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Efficiency enhancement of single-junction GaAs solar cells coated with europium-doped
silicate-phosphor luminescent-down-shifting layer

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Abstract

In this study, we investigated the electrical and optical performance of single-junction GaAs solar cells coated with an antireflective layer of indium tin oxide (ITO) via thermal sputtering deposition followed by a layer of SiO₂ doped with 3 wt% europium-doped (Eu-doped) silicate phosphors via spin-on film technique. The chemical composition of the Eu-doped silicate phosphors was analyzed using energy-dispersive X-ray spectroscopy and the luminescent downshifting (LDS) characteristics were examined in terms of photoluminescence, optical reflectance, and external quantum efficiency (EQE) response. Reverse saturation-current and ideality factor were used to evaluate the passivation performance of ITO films thermal sputtered on GaAs solar cells. The antireflective performance of the ITO film and the LDS effects of the Eu-doped silicate phosphor coatings were respectively evaluated in terms of optical reflectance and EQE response. The enhancement of photovoltaic performance due to LDS effects was confirmed by photovoltaic current density–voltage characteristics of cells under one-sun air mass 1.5G solar simulations. The efficiency enhancement of the cell with only an ITO/SiO₂ antireflective layer was 18.39%, whereas the cells coated a SiO₂ layer that included various species of Eu-doped phosphors (species-A, species-B, or species-C) on ITO achieved efficiency enhancements of 19.83%, 20.29%, and 21.07%, respectively.

Keywords: Europium-doped silicate phosphors; Indium tin oxide; Luminescence downshifting; Single-junction gallium arsenide solar cells

1. Introduction

Single-junction GaAs solar cells have the highest conversion efficiency among all types of single-junction solar cells [1]. Single-junction GaAs solar cells are also the most likely to achieve efficiencies approaching the Shockley-Queisser limit [2, 3]. Dielectric films of SiO_2 , TiO_2 , or Al_2O_3 are commonly applied to GaAs-based solar cells to provide antireflection or passivation effects [4-7]. Indium tin oxide (ITO) is widely used as a conducting oxide, due to its high electrical conductivity and high optical transparency [8-10]. ITO films have also been used on single-junction GaAs solar cells as a passivation and antireflection layer to improve conversion efficiency [11]. A number of methods have been devised to enhance conversion efficiency at short wavelengths, including the down-conversion (DC) or luminescent down-shifting (LDS) of the incident spectrum [12-17]. Europium-doped (Eu-doped) phosphors are excellent LDS species, due to their high luminescence quantum efficiency, large Stokes-shift, and persistent luminescence over a long lifespan, far exceeding that of CdS quantum dot-embedded silica films [18]. However, few studies have examined the LDS effects of the various species of Eu-doped phosphors on the device performance of GaAs solar cells [19-23].

In this study, we applied an ITO film as a passivation/antireflection layer on single-junction GaAs solar cells in conjunction with a SiO_2 layer that includes various species of 3 wt% Eu-doped silicate phosphors as an LDS layer with the aim of improving overall efficiency. The ITO coating was applied using thermal sputtering deposition and the SiO_2 layer with

Eu-doped silicate phosphors was deposited on the ITO using spin-on film technique. We examined the electrical and optical properties of the ITO film using measurements of dark current-voltage (I-V) and optical reflectance. The LDS characteristics of the Eu-doped silicate phosphors were examined in terms of photoluminescence, optical reflectance, and external quantum efficiency (EQE) response. Improvements in photovoltaic performance attributable to the LDS effects of the Eu-doped silicate phosphors were confirmed by characterizing the photovoltaic current density-voltage (J-V) characteristics of the cells under one-sun air mass 1.5G solar simulations.

2. Material and methods

2.1 Epitaxial layers of single-junction GaAs solar cell

Figure 1(a) presents the epitaxial layers of a single-junction GaAs solar cell grown by metal organic chemical vapor phase deposition (MOCVD) on a p⁺-type GaAs (100) substrate. Arsine and phosphine were used as group-V source gases, whereas trimethyl-gallium, trimethyl-indium, and trimethyl-aluminum were used as group-III precursors. Disilane and dimethyl-zinc were used for n- and p-type doping, respectively. Growth was conducted at a temperature of 640°C at a chamber pressure of 1.5×10^3 Pa. A p-GaAs buffer layer was first grown to a thickness of 300 nm, followed by layers of a p-InGaP back-surface field (70 nm), a p-GaAs emitter (100 nm), a n-GaAs base (3200 nm), an n-AlInP window as well as a front-surface field (30 nm) and a n⁺-GaAs contact (300 nm). The quality of the

epitaxial-layers was confirmed via measurements of photoluminescence, double crystal X-ray diffraction, and electrochemical capacitance-voltage.

