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RESEARCH ARTICLE

InGaP Nano-pattern Structure Realized by Thermally Dewetted Au Nanoparticles and Anisotropic Dry Etching

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Abstract: ***Background:*** Optical reflection loss can be reduced more than 30% when multilayers ARC are deposited on the optoelectronic devices surface. Besides that, sub-wavelength structures, which have a period sufficiently smaller than the wavelength of light, have been introduced as an antireflection layer to offer a new possibility to suppress the Fresnel reflection. Normally, e-bean and nano-imprint lithography techniques are used to create nano-scale etch mask patterns. Metallic nanoparticles, which can be formed by a thermal dewetting process of metal thin film without any nanolithography techniques, can be utilized as an etch mask for the nano structure fabrications. The nano-patterned structures were fabricated on a silicon nitride passivation layer of a GaInP/GaAs/Ge triple-junction solar cell and showed an enhancement of its performance due to improved optical transmission and current matching.

Objective: Investigate the influences of InGaP nano-pattern structures on the optical characteristics and applied for compound solar cells.

Methods: In this report, disordered InGaP nano-pattern structures were formed by thermally dewetted Au nanoparticles and anisotropic dry etching processes. The effects of the InGaP nano-patterned structure on the optical reflection characteristics were investigated.

Results: The result indicated that the InGaP nano-patterned structure can reduce the optical reflection in a wide range of wavelengths and, thus, can work as an antireflection layer. The InGaP nanostructure can improve up to 14.8% in the short circuit current density compared to that of the planar cell.

Conclusion: The InGaP nano structures have been successfully fabricated by thermal dewetted Au nanoparticles and anisotropic dry etching methods. The fabricated Au nanoparticles pattern was found to be the best when annealing temperature is 400°C for 30 minutes with the 5nm thick of Au film. By controlling dry etching time, the height of InGaP nanostructures can be varied from 95 nm to 150 nm. With the increasing of the height, the optical reflectance can be down to 22%. The InGaP nanostructure with the height of 150 nm was also introduced to the window layer of a single junction GaAs soar cell. The result indicated that the InGaP nanostructure only affects on the short circuit current density.

Keywords: Thermally dewetted au nanoparticles, InGaP nanostructure pattern, solar cell, antireflection coating, photocurrent enhancement, nanomask.

1. INTRODUCTION

Antireflection coatings (ARCs) have been widely utilized to eliminate unwanted surface reflections that may have a lot of detrimental effects on efficiency in optical components and optoelectronic devices [1-3]. In general, to reduce the reflection of incident light at the interface between optoelectronic devices and an outer medium, refractive index differences between the two media must be minimized. That can be realized by introducing a single or multilayers with lower reflective index values compared to that of the material of optoelectronic devices. ZnS, TiO_2, CeO_2, and Si_3N_4 are usually used as high refractive index materials and MgF_2, SiO_2, and BN are normally used as low refractive index materials in multilayer ARC [4-6]. Optical reflection loss can be reduced by more than 30% when multilayers ARC are deposited on the optoelectronic devices surface [6]. Besides that, sub-wavelength structures, which have a period sufficiently smaller than the wavelength of light, have been introduced as an antireflection layer to offer a new possibility to

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suppress the Fresnel reflection [7, 8]. The sub-wavelength structure exhibits polarization insensitive, broadband, and omnidirectional antireflective characteristics [9-12]. That is due to the spatially graded structural profile in a single layer. Moreover, the sub-wavelength structure can be robust and mechanically durable, making it particularly desirable for concentrator and space photovoltaic applications. The periodic sub-wavelength structure fabrication usually requires expensive and complicated processes. Normally, e-bean and nano-imprint lithography techniques are used to create nano-scale etch mask patterns. The periodic sub-wavelength structures formed using silica or polystyrene monolayer colloidal crystals are also reported for use in fabrication of sub-wavelength structure [13-15].

Metallic nanoparticles, which can be formed by a thermal dewetting process of metal thin film without any nanolithography techniques, can be utilized as an etch mask for the nano structure fabrications. This technique allows simple and low-cost processes over a large area [16-18]. Antireflective characteristics of the nano-patterned structures depend strongly on their geometric shape and dimension [16, 19]. For photovoltaic applications, broadband wide-angle nano-patterned structures are required. The nano-patterned structures were fabricated on a silicon nitride passivation layer of a GaInP/GaAs/Ge triple-junction solar cell and showed an enhancement of its performance due to improve optical transmission and current matching [15]. Nano-patterned structures are formed using a polystyrene nanosphere lithography technique followed by anisotropic etching with a nanosphere size of 600 nm in diameter. The period of this nano-patterned structure is still comparable with the light wavelength in the visible regime of the solar spectrum.

