Luminescent coverglass for improved absorption efficiency in III–V photovoltaic modules

W.I. Nam, E.K. Kang, H.G. Park, D.-H. Jun and Y.M. Song✉

An initial demonstration is reported in terms of maximising performance of photovoltaic modules. Experimental results of a triple junction solar cell covered with a 3 mm red-emitting luminous glass which can be efficiently excited by ultraviolet light indicate that this combination exhibits significantly enhanced efficiency of 36.5% under one-sun of AM1.5G. Integrating a luminescent (LSC) glass onto modules without converting any fabrication process at the device level is considered to be one of the predominant advantages of this device. Additionally, in order to achieve strong visible emission, it is mandatory to determine a thickness of LSC coverglass due to the edge reflection.

Introduction: Multi-junction III–V solar cells have recently been considered to be one of the imperative aspects to maximise performance of photovoltaic (PV) systems due to their strong durability and high photon absorption over the broadband range by controlling bandgaps of different materials, resulting in virtually ideal bandgap combination [1, 2]. Introducing broadband antireflection (AR) property, resulted from a nano-patterned surface, has also widely been proposed to enhance efficiency of PV cells. We have previously studied this concept based on a triple junction solar cell by a thin film coating which consists of gradually varying refractive index structures called 'moth-eye', thereby minimising parasitic reflection over the broad wavelength range [3]. Its central beneficial feature was unnecessary of altering any fabrication procedure at the device level. However, low ultraviolet (UV) response was observed since the cell was encapsulated with glass which absorbs UV light and the minimum controllable range by III–V compound semiconductor was still above the UV range (300–400 nm). To address the above limitation (i.e. enhancing UV responses), several research groups have developed diverse down-shifting materials [4]. Until recently, however, the majority of reported approaches were normally applied to crystalline silicon solar cell.

We therefore demonstrate a new concept, which has not been proposed yet, to improve efficiency of sub-receiver modules by combining a triple junction solar cell and a luminescent (LSC) coverglass for down-shifting, integrated onto a silicone resin instead of ordinarily used glass. In doing so, not only can we obtain an advantage in terms of fabrication procedure, providing no concern about modification of the fabrication process at the device level, but also we can enhance the UV responses of PV cells by down-shifting UV photons into visible photons, resulting in brilliant performance over the entire solar spectral range (300–1800 nm) with III–V triple junction solar cells. The effect of LSC glass thickness is also discussed.

Optical design of structure: Fig. 1 shows a schematic illustration of standard lattice-matched III–V triple junction solar cell [$Ga_{0.5}In_{0.5}P$, gallium arsenide (GaAs) and germanium (Ge) and active area = 0.3025 cm^2] with an LSC coverglass, which is made by Sumita [5]. A borosilicate coverglass (BORO33, Schumit) was also considered as a reference. As shown in inset in Fig. 1, the LSC glass exposed to UV light illumination, we used in our design, exhibits a red-emitting property, which means down-shifting UV photons into visible photons (red) without affecting light at longer wavelengths. As depicted, various light propagation mechanisms are indicated as red arrows. Light escaping at the edges of the LSC coverglass and a case of surface reflection unavoidably occurring at the interface between air and LSC glass due to difference of indices are analysed as detrimental contributions to efficiency of modules. However, light directly penetrating into the solar cell and a case undergoing total internal reflection at the interface between air and LSC glass are interpreted to improve UV responses, leading to enhance the performance of PV systems. To examine the effect of LSC glass thickness on down-shifting property, 1 mm (1T) and 3 mm (3T) of LSC coverglasses were considered.

Result and discussion: Fig. 2*a* shows the experimental results of emission (top) and excitation (bottom) spectra with different LSC thicknesses. The excitation and monitoring wavelengths are 325 and 613 nm, respectively. The reason why peak values of 3 T in both figures are visibly higher than that of 1T is due to light guiding effect as well as increased thickness. To provide further insight into the effect of down-shifting property with increasing thickness on performance of solar cells, transmittance demonstrated in Fig. 2*b* was measured as a function of wavelength over the entire solar spectrum. The dips of comparatively low transmittance are observed at 312, 361, 380, 393, 463 and 530 nm in which emissions of 613 nm occur as shown in bottom Fig. 2*a*. It is attributed to excitation due to material profile which is capable of converting invisible UV ray into visually observable visible ray.

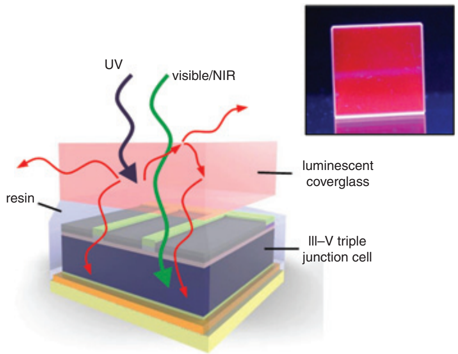

Fig. 1 *Schematic illustration of III–V triple junction [indium gallium phosphide/GaAs/Ge] solar cell with LSC coverglass. Red arrows indicate down-shifted light emission by UV light excitation. Inset shows photograph of red-emitting LSC glass due to UV illumination*

