cells is textured, the reflectance of the incident light can be reduced on the surface because the effective surface area increases. Scattering of the light on the patterned surface can also improve the light absorption and conversion efficiency of the solar cell. These technologies can also be applied to III–V solar cells.[9–10]

The deposition of metal nanoparticles on the surface of solar cells can be an alternative ARC technology. The metal nanoparticles can act as subwavelength scattering elements to trap the incident light. The light scattering from the metal nanoparticles increases the effective optical path length in the solar cells. Therefore, the short-circuit current and the conversion efficiency of the solar cells can be improved.[11–13] In addition, various deposition processes of metal nanoparticles have been studied, and the process cost has become lower.[14–16]

In this study, two techniques, surface patterning with micro-rod arrays and Au nanoparticle coating were combined using an Au colloidal solution to improve the light absorption and conversion efficiency of single-junction GaAs solar cells. The characteristics of the GaAs solar cells with and without the micro-rod arrays and Au nanoparticles were investigated to determine the anti-reflection effect.

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p-contact	Ti / Pt / Au	500 nm
p-ohmic	p⁺-GaAs	300 nm
Window	p^+-$In_{0.5}Ga_{0.5}P$	200 nm
Emitter	p-GaAs	500 nm
Base	n-GaAs	3,500 nm
BSF	n^+-$In_{0.5}Ga_{0.5}P$	50 nm
Buffer	n-GaAs	200 nm
Substrate	n^+-GaAs	350 μm
n-contact	AuGe / Ni / Au	500 nm

Fig. 1. Schematic of the fabricated GaAs single-junction solar cells.

2. EXPERIMENTAL DETAILS

The single-junction GaAs solar cell structures were grown by metal-organic chemical vapor deposition (AIXTRON: AIX2600G3 IC) on Si-doped *n*-type GaAs (100) substrates with a misorientation of 2° toward the ⟨111⟩ plane. Trimethylgallium (TMGa), trimetylindium (TMIn), arsine (AsH_3), and phosphine (PH_3) were used for the group III and V precursors. Silane (SiH_4) and diethylzinc (DEZn) were used for the *n*-type and *p*-type dopant precursors, and hydrogen (H_2) was used for the carrier gas. The reactor pressure and temperature were kept at 50 mbar and 680 °C, respectively.

A schematic of the fabricated GaAs single-junction solar cells is shown in Figure 1. The solar cell consisted of GaAs *p–n* junction layers, highly doped $In_{0.5}Ga_{0.5}P$ layers for the back surface field (BSF) and the window layer, a highly doped p^+-GaAs cap layer for the ohmic contact, and an *n*-GaAs buffer layer for high crystal quality. All the grown layers were lattice-matched with the GaAs substrates. Especially, the p^+-$In_{0.5}Ga_{0.5}P$ window layer was grown to 200 nm for the surface patterning process.

The solar cell devices were fabricated via photolithography, metal deposition, annealing, and wet chemical etching. The *n*-type and *p*-type contacts consisted of AuGe (800 Å)/Ni (200 Å)/Au (4000 Å) and Ti (200 Å)/Pt (200 Å)/Au (4600 Å), respectively. The metal structures were formed with an *e*-beam evaporator and annealed using a rapid thermal annealing system. The p^+-GaAs cap layer was selectively etched in a citric acid solution ($CA:H_2O_2:H_2O = 25:1:75$). The solar cells were divided with a dicing saw system. The aperture area of the fabricated solar cell was 0.25 cm^2.

Hexagonal micro-rod arrays were patterned on the surface of the fabricated solar cell via photolithography and wet chemical etching. The diameters of the micro-rods were 2 μm, 5 μm, and 10 μm, and the distance between the micro-rods was 2 μm. The micro-rod arrays were formed on top of the p^+-InGaP window layer via wet etching by dipping them into an $HCl:H_3PO_4:H_2O$ (1:1:1) solution for 1 minute at 22 °C. The morphology of the patterned surface was investigated via atomic force microscopy (AFM), and the measured AFM images are shown in Figure 2. The diameters of the micro-rods were (a) 2 μm, (b) 5 μm, and (c) 10 μm, and the etched depth was about 40 nm. The micro-rods were not cylindrical in shape because of the isotropic property of the wet chemical etching process.

