ANALYSIS OF OPTICAL ENHANCEMENT IN a-Si n-i-p SOLAR CELLS USING A DETACHABLE BACK REFLECTOR

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ABSTRACT

We have used a novel device structure to study optical enhancement and back reflectors (BRs) in a-Si n-i-p solar cells by separating the effects of substrate texture, BR texture, and BR reflectivity. QE and diffuse and total reflection are compared for devices on smooth or textured substrates, with smooth or textured BRs. There is little improvement in J_{sc} for substrate haze exceeding 5%. Substrate texture is much more effective at increasing red response than the BR texture. Smooth substrates with textured BRs have comparable diffuse reflection but much higher specular reflection than textured substrates with a smooth BR. Devices on textured substrates also have lower reflection losses in the blue regions, resulting in higher QE at all wavelengths. These results apply to both superstrate and substrate device configurations.

INTRODUCTION

Analyzing the optical enhancement in a-Si solar cells is a challenging problem for both superstrate (glass/TCO/p-i-n/BR) and substrate (SS/BR/n-i-p/TCO) device structures where BR is the back reflector, TCO is a transparent conductive oxide and SS is the stainless steel substrate. Typically, in a superstrate device the front TCO provides the texture and the rear BR provides reflectivity, while in the substrate device the BR provides both texture and reflectivity. The BR increases short circuit current (Jsc) and red response by reflecting and scattering (if textured) weakly absorbed photons. This increases their optical pathlength. The theoretical maximum for the enhancement in pathlength is m~60 [1] but this decreases rapidly with parasitic absorption in the device. Gains of m=2-5 in optical pathlength have been obtained experimentally [2,3] suggesting parasitic absorption losses exceeding 25% [1]. Despite considerable analysis, BR enhancement and parasitic losses are not well understood [4,5]. We have studied optical enhancement in a-Si n-i-p solar cells with detachable BRs by separating the effects of substrate texture, BR texture, and BR reflectivity. Detachable BRs have been previously used to study optical enhancements and were reported to have less parasitic losses than integral BRs [1].

DEVICE STRUCTURES

Substrates were glass with TCO layers having haze at 700 nm of 0, 1, 5 and 14%. The smooth TCO (0% haze) was sputtered ZnO, the TCO with 5% haze was LPCVD ZnO, and the TCO with 1 and 14% haze were APCVD SnO_2 [4]. Single junction a-Si n-i-p devices with ~0.25 um i-layers were deposited by glow discharge at ECD having a device structure: ITO/p-i-n/TCO/glass (fig. 1). For comparison, devices were codeposited on SS and textured ZnO/Ag/SS [6], which are standard substrates for the n-i-p device configuration. Reflection (R), transmission (T), quantum efficiency (QE), and J_{sc} (AM1.5 global) were measured for illumination through the ITO (front) and the glass (rear) sides. QE was measured at -1V to minimize collection losses. Then, a smooth Ag BR (Ag film evaporated on glass) or textured Ag BR (Ag film evaporated on the 14% haze SnO_2) was optically coupled to the glass substrate with an index matching coupling liquid having n=1.5, giving a removable external Ag BR (figure 1). This allowed measurements of three different BR (no Ag, smooth Ag, or textured Ag) on the same device sample, without changing the device structure or substrate texture.

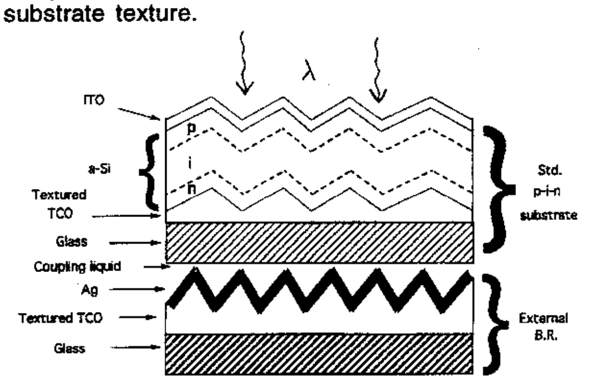

Fig. 1. ITO/p-i-n/TCO/glass device on textured TCO substrate with external BR and coupling liquid.

