

IMPROVEMENT OF SHORT-CIRCUIT CURRENT IN MULTIJUNCTION A-SI BASED SOLAR CELLS USING TiO₂ ANTI-REFLECTION LAYER

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ABSTRACT: The development of TiO₂ thin films as anti-reflection layer (ARL) has been investigated and the application of TiO₂ in a-Si based multijunction superstrate thin film solar cells has been demonstrated. First, the TiO₂ thin films have been applied to the a-Si single junction solar cell and with optimized TiO₂ thin films, the FF of the a-Si solar cells does not seem to be affected due to the incorporation of ARL in the device configuration. A slight decrease in the blue response (<500nm) of the solar is observed in the quantum efficiency, which is counterbalanced by the increase in the same from 500-800nm wavelength region. The TiO₂ thin films have been applied to double (a-Si/ μ c-Si) and triple (a-Si/a-SiGe/ μ c-Si) junction solar cells and ~10% improvement in the short-circuit current has been obtained without deterioration of other solar parameters.

Keywords: a-Si, TiO₂, multijunction solar cells

1 INTRODUCTION

In the recent years, improvement in efficiency of a-Si based solar cells has shown a clear direction to follow the multijunction structure in device fabrication. The most successful device configurations being double (a-Si/ μ c-Si) and triple (a-Si/a-SiGe/ μ c-Si) junction cells where a-Si, a-SiGe and μ c-Si layers have been used as active layers. The record efficiency in any amorphous silicon based devices has been reported as 15.1% [1]. Thanks goes to high short-circuit current (J_{sc}) drawn from each of the spectrum splitting component junctions, that mainly boosted up the efficiency level. However, when the increase in the current drawn from each component junctions is only associated with increase in the thickness of the individual intrinsic layers, severe light induced degradation is expected with a-Si based layers. The initial and stabilized performance of the a-Si based multijunction solar cell differs huge when the thickness of amorphous layers is increased to gain short-circuit current. Therefore, a precise current management is needed for the thin film solar cells, which minimizes associated loss of illumination in the device due to inefficient device design. This could reduce the thickening of the active layers without affecting the short-circuit current.

In case of a glass superstrate based device structure, such a loss of illumination occurs due to refractive index (n) mismatch between the transparent conducting oxide viz. ZnO ($n \sim 1.8$) and Si ($n \sim 3.6$) layers. A layer of TiO₂ ($n \sim 2.5$) at ZnO and silicon interface has shown to have potential to act as an anti-reflection layer (ARL) for improvement of the current loss due to refractive index mismatch [2]. In this paper, application of TiO₂ as an anti-reflection layer has been investigated for a-Si based solar cells, to be used as components in a multijunction device structure. The effect of incorporation of TiO₂ has been studied for double and triple junction solar cells where a-Si, a-SiGe and μ c-Si have been used as active layers.

2 EXPERIMENTAL

2.1 TiO₂ thin film

The TiO₂ thin films have been developed by rf-magnetron sputtering of TiO₂ target using Ar and O₂ gas mixture environment. The doping concentration of the TiO₂ target is varied where undoped and Nb₂O₅ doped ceramic targets have been used. In the preparation of TiO₂ films, the substrate temperature, rf-power, the O₂ concentration in gas phase and the layer thickness has been varied. The detail experimental process and consequent optimization of the TiO₂ film properties with electrical and optical characterizations is described elsewhere [Berginski et al, this conference]. The layer properties are also optimized with their application in single junction p-i-n solar cells.

2.2 Silicon thin films

The silicon thin films have been deposited by either RF (13.56 MHz) or VHF (95 MHz) PECVD method using SiH₄, H₂ and GeH₄ gases for the active layers and using PH₃ and TMB as dopant gases for n and p doped layers respectively. The a-Si, a-SiGe, μ c-Si materials have been used as active layers for the multijunction solar cells. Both the 10x10 cm² and 30x30 cm² substrate area compatible PECVD systems have been used for the thin film deposition process where low (<1 Torr) and high (3-10 Torr) pressure regimes in the deposition process have been used.

2.3 Solar cells

The glass substrate is used in superstrate p-i-n configuration for the fabrication of solar cells. The standard solar cells are deposited on ZnO coated glass, where the ZnO is texture-etched with HCl. In case of the solar cells with ARL, the TiO₂ layer has been deposited on the texture-etched ZnO and covered with a very thin film of ZnO (10nm) to protect it from H₂ plasma reduction process during exposure to PECVD silicon deposition. The rest of the fabrication process is same as that of a standard solar cell. The back contact of the solar

cells has been fabricated with either Ag or ZnO/Ag. The solar cells have been measured with solar simulator for evaluation of solar parameters. The quantum efficiency (QE) and thereby the integrated J_{sc} have been calculated for the solar cells. This integrated J_{sc} is used to evaluate the J_{sc} from each of the component cells in a multijunction stack.

