

Exploring the Limits and Balancing Efficiency, Transparency, and Esthetics in Ultrathin a-Si:H Transparent Photovoltaic Devices

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Transparent photovoltaic (TPV) devices represent a promising advance in photovoltaic technologies, particularly in building-integrated photovoltaics (BIPV). Unlike conventional photovoltaics, which primarily prioritize efficiency, TPV must balance between efficiency, transparency, and aesthetics. These additional dimensions introduce unique challenges on device architecture. This article reports the development of wide-bandgap, inorganic-based TPV devices integrating ultrathin hydrogenated amorphous silicon (a-Si:H) as a transparent absorber, with carrier selective contacts and transparent electrodes. The article analyzes how absorber thickness influences the electrical, optical, and aesthetic performance of devices, evaluating key parameters in TPV such as light utilization efficiency (LUE), average photopic transmittance (APT), color rendering index (CRI), and electrical properties such as power conversion efficiency (PCE). The device structure is SLG/FTO/AZO/a-SiC_x(n)/a-Si:H/V₂O₅/AZO. This approach results in PCE ranging from 1.7% with an APT of 60% to a PCE of 4.1% with an APT of 28%, yielding LUE values between 0.9% and 1.3%. Device characterization encompasses optical spectrophotometry, J–V measurements under standard test conditions, spectral response analysis, and variable illumination measurements (VIM). Additionally, color characterization is conducted using CIE 1931 color space maps to determine the chromaticity coordinates, CRI, and the variation of color as a function of absorber thickness.

1. Introduction

In the continuous quest for sustainable and efficient energy solutions, transparent photovoltaic (TPV) solar energy has emerged as an innovative and promising technology. In contrast to traditional solar cells,^[1] which are often opaque and visually intrusive, this new generation of photovoltaic technology offers the possibility of integrating solar energy harvesting directly onto transparent architectural elements, such as windows^[2] and building façades.^[3] This innovative approach not only harnesses available sunlight but also enhances the esthetic appeal and functionality of urban structures.^[4] These transparent solar cells have the potential to be integrated into architecture and sustainable construction and have a strong interest in the development of multifunctional optoelectronic devices.^[5] However, reducing manufacturing costs remains a critical objective to make this technology economically viable and competitive in the energy market,^[6] which could position hydrogenated amorphous silicon solar cells^[7,8] as an attractive option for clean and renewable energy generation in the future.

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The devices studied in this research are based on the integration of a nanometric hydrogenated amorphous silicon layer (a-Si:H)^[9] that is sandwiched between two charge-carrier selective contacts: a hole transport layer (HTL) and an electron transport layer (ETL).^[10] These selective layers play a crucial role in separating the photogenerated charge carriers. The HTL allows the flow of holes while blocking electrons and the ETL does a complementary work, allowing the pass of electrons while blocking holes. Various materials have been investigated for these layers, including MoO_x,^[11] V₂O_x,^[12] and NiO_x,^[13] as HTLs, and silicon-doped, AZO and TiO_x as ETLs. From this study, the optimal device configuration includes vanadium oxide (V₂O_x) as the HTL^[14] and n-type phosphorous-doped hydrogenated amorphous silicon carbide (a-SiC_xH_(n)) as the ETL.^[15] The transparent conductive oxides (TCOs) chosen to complete the device were fluorine-doped tin oxide (FTO) for the back contact and aluminum-doped zinc oxide (AZO)^[16] for the front contact^[17] enabling connection to an external circuit. The absorber material where photogenerated electron-hole pairs are created was intrinsic hydrogenated amorphous silicon (a-Si:H). This study focuses on analyzing the impact of absorber thickness (varied from 22 to 233 nm) on the performance of the TPV device while keeping other layers constant.^[12] The absorber thickness is critical for optimization, as increasing the thickness leads to higher photocurrent generation,^[18] that is, a major number of electron-hole pairs photogenerated per second,^[17] which is reflected in an increase in the short-circuit current density (J_{sc}). However, as one could expect it is also observed that a higher thickness results in lower average photopic transmittance (APT) and color rendering index (CRI).^[19]