2.2 Preparation and characterization of ITO and Eu-doped silicate phosphors layers

In this study, ITO film was used as a dual-function layer to provide antireflection as well as passivation effects. An ITO layer was applied to a thickness of 100 nm on the surface of the GaAs solar cells via RF sputtering (13.56 MHz) at a deposition rate of 0.064 nm/s with RF power of 40 W and a substrate temperature of 250 °C. A metallic target of In/Sn (90:10 wt%; 2 inch in diameter) with purity of 99.99% was used as the material source of the ITO. The distance between the substrate and the target was maintained at approximately 4 cm. The resistivity of the resulting ITO film was approximately $1.2 \times 10^{-4} \Omega\text{-cm}$, as determined using a four-point probe at room temperature. Thus, carrier mobility is expected to be approximately $20 \text{ cm}^2\text{V}^{-1}\text{S}^{-1}$. Average transparency of the resulting ITO film was > 81 %, as determined using an UV–VIS–NIR spectrophotometer (PerkinElmer LAMBDA 35, Waltham, MA, USA). To the silicate solution (Emulsitone Company product, Whippany, NJ, USA) was added various species of Eu-doped phosphor (InteMatix Company product, Fremont, CA, USA) at 3 wt%. The coating solution comprised 1.94 g of silicate solution combined with 0.06 g of Eu-doped phosphors of species-A (G2060TM), or species-B (EY4156), or species-C (O6040), respectively. The emission wavelengths of the Eu-doped phosphors were as follows: species-A (512 nm), species-B (550 nm), and species-C (610 nm). The mixed solutions were spin-coated onto clean silicon substrates at 3000 rpm for 60 s before being baked at 200 °C

for 30 min under an air atmosphere. The surface morphology and chemical composition of the samples with a SiO₂ layer (80 nm) comprising of Eu-doped silicate phosphors were examined using scanning electron microscopy and energy-dispersive X-ray spectroscopy (EDS; Hitachi S-4700, Hitachi High-Tech Fielding Corporation, Tokyo, Japan). The EDS major operating parameters are an emission current of 10 μ A, an accelerating voltage of 15 kV and a work distance of 12 mm in the analysis mode. The fluorescence emission of the Eu-doped silicate phosphor layers was confirmed by measurements of photoluminescence (PL; Ramboss 500i Micro-PL Spectroscopy, DONGWOO Optron, Korea) at room temperature using a solid-state UV laser with emission wavelength of 266 nm and emission power of 20 mW (MPL-F-266, Changchun New Industries Optoelectronics Technology Co., Ltd., P.R. China). The reflectance, LDS, and light scattering effects of the silicate layer with and without Eu-doped phosphors particles were characterized using an UV–VIS–NIR spectrophotometer (PerkinElmer LAMBDA 35, Waltham, MA, USA).

2.3 Fabrication and characterization of GaAs solar cells coated with ITO and Eu-doped silicate phosphors

Figure 1(b) presents a schematic diagram of single-junction GaAs solar cell coated with an ITO layer (100 nm) and a SiO₂ layer (80 nm) that includes 3 wt% Eu-doped silicate phosphors. The fabrication of bare-type single-junction GaAs solar cells involved the deposition of an n-ohmic contact of AuGe/Ni/Au films in a grid pattern on the n⁺-GaAs contact layer and an p-ohmic contact of AuBe/Ti/Au films on the rear surface of the p⁺-type