After the surface patterning, the patterned surface of the solar cells was coated with Au nanoparticles. A solution that contained colloidal Au nanoparticles (Nano M) was dropped on the patterned surface with a micro-pipette and dried at room temperature. Figure 3 shows field emission scanning electron microscope (FE-SEM) images of the patterned surfaces of the solar cells with Au nanoparticles. The size of the Au nanoparticles was from 10 nm to 20 nm, and the density of the Au nanoparticles on the patterned surface was approximately 5.6×10^9 cm^{-2}.

3. RESULTS AND DISCUSSION

The reflectance at the interface of the air and the surface of the fabricated solar cell was measured with a UV-VIS-NIR spectrophotometer (Varian: Cary 5000). Figure 4 shows the measured reflectance of the GaAs solar cell with and without the micro-rod arrays and Au nanoparticles. It was observed that the reflection of the incident light was reduced when the surface was patterned with the micro-rod arrays on the surface of the GaAs solar cells. The reflectance of the solar cell with 2 μm rod arrays (c) was lower than that of the solar cell without a micro-rod array (a), especially in the short-wavelength region. The reduction in the reflectance at short wavelengths was mainly due to the differences in the top surface reflections

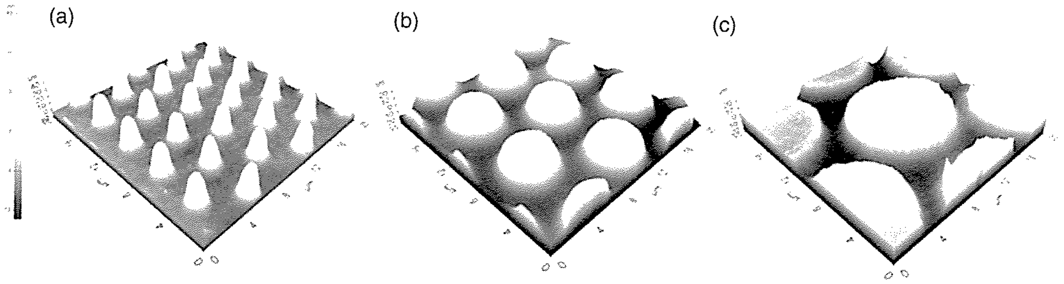

Fig. 2. AFM images of the micro-rod arrays with diameters of (a) 2 μm, (b) 5 μm, and (c) 10 μm on the surface of the GaAs solar cell.

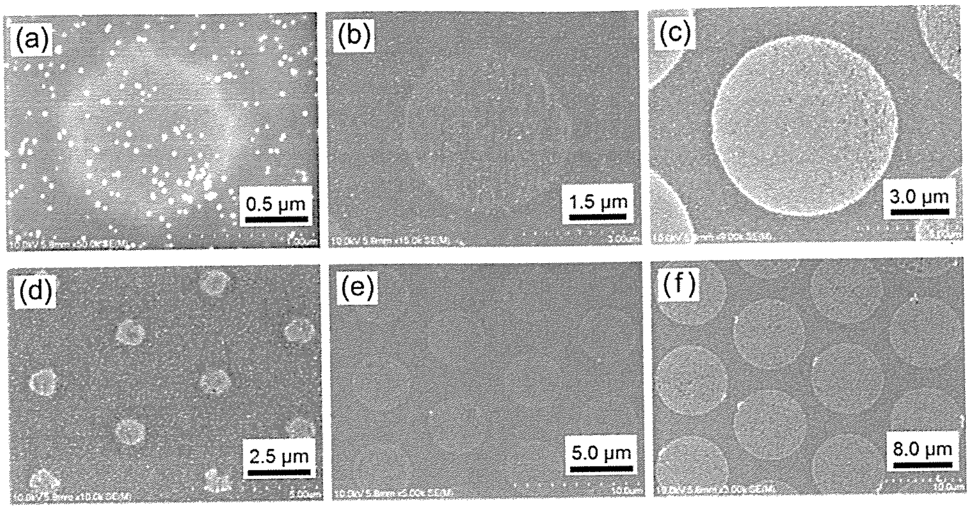

Fig. 3. FE-SEM images of the patterned surfaces with (a), (d) 2 μm, (b), (e) 5 μm, and (c), (f) 10 μm rod arrays after the deposition of the Au nanoparticles.