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RESULTS

Figure 2 shows the QE for light through the ITO/p front contact for the four different TCO/glass substrates without any Ag BR. Note the large improvement in red QE as haze increases from 0 to 5%, but there was no further gain in red QE for haze above 5%. Table 1 lists J_{SC} and QE at 700 nm for the devices before and after applying the external smooth Ag BR, confirming the limited increase in J_{SC} for haze greater than 5%. Similar conclusions have been reached for superstrate p-i-n devices [7,8]. Devices on ECD's ZnO/Ag BR had slightly higher J_{SC} than the 14% textured TCO with Ag BR. The J_{SC} and QE are very similar and low for the devices on smooth ZnO and on SS, indicating very little reflection or optical enhancement for either. Also note that the smooth Ag BR increases the QE at 700 nm by ~0.1 for all textured devices but has a much smaller effect on the smooth device (0% haze). Figure 2 and Table 1 indicate a significant increase in optical enhancement with even 1% haze over a smooth substrate. For example, with the smooth Ag BR, the substrate with 1% haze TCO provides over half of the gain in J_{SC} and QE achieved by the 14% haze substrate.

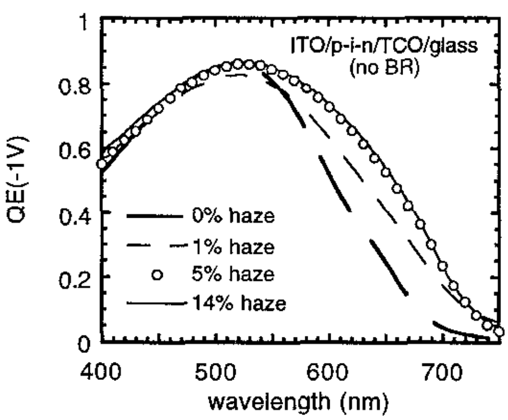

Fig. 2. QE for devices on textured TCO substrates with different haze (no BR).

Figure 3 shows the QE at -1V with different external back reflectors for devices having the least (0%) and greatest (14%) haze. Since the BRs were externally coupled, they only increase reflection and/or scattering of weakly absorbed light but do not affect the a-Si surface texture, substrate or n/TCO reflectivity. This is a unique feature of these devices. Enhanced QE with the optically coupled smooth Ag BR was equivalent to that found by evaporating an Ag film directly on the back of the glass substrate, indicating no additional losses associated with the coupling of the external BR. Table 2 shows J_{SC}, both absolute and normalized to the smooth TCO without an Ag BR (11.6 mA/cm^2), along with the QE, and total reflection and transmission all at 700 nm. The device with 0% haze shows that J_{SC} increases by 12% with the external smooth Ag BR and 15% with the external textured Ag BR. Thus, most of the increase occurs due to increased reflectivity of the smooth Ag. The texture of the BR has a smaller impact than the reflectivity of the BR. The reflection at 700 nm for the device with 0% haze increases substantially, by ~0.20, with either the smooth or textured Ag BR, yet the QE only increases by 0.02 or 0.06, respectively. Thus, at most one tenth of the light transmitted through the smooth device at 700 nm is captured when an Ag BR applied.

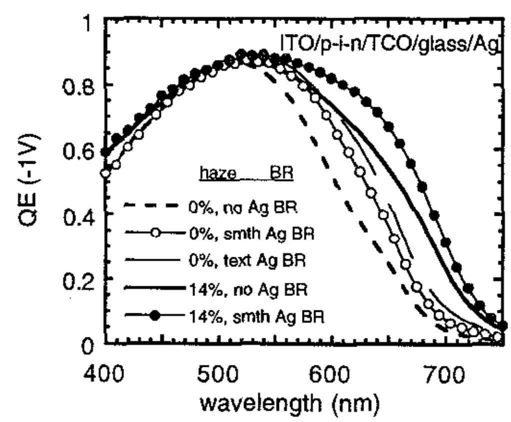

Fig. 3. QE for devices on smooth and textured TCO with no BR, smooth Ag BR, and textured Ag BR. QE for device on textured TCO with textured BR was same as for smooth BR (solid circles), hence not shown.