GaAs substrate via electronic-beam evaporation. Following lift-off and cleaning processes, the samples were annealed at 385 °C under ambient N₂ for 5 min. Citric acid was used for the selective removal of the n⁺-GaAs layer to expose the AlInP front surface field layer, followed by mesa etching of the p-GaAs buffer layer to isolate the cell. A 100-nm thick ITO layer was deposited on the surface of the GaAs solar cell via thermal sputtering. A silicate solution mixed with 3 wt% of Eu-doped phosphor powder was subsequently applied to the surface of the ITO using spin-on film coating. The passivation effects of the ITO film were characterized by measuring the dark current-voltage (I-V) curves using a semiconductor parameter analyzer (HP 4145B) at room temperature. The antireflective properties of the ITO layer coated with a SiO₂ layer with Eu-doped silicate phosphors were derived from measurements of optical reflectance using a UV/VIS/NIR spectrophotometer and external quantum efficiency (EQE; EQE-RQE-R3015, Enli Technology Co., Ltd., Kaohsiung, Taiwan). The EQE response was measured over a range of wavelengths from 350 to 1100 nm. The photovoltaic current density-voltage (J-V) characteristics of the proposed cells were measured using a solar simulator (XES-151S, San-Ei Electric Co., Ltd., Osaka, Japan) and source meter (Keithley 2400, Keithley Instruments, Inc., Ohio, USA) at 25 °C. The solar simulator was calibrated according to an NREL-certified crystalline silicon reference cell (PVM-894, PV Measurements Inc., Colorado, USA) before obtaining measurements.

3. Results and discussion

EDS is an analytical technique used for element analysis and chemical characterization. Each element within the sample has a unique atomic structure, which produces a unique set of peaks in its electromagnetic emission spectrum. Figure 2 presents the EDS spectrum of species-C (O6040) of Eu-doped silicate phosphor, with energy peaks corresponding to various elements in the sample. According to our EDS result, species-C was shown to be composed primarily of O, Sr, Si, Ba, and Ti with small quantities of Eu and Mn. The emission wavelength of species-C was 612 nm, as obtained from the InteMatix product data sheet. In this study, we derived the spectrum of only species-C because it provides the highest performance, and the EDS of species-A has already been published in a previous work [17].

Figure 3 presents the PL fluorescence emission spectra of samples of Eu-doped phosphors (species-A, species-B, or species-C). The wavelength of the excitation light source in the PL system was 266 nm. Table 1 lists the PL emission peaks and wavelength range of PL emissions at 10% of the maximum PL intensity using various species of Eu-doped phosphor. These results indicate that most of the incident photons at UV wavelengths were absorbed by the Eu-doped phosphors particles and re-emitted at visible wavelengths (450–775 nm), thereby demonstrating LDS behavior. The downshifted photons were re-emitted incidental to the GaAs cell, which means that they were absorbed closer to the depletion region of the p–n junction. This effect promoted the collection of photo-generated charge carriers and suppressed the recombination of charge carriers of short-wavelength (300–450 nm), which

were generated near the surface. The photo-responsivity curve of a bare single-junction GaAs solar cell is also plotted in Fig. 3 for further comparison. Responsivity is a measure of electrical output of a photodiode per optical input, and is a function of the wavelength of the incident radiation. A higher responsivity value is indicative of higher photo-generated current output at the same wavelength and incident optical power. High efficiency photovoltaic devices require a wider PL emission band and photon emissions at wavelengths in which the semiconductor has high responsivity. Thus, based on the responsivity values of GaAs material, coating the cells with species-C is preferable to coating the cell with either species-B or species-A.

Figure 4 presents the measured optical reflectance of the bare GaAs cell, a cell with an ITO layer, a cell with an ITO/SiO₂ layer, and cells with a SiO₂ layer containing Eu-doped phosphors on the ITO. The reflectance of the cells with ITO on the GaAs cell was lower than that of the bare GaAs solar cell across the range of wavelengths, thereby demonstrating the excellent anti-reflective performance of ITO films when deposited via thermal RF sputtering. The cells with a SiO₂ layer with Eu-doped phosphors deposited over the ITO presented reflectance values lower than those of the cell with only an ITO/SiO₂ layer in a wavelength range of 350 to 450 nm. This can be attributed to the absorption of incident light by the Eu-doped phosphors. Similarly, cells coated with a SiO₂ layer with various species of Eu-doped phosphor presented reflectance values lower than those of the cell with only an ITO/SiO₂ in a wavelength range of 450 to 700 nm. This is indicative of the forward scattering

of incident photons by Eu-doped phosphor particles. We also calculated the average weighted reflectance values (R_W) from 350 to 450 nm and from 350 to 1000 nm, as shown in Table 2. The R_W of cells coated with a SiO_2 layer with Eu-doped phosphors was approximately 4% lower than that of the cell with only an ITO/ SiO_2 layer, due to the absorption of incident light by the Eu-doped phosphors. Reducing the reflectivity of photovoltaic devices means that a larger number of incident photons enter the active layer of the photovoltaic devices to produce higher EQE values.