from the solar cells.[5] The difference in the reflectance according to the diameter of the micro-rod was clear in the wavelengths below 500 nm, and the reflectance of the GaAs solar cell with 2 μm rod arrays was the lowest. This means that the reflectance of the patterned solar cell can be reduced more efficiently when the density of the micro-rods increases, similar to the result of a previous study.[10]

The anti-reflection effect of the Au nanoparticle coating was also found in the comparison of the reflectances of the solar cells with and without Au nanoparticles. The reflectance of the solar cell with Au nanoparticles (b) was lower than that of the solar cell without Au nanoparticles (a) throughout the entire 350 nm to 900 nm wavelength region. This is because of the light scattering from the Au nanoparticles. When small metal nanoparticles are placed close to the interface between two dielectrics, light scatters preferentially into the dielectric with the larger permittivity.[13] Therefore, the solar cell with Au nanoparticles can absorb the additional light at incident angles beyond the critical angle for reflection. Moreover, the effective optical path length increases because light can be trapped between the top surface with Au nanoparticles and the metal back contact. The light scattering effect at short wavelengths is smaller than at long wavelengths due to the phase mismatch that is closely related to the polarizability of the particle.[15]

Figure 5 shows the external quantum efficiency (EQE) of the GaAs solar cell with and without the micro-rod arrays and Au nanoparticles, which was measured with the solar cell quantum efficiency measurement system (PV Measurements: QEX7). Trends similar to those of the reflectance can be found in the EQE of the solar cells. Higher EQEs were observed clearly at long wavelengths when the surface was patterned with the micro-rod arrays and coated by the Au nanoparticles. This means that the light absorption property of the solar cell improved with the reduction in the surface reflection and the additional carrier generation. The differences in the EQEs decreased

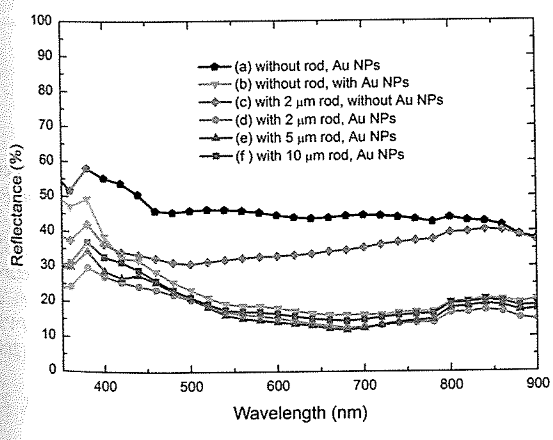

Fig. 4. Reflectance at the surface of the GaAs solar cell with and without the micro-rod arrays and Au nanoparticles.

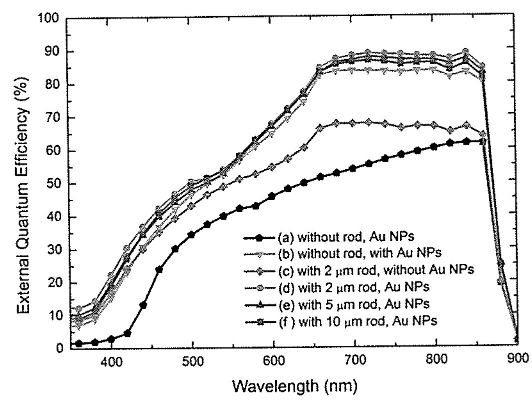

Fig. 5. External quantum efficiency of the GaAs solar cell with and without the micro-rod arrays and Au nanoparticles.