Table 1. J_{SC} and QE for devices of Figure 2 without and with a smooth external Ag BR. Devices deposited on ECD's standard n-i-p substrates SS (no BR) and textured ZnO/Ag/SS (BR) shown for comparison.

haze	J_{SC} (mA/cm^2)	J_{SC} (mA/cm^2)	QE@700 nm	QE@700 nm
	no Ag BR	smooth Ag BR	no Ag BR	smooth Ag BR
0%	11.6	13.0	0.05	0.07
1%	12.5	14.1	0.12	0.22
5%	13.7	14.7	0.22	0.32
14%	13.9	15.1	0.22	0.32
ECD	11.3 (SS)	15.5 (ZnO/Ag)	0.04	0.39

Table 2. J_{sc} data for devices of Figure 3 with 0 and 14 % haze and different Ag BRs. (J_{sc} ratio is improvement relative to 0%, no Ag).

Haze	external BR	J_{sc} (mA/cm^2)	J_{sc} ratio	QE @700nm	T @700 nm	R @700 nm
0%	none	11.6	1.00	0.05	0.52	0.27
	smooth Ag	13.0	1.12	0.07	0	0.46
	text. Ag	13.3	1.15	0.11	0	0.48
14%	none	13.9	1.20	0.22	0.20	0.15
	smooth Ag	15.0	1.30	0.32	0	0.18
	text. Ag	15.0	1.30	0.32	0	0.18

Instead, a much larger fraction of the previously transmitted light escapes the device by reflection from the front. Regarding the device on the textured substrate (14% haze), Jsc increases by 20% without any BR compared to the smooth substrate. Either the smooth or textured rear Ag BR gives an additional 10% increase in J_{sc} for the device on the textured substrate. With the BR, half of the light transmitted through the textured device at 700 nm without the BR is absorbed and contributes to increased QE (from 0.22 to 0.32). Thus, a textured substrate without a BR, even though transparent, is much more effective at light trapping than a textured Ag BR on a smooth device. This suggests that the replication of the substrate texture on the top a-Si surface is crucial to enhance multiple scattering from the underlying substrate.

Comparing the total and diffuse reflection, shown in Figures 4 and 5, can give further insight to the QE results of Figure 3. The total reflection for the device on the smooth TCO substrate with either no BR or the smooth Ag BR (Fig. 4) shows strong interference beyond 600 nm, and negligible diffuse reflection (<0.04), as expected for a smooth device and smooth BR. Interference effects would be expected for a device deposited on a smooth integral Ag BR (p-i-n/Ag/glass). The smooth or textured Ag BR causes a significant increase in the red reflection, but little increase in red QE (Table 2). Figure 5 shows that a device on a textured substrate has identical total or diffuse reflection with either the smooth or textured Ag BR. There is no additional diffuse reflection with a textured substrate having a textured BR nor was there any increase in Jsc or QE (table 2). Note that the reflection between 400-500 nm is lower for the device on the textured substrate (Fig. 5) compared to the device on the smooth substrate. The QE in this region is higher for the device on the textured substrate as expected (Fig. 3). The textured substrate produces a textured front surface, which has lower total reflection but much higher diffuse reflection compared to a smooth device. This has also been found for p-i-n devices in the superstrate configuration [9].

Thus, devices on textured substrates have higher QE in the blue due to lower front surface specular reflection, and higher QE in the red due to enhanced light trapping and lower rear specular reflection.