It is relevant to highlight that these devices are made to avoid the use of the cataloged Critical Raw Material (CRM) or toxic/hazardous materials. In this sense, diborane (which is usually used for the HTL deposition on traditional amorphous silicon devices) has been avoided. It is worth mentioning that all the layers are deposited at relatively low temperatures (below 200 °C) resulting in a low thermal-budget fabrication process. Additionally, the different deposition techniques involved in the device manufacturing allow a conformal and controlled deposition of the different nanometric layers that compose the solar cell structure.

2. Experimental Design, Results, and Discussion

Planar ultrathin TPV devices were fabricated with the following architecture: SLG/FTO/AZO/a-SiC_xH_(n)/a-Si:H/V₂O_x/AZO.

This work focuses on studying the effect of varying the thickness of the absorber layers, while AZO, a-SiC_xH_(n) and V₂O_x are kept unchanged for a more accurate comparison. For this study, seven samples were prepared with the following absorber layer thickness: 22, 35, 56, 70, 76, 123, and 233 nm. The absorber deposition was carried out using a mixture of 36 sccm of silane (SiH₄) and 12 sccm of methane (CH₄). Throughout the process, pressure, temperature, and gas flow conditions were kept constant, with only the deposition time varied to adjust the absorber thickness, as shown in Figure 1.

Once each sample was fully grown, the active area of the cells was defined and isolated using a conventional UV photolithographic process (Figure 2a), followed by wet chemical etchings. In this way, an effective electrical isolation of the cells is achieved and setting, at the same time, the active cell area (0.25 cm²), as shown in Figure 2b.

3. Optical Characterization

Transmittance and reflectance spectra were employed to determine the values of APT and CRI, as per the equations provided in the methodology outlined by Traverse et al.^[20] APT was calculated using Equation (1), where T is the transmission, P is the photopic response of the human eye, and S is the solar photon flux (AM1.5G). In this equation, the integration limits were defined between 380 and 825 nm. For more detailed information on APT and CRI calculations, see ref. [20] (please note that ref. [20] names this parameter as average visible transmittance). However, we establish the nomenclature to be average photopic transmittance (APT) as it is more precise and also because the term average visible transmittance can be confounded with the concept of mean visible transmittance, which does not account for the human eye's photopic response $P(\lambda)$ which governs our perception of color).

$$APT = \frac{\int T(\lambda)P(\lambda)S(\lambda)d\lambda}{\int P(\lambda)S(\lambda)d\lambda} \quad (1)$$

The optical properties of the completed TPV devices were characterized by measuring the reflectance and transmittance spectra that are shown in Figure 3a. The transmittance spectra revealed a decrease in both parameters (APT and CRI) as the absorber thickness increased. Reflectance spectra (Figure 3b) showed minor variations with a notable maximum between 390 and 550 nm, centered at 450 nm, which suggests significant

	S0	S1	S2	S3	S4	S5	S6
TCO ₂	AZO	AZO	AZO	AZO	AZO	AZO	AZO
HTL	V ₂ O _x	V ₂ O _x	V ₂ O _x	V ₂ O _x	V ₂ O _x	V ₂ O _x	V ₂ O _x
Absorber	22 nm	35 nm	56 nm	70 nm	76 nm	123 nm	233 nm
a-Si:H							
ETL	a-SiC _x H _(n)	a-SiC _x H _(n)	a-SiC _x H _(n)	a-SiC _x H _(n)	a-SiC _x H _(n)	a-SiC _x H _(n)	a-SiC _x H _(n)
TCO ₁	AZO	AZO	AZO	AZO	AZO	AZO	AZO
	FTO	FTO	FTO	FTO	FTO	FTO	FTO
	Glass	Glass	Glass	Glass	Glass	Glass	Glass

Figure 1. Device structure with absorber thickness variations.