Figure 5 presents the measured EQE response of a bare GaAs cell, a cell with an ITO/ SiO_2 layer, and cells with a SiO_2 layer that includes various species of Eu-doped phosphors on the ITO. The average weighted external quantum efficiency (EQE_W) values were calculated at wavelengths from 350 to 450 nm and from 350 to 1000 nm, as shown in Table 2. The EQE responses of the cell with an ITO/ SiO_2 layer and cells with a SiO_2 layer with Eu-doped phosphors on ITO are in strong agreement with the results of optical reflectivity. The EQE_W of cells coated with a SiO_2 layer with Eu-doped phosphors was approximately 2 to 4% higher than that of the cell with only an ITO/ SiO_2 layer due to the LDS effects imposed by the Eu-doped phosphors. Furthermore, the EQE_W value of the cell coated with a SiO_2 layer that included species-C (64.83%) was higher than that of the layer with species-B (64.13%) as well as the layer with species-A (63.61%) in the wavelength range of 350 to 450 nm. These results are in strong agreement with the PL results, due to the fact that the emission of photons

by species-C is within the range of wavelengths where the semiconductor has high responsivity.

Figure 6 presents the dark I-V curves of a bare GaAs cell, a cell with an ITO layer, a cell with an ITO/SiO₂ layer, and cells with a SiO₂ layer with various species of Eu-doped phosphors on ITO. The reverse saturation current-density (J_0) and ideality factor (n) were extracted from the dark current-voltage curves for evaluation of the passivation performance of the various coatings on the GaAs solar cells. The calculated n and J_0 values were as follows: bare cell (2.89 and 8.37×10^{-10} A/cm²), cell with ITO layer (2.71 and 5.33×10^{-10} A/cm²), cell with ITO/SiO₂ layer (2.74 and 5.55×10^{-10} A/cm²), and cells with a SiO₂ layer with various species of Eu-doped phosphor on ITO (2.76 and 5.68×10^{-10} A/cm²). The J_0 and n of the GaAs cell coated with ITO, ITO/SiO₂, and SiO₂ layers with Eu-doped phosphors on ITO were smaller than that of the bare GaAs cell. Generally, lower n and J_0 values are indicative of low surface recombination as well as superior passivation effects.

Figure 7 presents the photovoltaic J-V curves of a bare GaAs cell, a cell with an ITO layer, a cell with an ITO/SiO₂ layer, and cells with a SiO₂ layer that includes various species of Eu-doped phosphors on ITO. In this work, the bare GaAs solar cells with much the same level of J_{sc} of were firstly screen out, then those solar cells coated with a SiO₂ layer comprising of various species of Eu-doped phosphors upon the ITO layer were measured and compared to examine the contribution of LDS effects. After screening, the solar cells were grouped into 3 batches (batch #1, #2 and #3) for device processing and characterization. Table 3 summarizes

the photovoltaic performance of the batch #1 evaluated cells. The short-circuit current density (J_{sc}) of a solar cell is a function of the cell's external quantum efficiency EQE (λ) and the AM1.5G photon flux density $\phi(\lambda)$, as determined in the following:

$$J_{sc} = q \int_{\lambda_1}^{\lambda_2} EQE(\lambda) \times \phi(\lambda) d\lambda. \quad (1)$$