In this report, disordered InGaP nano-pattern structures were formed by thermally dewetted Au nanoparticles and anisotropic dry etching processes. The effects of the InGaP nano-patterned structure on the optical reflection characteristics were investigated. It was found that the InGaP nano-patterned structure can reduce the optical reflection in a wide range of wavelengths and, thus, can work as an antireflection layer that could be useful for the application of photovoltaic devices.

2. MATERIALS AND METHODS

To form the Au nanoparticles pattern, 5 nm - thick Au thin film was deposited on the InGaP layer by an e-beam evaporator followed by an annealing process in a furnace at various temperatures of 200, 300, 400, and 450°C in argon environment. Heating and cooling speeds were set to 15°C/min and 5°C/min, respectively. The annealing time was fixed at 30 minutes for all samples. Top-view scanning electron microscopy (SEM) images of the dewetted Au nanoparticles pattern depended on annealing temperatures are shown in Fig. (**1**). The fabricated Au nanoparticles pattern was found to be the best when the annealing temperature is 400°C for 30 minutes. The Au nano-patterns were transferred to the InGaP window layer by an inductively-coupled-plasma reactive-ion-etching (ICP-RIE). The ICP-RIE system was operated with 200 W ICP and 50 W RF power at a chamber pressure of 10 mTorr under a gas mixture of BCl_3 and Cl_2 through individual electronic mass flow controllers. InGaP nano structures were controlled by ICP etching time that was varied from 30 to 50 s. The nano structure geometry was investigated using a field emission scanning electron microscopy (FE-SEM). The loss of incident light was evaluated by reflectance spectra from 1.5 to 4.0 eV photon energies which were measured using an UV-Vis-NIR Cary 5000 Spectrometer.

3. RESULTS AND DISCUSSION

The surface morphology of 5nm thick Au film was examined by SEM and shown in Fig. (**1a**). The image indicated that the surface of Au film was smooth and uniform. Figs. (**1b**-**1e**) show the SEM images of the Au film after annealing at 200, 300, 400, and 450°C for 30 minutes, respectively. It is indicated that Au nanoparticle is clearly formed when annealing temperature is higher 300°C. At 400°C and 450°C,