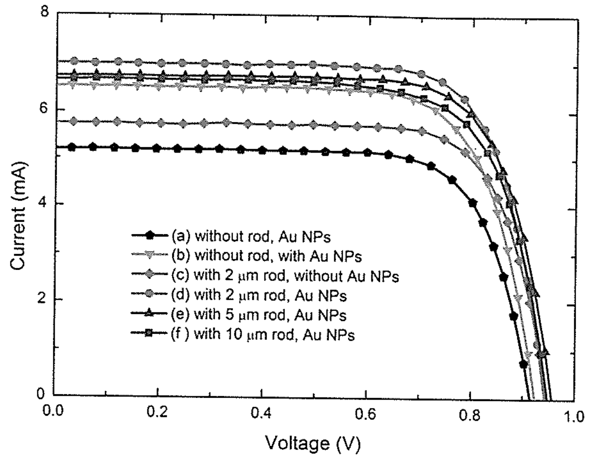

Fig. 6. Photovoltaic *I–V* characteristics of the GaAs solar cells with and without the micro-rod arrays and Au nanoparticles.

in the wavelengths below 660 nm, however, because of the thermalization loss.

The photovoltaic current–voltage (*I–V*) characteristics were measured with a solar simulator (McScience: K3000) under 1 sun air-mass (AM) 1.5 global illumination with a cell area of 0.25 cm^2. Figure 6 shows the photovoltaic *I–V* characteristics of the GaAs solar cells with and without the micro-rod arrays and Au nanoparticles, and the specific measured device parameters are summarized in Table I. The short-circuit current density (J_{SC}) increased to up to 10.8%, 7.2%, and 6.9% when the 2 μm, 5 μm, and 10 μm rod arrays were patterned on the surface of the GaAs solar cell, respectively. J_{SC} also increased to over 20% when the surface of the GaAs solar cell was coated with the Au nanoparticles. The open-circuit voltage (V_{OC}) and the fill factor (FF) did not change significantly, compared to J_{SC}. As a result, the maximum conversion efficiency (η) of 19.9% was obtained in the GaAs solar cell with 2 μm rod arrays and Au nanoparticles. In comparison with the GaAs solar cell without micro-rod arrays and Au nanoparticles, the J_{SC}, V_{OC}, and FF increased to up to 34.9%, 3.3%, and 1.4%, respectively. These prove that the increase in the solar cell efficiency was mainly due to the improvement in the light absorption property.

Table I. Characteristics of the GaAs solar cells with and without the micro-rod arrays and Au nanoparticles.

	Micro-rod	V_{OC} (V)	J_{SC} (mA/cm^2)	FF	η (%)
Without Au NPs	Without	0.91	20.78	0.74	14.10
	2 μm	0.94	23.02	0.75	16.36
	5 μm	0.95	22.27	0.75	15.78
	10 μm	0.94	22.22	0.72	15.05
With Au NPs	Without	0.92	26.11	0.74	17.78
	2 μm	0.94	28.04	0.75	19.90
	5 μm	0.96	26.99	0.75	19.24
	10 μm	0.94	26.68	0.73	18.33

The micro-rod surface patterning and the Au nanoparticle coating separately induced the anti-reflection effects. When the two ARC technologies were applied together to the GaAs single-junction solar cells, the anti-reflection effect became large enough to replace the conventional expensive ARC techniques. In addition, further efficiency improvements can be achieved with surface nanopatterning technologies with optimized metal nanoparticles.

4. CONCLUSIONS

Micro-rod arrays with different diameters were fabricated on the surfaces of GaAs single-junction solar cells, after which the patterned surfaces were coated with Au nanoparticles. The characteristics of the GaAs solar cells with and without the micro-rod patterns and Au nanoparticles were investigated by measuring the reflectance, EQE, and photovoltaic *I–V* curves. The reflection of the incident light was reduced and the light absorption of the GaAs solar cell improved. The GaAs solar cell with 2 μm rod arrays and Au nanoparticles showed the maximum conversion efficiency of 19.9%. J_{SC} increased up to 34.9%, and the conversion efficiency improved from 14.1% to 19.9% under the AM 1.5G illumination. These results mean that both the micro-rod surface patterning and the Au nanoparticle coating improved the light absorption of the GaAs solar cell. Therefore, they can be applied together for a novel cost-effective anti-reflection technology.

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