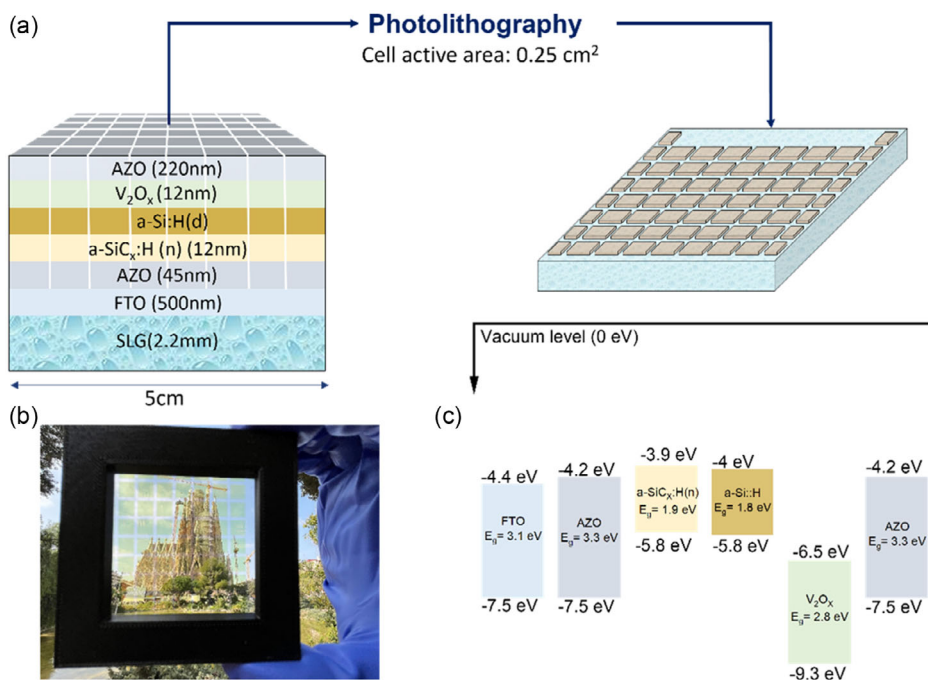


Figure 2. a) (left) Schematic illustration of the TPV device architecture (not to scale). (right) Schematic illustration of the TPV device reference architecture after photolithography with 49 cells of 0.25 cm². b) Picture of the full device, taken outdoors in broad daylight; the picture shows the TPV device (S1), which shows the Sagrada Familia Cathedral in Barcelona through the finished device. c) Band diagram of the different films that conform to the device.

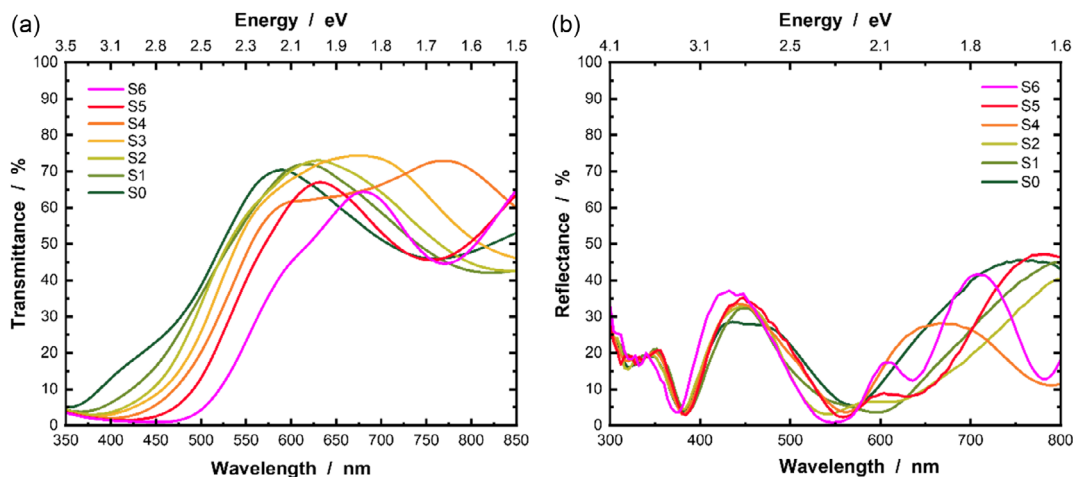


Figure 3. a) Transmittance spectra and b) reflectance spectra of TPV device.