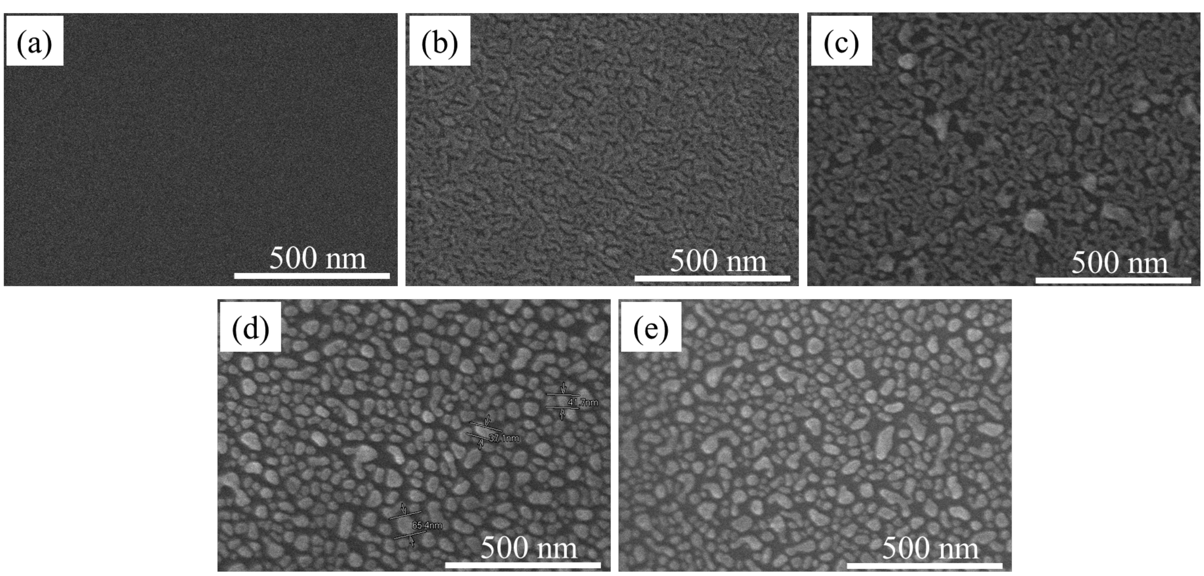

Fig. (1). Top-view FE-SEM image of (**a**) 5nm thick Au film, the Au nanomask after annealing at (**b**) 200°C, (**c**) 300°C, (**d**) 400°C, and (**e**) 450°C for 30 min in Ar environment.

the Au nanomask is composed of high-density randomly arranged nanoparticles with various shapes. The average size of the Au nanoparticles is about 50 nm. Therefore, in this work, annealing temperature of 400°C can be used to fabricate an Au nanomask from a 5nm thick Au film by thermally dewetted method.

The InGaP nano structures after dry etching using the Au nanomasks are shown in Fig. (**2**). The corresponding cross-sectional SEM images are also shown in Fig. (**2**). All the samples were etched under a gas mixture of 5 sccm BCl_3 and 30 sccm Cl_2 plasma condition. After dry etching, the InGaP nano structure was formed in conical shapes. The height of the cone was measured to be 95, 125, and 150 nm when etching time is 30, 40, and 50 s, respectively.

The optical reflectance spectra and the average optical reflectance of the samples after annealing at 400°C and etched with the different cone height can be seen in Figs. (**3a**) and (**3b**), respectively. The InGaP nano-patterned structures exhibited lower reflectance values, especially at the high photon energy region. The suppression of surface reflectance by the nano-patterned structure is mainly caused by two effects [14]. Firstly, at the photon energies which has photon wavelengths less than the spacing of the nanostructure, the redistribution of the incident light will lower the reflectance since the spacing of the protuberances is not sufficiently small. Secondly, at longer wavelengths, the reflectance is reduced by the gradual change in the refractive index, resulting in the Fresnel reflection suppression. Therefore, these combined effects were capable of reducing the reflectance of the solar cells over a wide regime of wavelengths. Another important component to reduce the reflectance is the relationship between height and wavelength [17].

Based on the suppression of surface reflectance by the nano-patterned structure, the InGaP nanostructure with the cone height of 150 nm was transferred to the window layer of a GaAs single junction solar cell. Fig. (**4a**) shows the current density – voltage (J-V) characteristics of the GaAs solar cells with and without the InGaP nano-patterned structure. The J-V characteristics indicated that the open circuit voltage (V_{oc}) and fill factor (FF) were almost unaffected by the InGaP window nanostructure. The short circuit current density (J_{sc}) was increased up to 18.57 mA.cm^{-2} when the InGaP nanostructure was introduced to the window layer of the single junction GaAs solar cell resulting in an increase of 14.8% in the J_{sc} of the patterned cell compared to that of the flat cell. This also indicates that the conversion efficiency enhancement is indeed attributed to the increase in the short circuit current density.

The suppression of the Fresnel reflection contributes to the optical absorption enhancement, which has also verified