Table 3 presents the short-circuit current density (J_{sc-EQE}) of the proposed solar cells calculated from the EQR response (Fig. 5) using Eq. (1) with integration. Table 3 compares the short-circuit current density ($J_{sc-AM1.5G}$) of the proposed solar cells, based on AM 1.5G solar simulations. Our results reveal that the calculated and measured short-circuit current density values are similar. The application of an ITO/SiO₂ layer on the bare solar cell was shown to increase the J_{sc} by a factor of 18.57% (from 22.19 to 26.31 mA/cm²) and the efficiency (η) by a factor of 18.39% (from 19.36% to 22.92%), due to the antireflective properties. Due to LDS effects, cells with a SiO₂ layer with Eu-doped phosphors (species-A, species-B, or species-C) respectively presented an increase in J_{sc} (ΔJ_{sc}) of 1.22%, 1.61%, and 2.27%, compared to the cell with a SiO₂ layer but without Eu-doped phosphors. Furthermore, the conversion efficiency of the cell with species-C was 23.44%, exceeding that of the cell with species-B (23.29%) and the cell with species-A (23.20%) Eu-doped phosphors. Moreover, the obtained performances of J_{sc} and η of three batches solar cells are listed in Table 4. The statistically calculated results were presented the average values and standard deviations of J_{sc} and η , respectively. The photovoltaic current density–voltage characteristics

under one-sun air mass 1.5G solar simulation confirms that the photovoltaic performance of the cells was improved by the LDS effects imposed by the Eu-doped phosphors.

Figure 8 presents the photovoltaic J-V curves of the proposed cells, which were obtained by measuring the voltage from -1 V to 1.2 V. The bare cell, the cell with an ITO/SiO₂ layer, and cell with an SiO₂ layer with species-C Eu-doped phosphors on ITO respectively presented photovoltaic current-density values (J_{ph}) of 22.23, 26.34, and 26.93 mA/cm² under reverse bias voltage of -1 V, which is slightly higher than the 22.19, 26.31, and 26.89 mA/cm² obtained at zero voltage. The reverse leakage current on the proposed cells was low (in the sub-microampere range), which indicates that device processing was well-controlled.

4. Conclusions

This study experimentally demonstrated the degree to which the efficiency of single-junction GaAs solar cells could be enhanced by LDS effects imposed by a coating of SiO₂ with various species of Eu-doped silicate phosphors over an ITO layer. The ITO film applied via thermal sputtering presented good passivation and antireflective properties. The LDS effects of various species of Eu-doped silicate phosphor were examined in terms of optical reflectance, external quantum efficiency, and photovoltaic current density–voltage measurements. Coating the cells with Eu-doped phosphors was shown to improve efficiency by > 20%, compared to the 16.94% efficiency obtained from cells without Eu-doped phosphors. The Eu-doped phosphors presented wider LDS emission bands and greater photon emissions at wavelengths

in which the responsivity of the semiconductor is high. This is particularly beneficial in single-junction GaAs solar cells.

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Figure captions

Figure 1: (a) Epitaxial layers of single-junction GaAs solar cell grown by MOCVD; (b) schematic diagram showing single-junction GaAs solar cell coated with ITO layer and SiO₂ layer that includes 3 wt% Eu-doped silicate phosphors

Figure 2: Energy-dispersive X-ray spectroscopy (EDS) spectrum of species-C (O6040) Eu-doped silicate phosphor

Figure 3: Photoluminescence (PL) fluorescence emission spectra of samples with species-A (G2060TM), species-B (EY4156), and species-C (O6040) Eu-doped phosphors at room temperature

Figure 4: Measured optical reflectance of bare GaAs cell, cell with ITO layer, cell with ITO/SiO₂ layer, and cells with SiO₂ layer that includes various species of Eu-doped phosphor on ITO

Figure 5: Measured EQE response of bare GaAs cell, cell with ITO/SiO₂ layer, and cells with SiO₂ layer that includes various species of Eu-doped phosphor on ITO

Figure 6: Dark I-V curves of bare GaAs cell, cell with ITO layer, cell with ITO/SiO₂ layer and

cells with SiO_2 layer that includes various species of Eu-doped phosphor on ITO

Figure 7: Photovoltaic J-V curves of bare GaAs cell, cell with ITO layer, cell with ITO/ SiO_2 layer and cells with SiO_2 layer that includes various species of Eu-doped phosphor on ITO

Figure 8: Photovoltaic J-V curves of proposed cells showing reverse bias current by measuring voltage from -1 V to 1.2 V

Table captions

Table 1: PL emission peaks and the wavelength range of PL emission at 10% of maximum PL intensity of various species of Eu-doped phosphor