reflectance losses in this specific wavelength region. These losses are particularly relevant to the external quantum efficiency (EQE) and internal quantum efficiency (IQE) analysis, discussed in the following section. The variations in reflectance and transmittance for wavelengths higher than 650 nm are basically due to increased absorber thickness (for samples S4 to S6) which present optical interference fringes. Nevertheless, these variations do not affect the device efficiency as these photons of energy below the bandgap are not absorbed.

3.1. Chromaticity Analysis of TPV Devices

For building integration applications, APT is a crucial parameter; however, the transmission and reflection color characteristics also play an essential role in device esthetics. The color coordinates were determined using the CIE 1931 XY diagram^[21] (Figure 4) with values presented in Table 1.

The CIE 1931 chromaticity diagram reveals that absorber thickness in TPV devices significantly affects the perceived color

CIE 1931

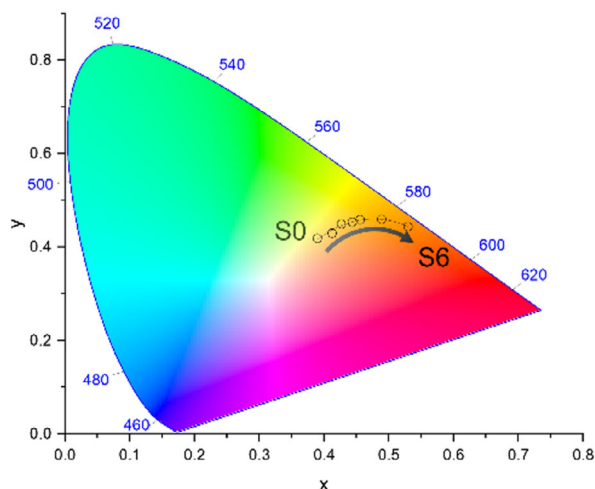


Figure 4. CIE 1931 plot of the color coordinates for TPV, CIE calculated from transmittance spectra.

Table 1. CIE coordinates calculated for the sample set.

	X	Y	L*	a*	b*
S0	0.390	0.418	81.395	−2.488	41.902
S1	0.413	0.429	79.848	1.679	50.070
S2	0.427	0.449	79.819	0.274	60.511
S3	0.444	0.453	77.786	4.125	65.710
S4	0.456	0.458	73.510	6.037	68.453
S5	0.489	0.459	70.170	14.531	78.799
S6	0.530	0.443	58.655	25.632	79.456

of transmitted light. As thickness increases, the samples shift away from the diagram center, indicating a move toward more saturated, less neutral colors. Thinner absorbers, like sample S0 (22 nm), remain closer to neutral white, making them ideal for applications where transparency and color fidelity are crucial, such as in windows or building facades. Conversely, thicker absorbers, such as sample S6 (233 nm), enhance light absorption but cause a noticeable shift in color perception, which may be less desirable in visually sensitive applications. This analysis highlights the importance of balancing energy efficiency with esthetic considerations in the design of TPV devices, especially those using absorbers with bandgap energy lying within the visible range.

Figure 5 shows the recreated color and transparency of the samples based on chromaticity data and transmittance spectra. The image clearly illustrates how absorber thickness affects CRI, APT, and esthetic performance in building-integrated photovoltaic (BIPV) applications such as windows.