3 RESULTS AND DISCUSSIONS

3.1 TiO₂ thin films

The TiO₂ thin films have been deposited on Corning glass for the characterization of their electrical and optical properties. The evaluation and optimization of the properties of the films have been described in detail in another article in this conference [3]. The further optimization of the TiO₂ films has been done with respect to their application in solar cells and consequent evaluation of the performance of those solar cells.

3.2 Single junction solar cells with ARL

The TiO₂/ZnO bilayer as ARL is applied in the fabrication of a-Si solar cells on texture-etched-ZnO coated glass substrate. Either in a single or multijunction configuration, the ARL and the p-layer of an a-Si p-i-n solar cell, form a new interface compared to a standard cell. Therefore, the application of ARL has been first studied for an a-Si single junction cell which could serve as a top cell in a multijunction stack. The results are showing the feasibility of introducing such an ARL in the device. A number of depositions have been done with variation in the O₂ concentration in Ar in gas phase during its sputter-deposition process. The other deposition conditions have been already optimized during materials development and kept same for the solar cell application. The results of the performance of the solar cells are given in Table 1. The J_{sc} increases slightly with application of the ARL, without any reduction in the FF, indicating no deterioration of the interface quality with this bilayer structure.

Table I: Solar parameters of a-Si single junction cells with ARL deposited with variation of O₂ in Ar.

	V _{oc} (V)	FF	J _{sc} (mA/cm ²)	η (%)
Standard	0.92	0.70	15.46	9.9
ARL I (0.2% O ₂)	0.91	0.71	15.47	10.0
ARL II (0.5% O ₂)	0.91	0.69	15.51	10.0

The quantum efficiency curves for the solar cells for standard and with ARL I have been shown in Fig. 1. The QE curves show wavelength dependence of the effect of ARL in the a-Si solar cell. At shorter wavelength (<500nm) the QE decreases whereas in the 500-700nm region a clear increase in QE is observed. The decrease in blue response should be recovered to exploit this gain efficiently and further investigations on the bilayer and p-layer properties and on their interface are needed for this purpose.

The same ARL is also applied to μ c-Si and a-SiGe single junction solar cells to study the effect on QE of these solar cells. Fig. 2 and Fig. 3 shows the QE curves of the μ c-Si and a-SiGe solar cells respectively, comparing the standard and with ARL I.

In case of the μ c-Si cells, increase in QE is noticed for 550-800nm, however, without significant reduction in short wavelength region. The decrease in short wavelength (<450nm) QE from the a-SiGe cell is counterbalanced with a considerable increase in the wavelength region >450nm.

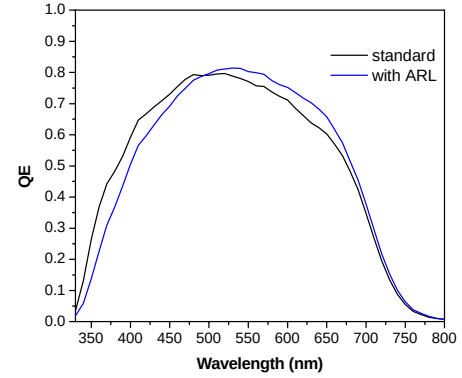


Figure 1: QE curves of the a-Si solar cells for standard and with ARL I.

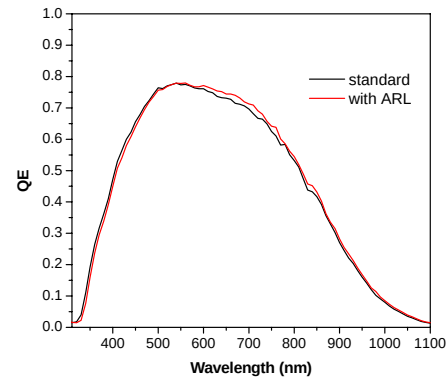


Figure 2: QE curves of the μ c-Si solar cells for standard and with ARL I.

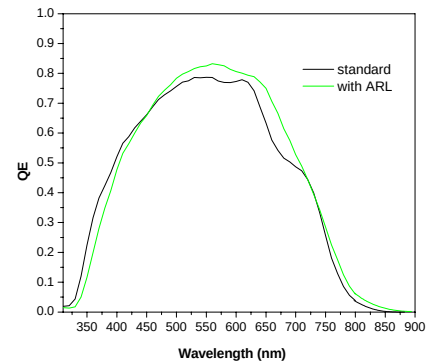


Figure 3: QE curves of the a-SiGe solar cells for standard and with ARL I.