Table 2: Average weighted reflectance (R_w) and average weighted external quantum efficiency (EQE_w) values calculated from 350 to 450 nm and from 350 to 1000 nm

Table 3: Photovoltaic performance of bare GaAs cell, cell with ITO layer, cell with ITO/SiO₂ layer, and cells with SiO₂ layer that includes various species of Eu-doped phosphor on ITO

Table 4: The obtained photovoltaic performances and statistically calculated results of the average values and standard deviations of J_{sc} and η of three batches solar cells

Table 1:

Species of Eu-doped silicate phosphors	PL emission		Responsivity
	peak (nm)	wavelength range (nm)	(A/W)
		@ 10% of max. PL intensity	@ PL emission wavelength range
Species-A (G2060TM)	516.4	458 - 604	0.393 - 0.514
Species-B (EY4156)	553.7	481 - 720	0.402 - 0.601
Species-C (O6040)	608.6	527 - 733	0.441 - 0.642

Table 2:

GaAs solar cell	Rw (%)	Rw (%)	EQE _w (%)	EQE _w (%)
	@350 - 450 nm	@350 - 1000 nm	@350 - 450 nm	@350 - 1000 nm
Bare solar cell (SC)	31.08	28.21	51.90	59.85
SC/ITO/SiO ₂	18.61	15.55	60.84	70.31
SC/ITO/SiO ₂ comprising species-A	14.56	12.46	63.61	72.11
SC/ITO/SiO ₂ comprising species-B	14.46	12.41	64.13	72.47
SC/ITO/SiO ₂ comprising species-C	14.11	12.30	64.83	72.62

Table 3:

GaAs Solar Cell	V_{oc} (V)	$J_{sc-AM1.5G}$ (mA/cm ²)	J_{sc-EQE} (mA/cm ²)	Fill Factor (%)	η (%)	ΔJ_{sc} (%)	$\Delta \eta$ (%)
Bare solar cell (SC)	1.048	22.19	22.00	83.21	19.36	---	---
SC/ITO	1.054	25.94	26.22	82.76	22.64	16.90	16.94
SC/ITO/SiO ₂	1.053	26.31	26.01	82.74	22.92	18.57	18.39
SC/ITO/SiO ₂ comprising species-A	1.053	26.66	26.64	82.63	23.20	20.14	19.83
SC/ITO/ SiO ₂ comprising species-B	1.053	26.72	26.71	82.76	23.29	20.41	20.29
SC/ITO/SiO ₂ comprising species-C	1.053	26.89	26.74	82.77	23.44	21.18	21.07

$J_{sc-AM1.5G}$: measured under AM1.5G solar simulation

J_{sc-EQE} : calculated by EQE response

Table 4:

	Batch #1	Batch #2	Batch #3	Avg.	Std. Dev.
	Jsc	Jsc	Jsc	of Jsc	of Jsc
	(mA/cm ²),	(mA/cm ²),	(mA/cm ²),	(mA/cm ²),	(mA/cm ²),
	η (%)	η (%)	η (%)	η (%)	η (%)
GaAs Solar Cell (SC)	22.19,	22.07,	22.15,	22.14,	0.061,
	19.36	19.26	19.33	19.32	0.051
SC/ITO	25.94,	25.85,	25.89,	25.89,	0.045,
	22.64	22.56	22.60	22.60	0.040
SC/ITO/SiO ₂	26.31,	26.23,	26.27,	26.27,	0.041,
	22.92	22.86	22.88	22.89	0.031
SC/ITO/SiO ₂ comprising species-A	26.66,	26.53,	26.64,	26.61,	0.070,
	23.20	23.09	23.17	23.15	0.057
SC/ITO/SiO ₂ comprising species-B	26.72,	26.65,	26.70,	26.69,	0.036,

	23.29	23.25	23.27	23.27	0.020
SC/ITO/SiO ₂	26.89,	26.79,	26.85,	26.84,	0.050,
comprising species-C	23.44	23.31	23.41	23.39	0.068

Highlights

1. Luminescent down-shifting (LDS) of species of Eu-doped phosphors was investigated.
2. The performance of GaAs solar cell was enhanced using LDS of Eu-doped phosphors.
3. The impressive efficiency enhancement of 21.07% was obtained due to LDS effects.