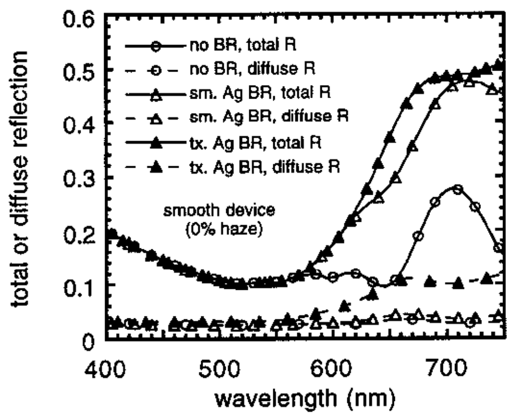

Fig. 4. Total and diffuse reflection from front ITO/p surface for device on smooth TCO (0% haze) with no BR, smooth BR, and textured BR.

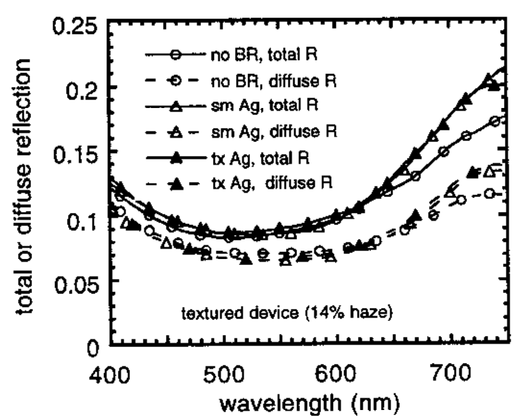

Fig. 5. Total and diffuse reflection from front ITO/p surface for device on textured TCO (14% haze) with no BR, smooth BR, and textured BR.

EFFECT OF ILLUMINATION DIRECTION: n-i-p vs p-i-n

QE was also measured through the glass side on devices without any Ag BR. Figure 6 compares the QE through the front ITO/p contact and through the rear glass/textured TCO contact for the most textured (14% haze) device . The QE beyond 600 nm was the same through the glass side as through the ITO. This was true for devices with 1% and 5% haze as well. Thus, superstrate p-i-n and substrate n-i-p devices can achieve equivalent optical enhancement from a given textured substrate, before application of a Ag BR, in agreement with ref. 10.

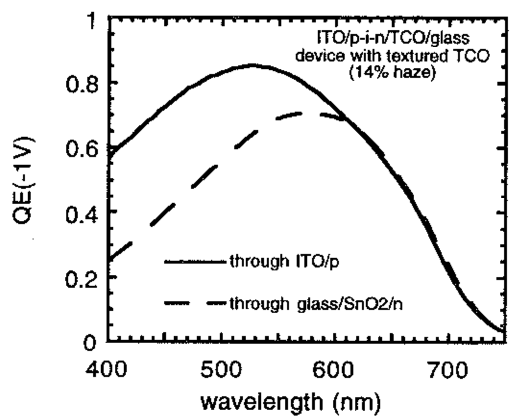

Fig 6. QE for device on textured (14% haze) TCO through ITO/p and glass/TCO/n sides, no BR.

DISCUSSION AND CONCLUSIONS

The effect of substrate and BR texture and BR reflectivity on optical enhancement has been analyzed and separated in ITO/p-i-n/textured TCO/glass devices with a range of substrate texture. There is negligible increase in J_{SC} and red response for haze greater than 5%, in agreement with studies on superstrate p-i-n devices. A textured substrate is significantly more effective at increasing red response than a smooth substrate with external textured Ag BR. Devices on smooth substrates with a textured Ag reflector have much higher specular reflection losses than devices on textured substrates with smooth Ag reflectors. Applying the external BR to a device on a smooth substrate increases the red QE only slightly. Instead, the reflection of red light escaping the front surface after being reflected at the BR increases due to incomplete internal reflection. Textured substrates have lower front reflection losses and hence higher blue response , thus having higher QE at all wavelengths. There appears to be no advantage to having a highly textured BR in addition to a separate highly textured substrate. These results have direct consequences for designs which propose to improve stability by depositing very thin devices on smooth substrates, to avoid shunting problems, and achieve optical enhancement with an external textured BR as studied here . Such devices will have inefficient light trapping and reduced Jsc compared to a device on a textured substrate, independent of whether they are a superstrate or substrate configuration.

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