3.3 Multijunction solar cells with ARL

The optimized ARL for the single junction cells has been applied in the development of a-Si/ μ c-Si double junction solar cells. During the fabrication process, the deposition condition for the all silicon layers has been kept unaltered, and the standard double junction cell has been compared with that developed with TiO₂/ZnO

bilayer ARL. The result of the introduction of the ARL has been studied with the performance of the solar cells. The results for the standard and the same cell with ARL have been shown in the Table II.

Table II: Solar parameters of a-Si/ μ c-Si double junction cells for standard and with ARL

	V_{oc} (V)	FF	J_{sc} (mA/cm ²)	η (%)
Standard	1.37	0.70	10.54	10.1
ARL	1.40	0.70	11.47	11.3

The application of ARL clearly indicates the increase in J_{sc} of the solar cell and the J_{sc} increases by 8.8% for the a-Si/ μ c-Si double junction solar cell. In the case of double junction cells also, no deterioration of the FF is observed with the incorporation of ARL in the device design. The quantum efficiency curves for the standard cell and the cell with ARL have been shown in Fig. 4. This QE curves depicts the wavelength dependent variation due to incorporation of ARL. The short-wavelength (<450nm) response decreases slightly from the top a-Si cell with ARL. However, the response in the wavelength region of 450-850nm increases significantly from both the component cells with ARL.

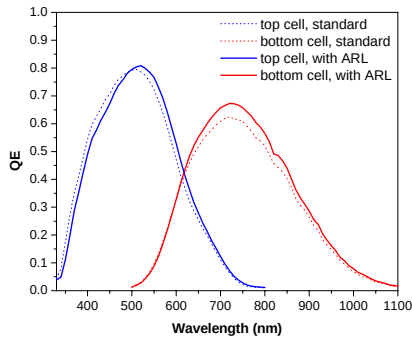


Figure 4: QE curves of the a-Si/ μ c-Si double junction solar cells for standard and with ARL.

Thus, the significant enhancement in QE is observed in the wavelength range between 500-800nm with the incorporation of the optimized ARL in a-Si based solar cells of single and double junction device configurations.

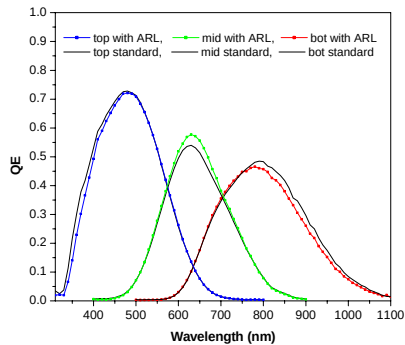


Figure 4: QE curves of the a-Si/a-SiGe/ μ c-Si triple junction solar cells for standard and with ARL.

This wavelength region corresponds to the absorption from a middle junction component cell in a triple

junction stack. Thus, the application of the ARL should have beneficial effect in enhancing the J_{sc} of the middle component cell in a triple stack. The triple junction a-Si/a-SiGe/ μ c-Si solar cells have been fabricated in this program to study the effect of incorporation of ARL to a standard device configuration. In Fig. 5 the QE curves of the triple junction cells for the standard one and the same with ARL has been shown. In Table III, the J_{sc} measured from I-V characteristics and the integrated J_{sc} from the QE measurements for the triple junction cells have been shown.

Table III: J_{sc} of the a-Si/a-SiGe/ μ c-Si triple junction cells and the contributions from each component cells for standard and with ARL

J_{sc} (mA/cm ²)	I-V	QE		
		Top	Middle	Bottom
Standard	7.14	8.08	7.12	7.80
ARL	8.01	7.95	7.46	7.46

An increase in J_{sc} is observed with triple junction solar cell deposited with ARL. The J_{sc} from individual component cells indicate that the current is limited by that from the middle component cell and the improvement in J_{sc} is from the middle component is also reflected in the J_{sc} obtained from the I-V measurement (12.5%). Further optimizations are needed regarding the fabrication of triple junction cells with proper current matching to utilize the improvement of J_{sc} with application of ARL.

4 CONCLUSIONS

- TiO₂ thin films have been developed by rf-sputtering method and optimized for application as anti-reflection layer.
- Application of TiO₂/ZnO bilayer as ARL has been demonstrated for single junction a-Si solar cells. The incorporation of the optimized ARL does not deteriorate the interface properties as reflected in FF of the solar cells.
- The ARL is applied for double (a-Si/ μ c-Si) and triple (a-Si/a-SiGe/ μ c-Si) junction solar cells. Considerable improvement in J_{sc} (~10%) is obtained from the multijunction solar cells corresponding to the enhancement of QE in the wavelength region of 500-800nm.

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6 REFERENCES

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