(a)

Contact	n-GaAs:Si	(300 nm)
FSF	n-AlInP:Si	(30 nm)
Base	n-GaAs:Si	(3200 nm)
Emitter	p-GaAs:Zn	(100 nm)
BSF	p-InGaP:Zn	(70 nm)
Buffer	p-GaAs:Zn	(300 nm)
p-GaAs (100) substrate		(550 μ m)

(b)

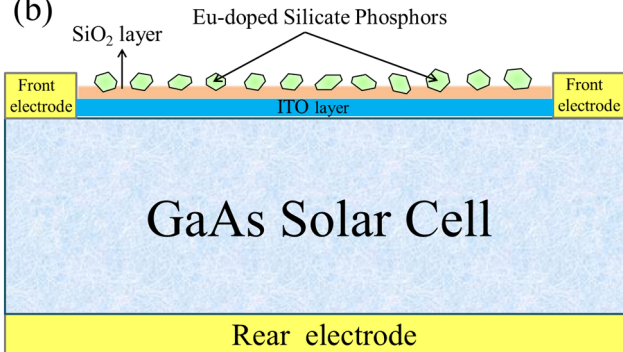


Figure 1

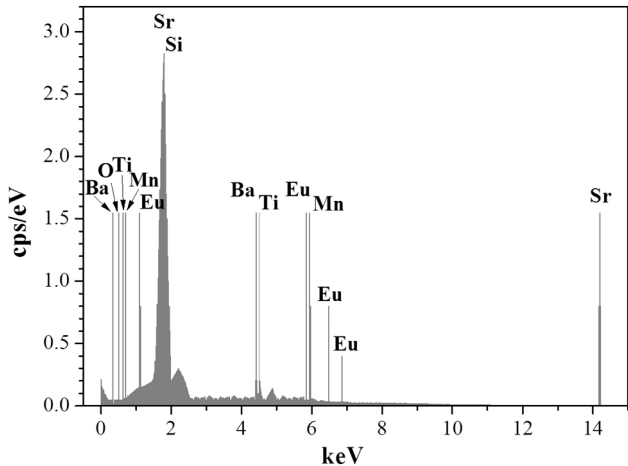


Figure 2