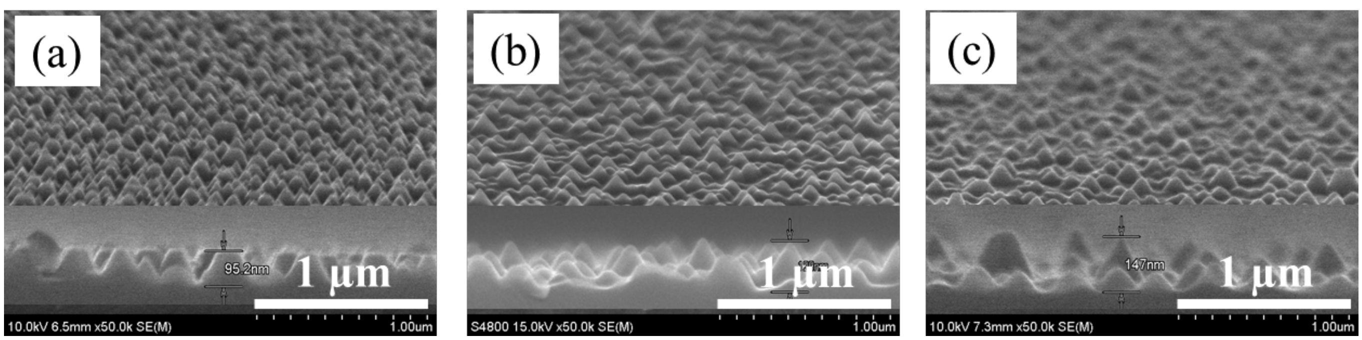

Fig. (2). Top- and side-view (inset) FE-SEM images of the InGaP nano-patterned structures after annealing at 400°C for 30 min and (**a**) 30s, (**b**) 40s, (**c**) 50s anisotropic etching time.

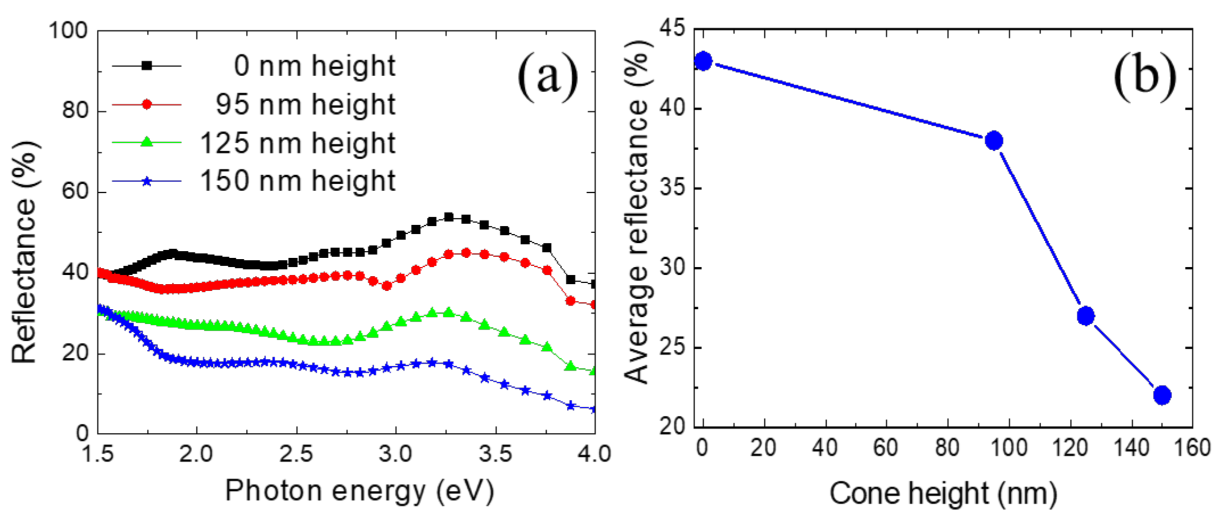

Fig. (3). (**a**) Optical reflectance spectra of the samples with various cone heights, (**b**) Relationship between average optical reflectance and cone height.