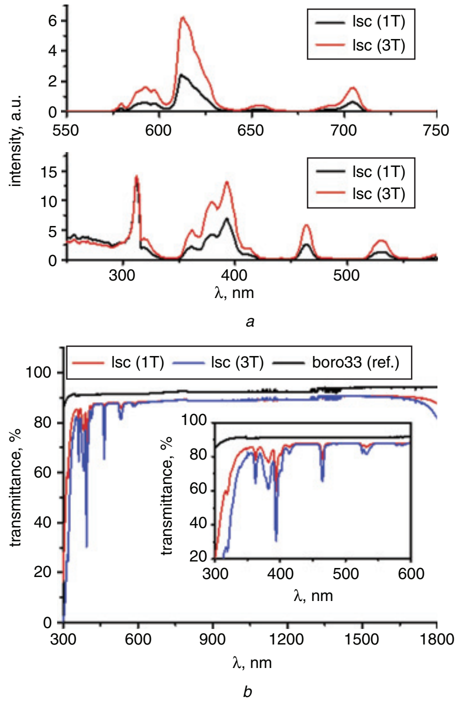

Fig. 2 *Optical properties of LSC coverglass with different thicknesses*

a Emission (top) and excitation (bottom) spectra for thicknesses of 1 and 3 mm. Excitation and monitoring wavelengths are 325 and 613 nm, respectively
b Measured transmittance as function of wavelength
Inset: magnified plot of (b)

Fig. 3*a* displays digital photographs of three different PV sub-receiver modules with (i) a conventional coverglass (BORO33), (ii) a thickness of 1 mm LSC and (iii) a thickness of 3 mm LSC. For the case of UV light illumination is shown in bottom figure. As depicted, it is inadequate to assert that 1T LSC glass exhibits high performance of down-shifting profile since no dramatic difference is observed between (i) and (ii). However, for the case of 3 T, red-emitting property is straightforwardly noted compared with other two devices. This result indicates that a thickness of LSC glass which strongly influence performance of down-shifting property should be considered in order to maximise efficiency of triple junction solar cells.

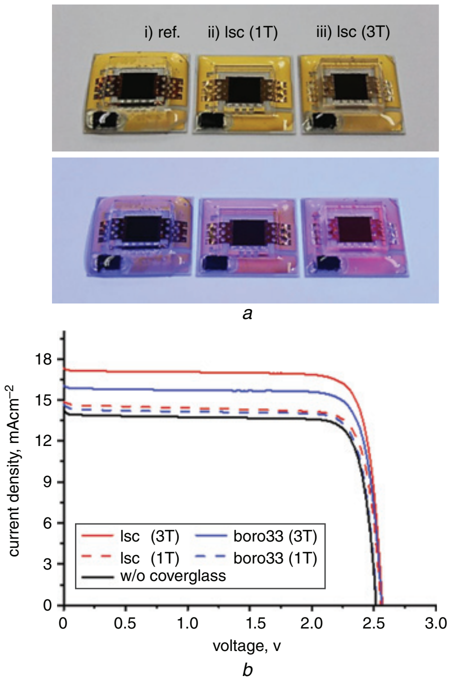

Fig. 3 *Digital photographs and J–V curves of sub-receiver modules*

a (i) BORO33, (ii) LSC (1T) and (iii) LSC (3T) before (top) and after (bottom) UV illumination
b Measured of *J–V* characteristics with five different types under AM1.5G one-sun

To study further the effect of LSC glass on efficiency of solar cells, *J–V* curves of sub-receiver modules demonstrated in Fig. 3*b* were measured under one-sun of AM1.5G. A triple junction solar cell without a coverglass exhibits a short-circuit current (J_{sc}) of 14.3 mA cm^{-2} and both BORO33 and LSC glass with a thickness of 1 mm show slightly improved J_{sc} of 14.6 and 14.9 mA cm^{-2}, respectively. As we mentioned before, difference between these two devices is still subtle, which means that down-shifting property of 1T LSC coverglass is improper for enhancing efficiency of solar cells. However, the thicker the glasses (3Ts), the higher the short-circuit current due to the edge reflection. For the case of 3Ts, difference between LSC and BORO33 is larger than that of 1Ts, denoting that down-shifting property is considerably improved.

The performance characteristics of the modules with diverse coverglasses are summarised in Table 1. The largest enhancement of J_{sc} (17.3 mA cm^{-2}) was achieved by the case of 3T LSC coverglass, leading to the highest efficiency (36.5%) among devices. Any distinct improvement is not discovered in terms of circuit voltage (V_{oc}), meaning no deterioration in electrical properties and fill factor (FF) was slightly developed compared with other devices. This result can be a significant step in the design of future generations of high-performance solar cells.

Table 1: Device characteristics of PV modules for five different types

Types	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF (%)	η (%)
w/o coverglass	2.5	14.3	80.7	29.1
BORO33 (1T)	2.5	14.6	81.0	29.6
BORO33 (3T)	2.6	16.1	81.4	33.6
LSC (1T)	2.6	14.9	80.3	30.6
LSC (3T)	2.6	17.3	82.0	36.5

Conclusion: In conclusion, triple junction PV modules with various coverglasses were investigated. Our studies indicate that in order to obtain the highest performance of III–V triple junction solar cells, material of coverglass and its thickness should be considered. A combination of triple junction solar cell and LSC coverglass which is capable of exhibiting fluorescence in the visible region by UV ray excitation can be adopted for current commercial solar modules without altering fabrication process at the device level. In this regard, this concept can be expected to provide a promising potential in designing various PV devices to maximise their efficiencies. Further performance enhancement can be obtained by introducing AR property such as nano-patterning to suppress unnecessary reflection at the interface between air and coverglass.

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W.I. Nam (*Department of Electronics Engineering, Pusan National University, Geumjeong-gu, Busan 609-735, Republic of Korea*)

E.K. Kang, H.G. Park and Y.M. Song (*School of Electrical Engineering and Computer Science, Gwangju Institute of Science and Technology, Gwangju 61005, Republic of Korea*)

✉ E-mail: ymsong@gist.ac.kr

D.-H. Jun (*Nano Business Support Center, Korea Advanced Nano-fab Center, Suwon 16229, Republic of Korea*)

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