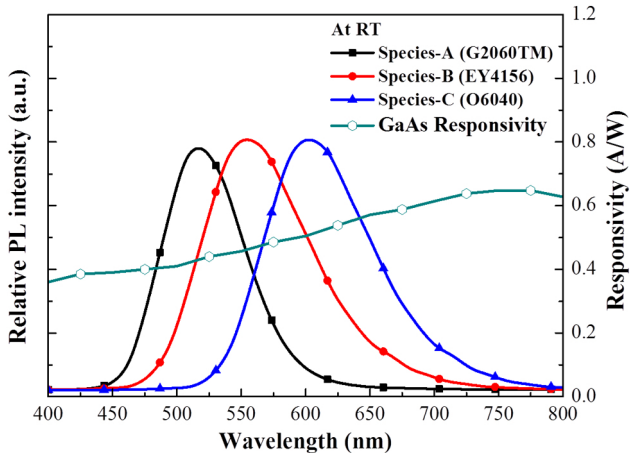


Figure 3

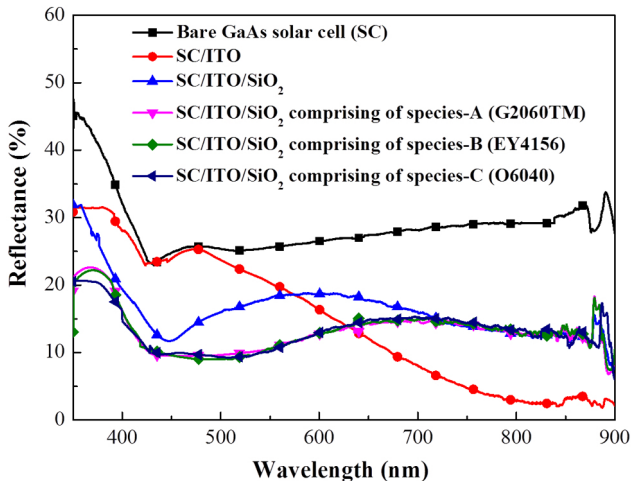


Figure 4

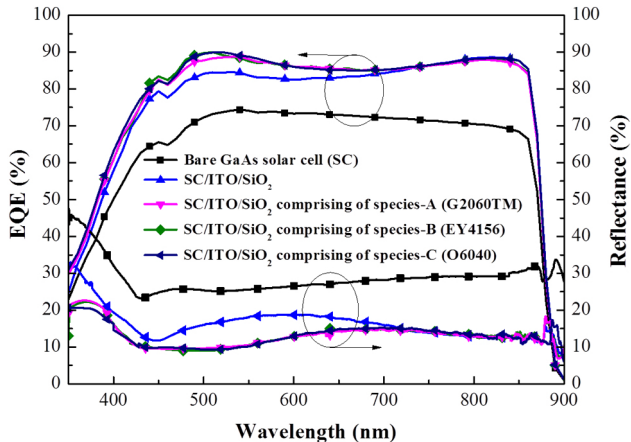


Figure 5

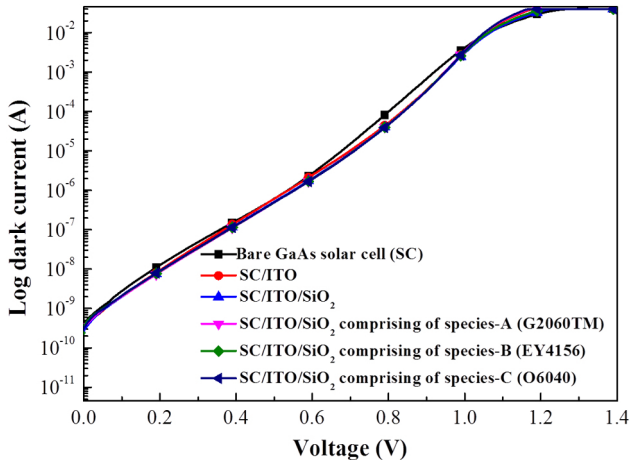


Figure 6

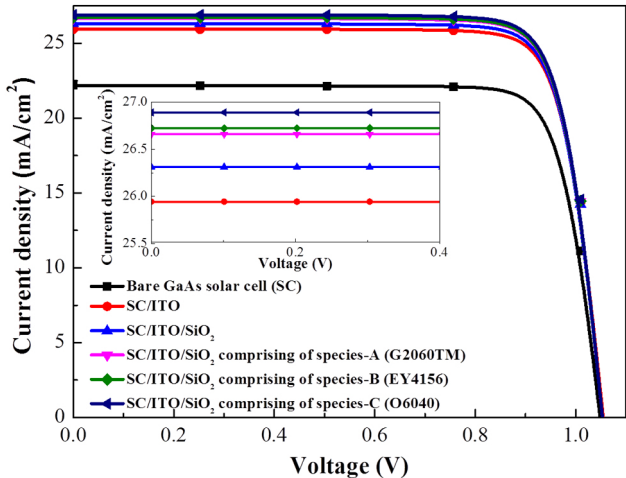


Figure 7

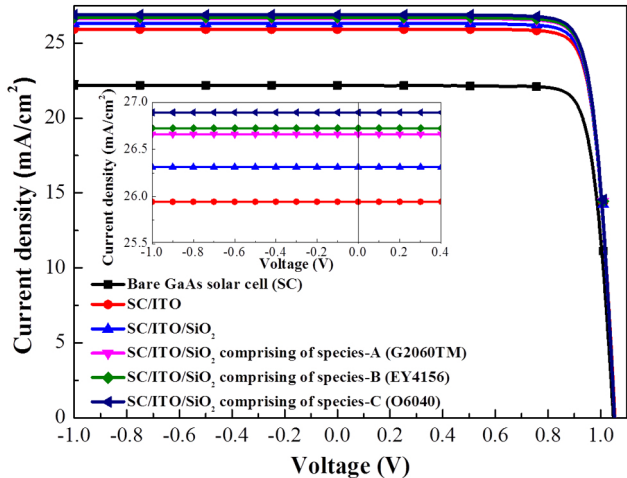


Figure 8