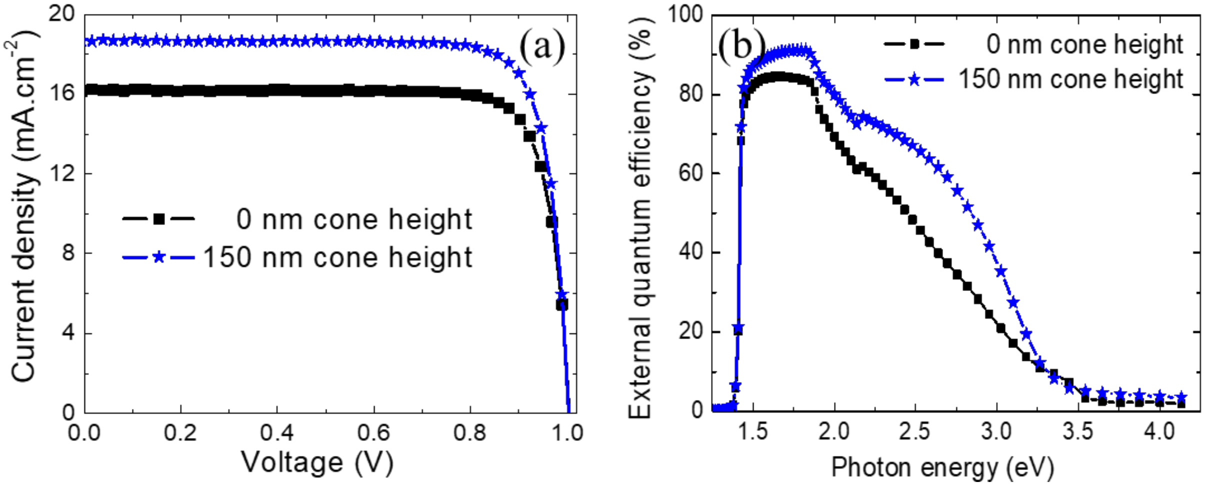

Fig. (4). (**a**) J–V curves and (**b**) external quantum efficiency (EQE) of the single junction GaAs solar cells with and without the InGaP nano-patterned structure.

in the EQE characteristics of the fabricated cells as shown in Fig. (**4b**). As can be seen in this figure, an improvement in the photocurrent response of the nano-patterned cell can be obtained in a range of photon energies from 1.5 eV to 4.5 eV compared to that of a planar cell. The improvement of the photocurrent response is caused by an excess carrier generation in the p-n junction of the single junction GaAs solar cell. In our work, the spacing of the InGaP nano-patterned structure is smaller than 300 nm. Therefore, the light absorption is mainly improved by the gradual change in the refractive index of the InGaP nano-patterned structure.

To deeply understand the observed external quantum efficiency, the EQEs of the patterned cell were normalized by that of the planar cell that is shown in Fig. (**5**). It was revealed that the external quantum efficiency was increased more over the high photon energies than the low photon energies. The average of the enhancement factor was approximately 1.24 for the cell with the InGaP nano-patterned structure. This enhancement is suitable for the suppression of the Fresnel reflection and the improvement in the short circuit current density results.

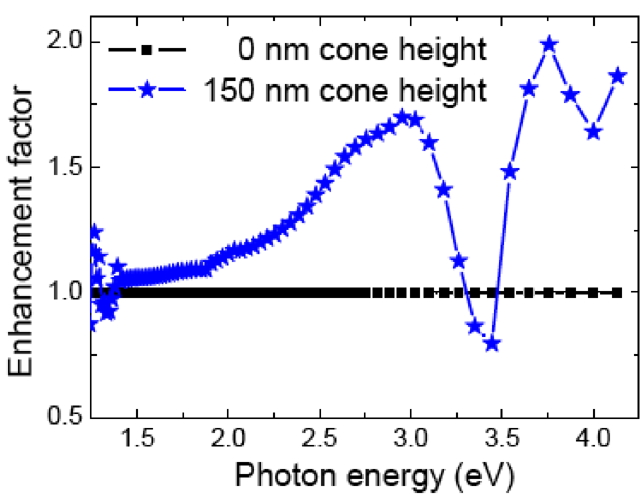

Fig. (5). Enhancement faction of the InGaP nano-patterned cell against a planar cell.

CONCLUSION

InGaP nano structures have been successfully fabricated by thermal dewetted Au nanoparticles and anisotropic dry etching methods. The fabricated Au nanoparticles pattern was found to be the best when the annealing temperature is 400°C for 30 minutes with the 5nm thick of Au film. By controlling dry etching time, the height of InGaP nanostructures can be varied from 95 nm to 150 nm. With the increase in height, the optical reflectance can be down to 22%. The InGaP nanostructure with the height of 150 nm was also introduced to the window layer of a single junction GaAs soar cell. The result indicated that the InGaP nanostructure only affects the short circuit current density that can be improved up to 14.8% compared to that of the planar cell.

LIST OF ABBREVIATIONS

ARCs	=	Antireflection coatings
EQE	=	External quantum efficiency
FF	=	Fill factor
ICP-RIE	=	Inductively-coupled-plasma reactive-ion-etching
J-V	=	Current density – voltage
SEM	=	Scanning electron microscopy

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

HUMAN AND ANIMAL RIGHTS

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

Not applicable

CONSENT FOR PUBLICATION

Not applicable.

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CONFLICT OF INTEREST

The authors declare that they have no competing interests

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Declared none.

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