The reflectance spectrum analysis in the CIE 1931 diagram shows that the samples, despite varying absorber thicknesses, reflect light in similar color ranges, primarily in bluish tones. The samples exhibit minimal variation in color perception, with

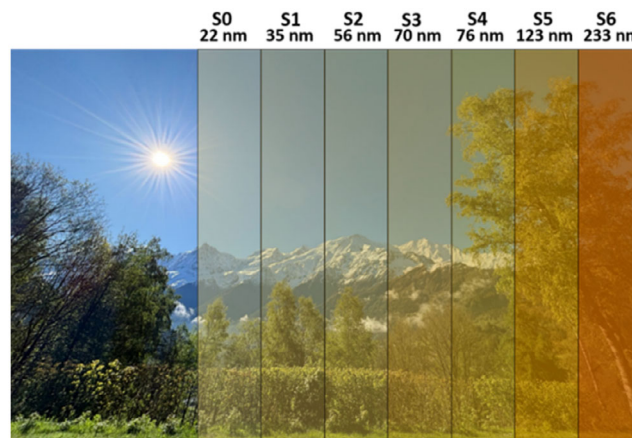


Figure 5. Color and transparency change depending on the variation absorber thickness; the image shows the color and transparency of the samples recreated using data obtained from chromaticity analysis and transmittance spectra.

thicker absorbers slightly enhancing reflectance intensity, particularly in specific tones like green and blue. Luminosity differences suggest that thinner absorbers, like S0, appear brighter. These findings indicate that absorber thickness has a less significant impact on reflectance compared to transmittance, with the overall reflectance being more influenced by the properties of the top layer. This is particularly relevant for applications where the visual appearance under natural light is important.^[22]

CRI is applied to evaluate the ability to portray a variety of colors of the transmittance daylight through TPV device compared to those observed directly under daylight without the TPV device.^[22] It is a parameter measured between 0 and 100.^[23]

$$\text{CRI} = \frac{1}{8} \sum_{i=1}^8 \left[100 - 4.6 \sqrt{(\Delta u_i^*)^2 + (\Delta v_i^*)^2 + (\Delta l_i^*)^2} \right] \quad (2)$$

The CRI values were calculated using Equation (2), where 8 different tabulated test sources are averaged in order to obtain the variation in chromaticity coordinates (Δu), (Δv) as well as the luminosity (Δl). The CRI results are indicated in **Table 2**.

Table 2. Summary of TPV parameters extracted from optical and electrical characterization of the different devices studied.

Device	APT [%]	CRI	V _{oc} [mV]	J _{sc} [mA cm ^{−2}]	FF [%]	PCE [%]	LUE [%]
S0	60	80	788	3.2	69	1.7	1.02
S1	58	73	799	4.2	62	2.1	1.22
S2	57	68	785	4.9	60	2.3	1.31
S3	54	62	808	5.2	58	2.5	1.33
S4	47	59	808	5.4	59	2.6	1.21
S5	43	47	811	6.1	59	2.9	1.25
S6	28	29	817	8.6	58	4.1	1.13

3.2. Optoelectronic Characterization

3.2.1. *J-V Characteristics: Power Conversion Efficiency and Light Utilization Efficiency*

The analysis of these solar cells shows that increasing absorber thickness enhances current generation and overall efficiency (PCE) but reduces transparency (APT) and color neutrality (CRI). *J-V* measurements were made under standard test conditions using a AAA-class solar simulator (1 kW m^{-2} AM1.5G solar spectrum and 25°C). Table 2 summarizes the main photovoltaic parameters, including APT, CRI, and LUE (light utilization efficiency). This last parameter has been proposed as a suitable figure of merit for TPV devices^[20] and is given by the product of the PCE by the APT. Additionally, the statistics for all the optoelectronic parameters for each sample are presented in Figure S1, Supporting Information.

Figure 6 shows that increasing the absorber thickness in TPV devices improves J_{sc} (almost linear increase with the absorber thickness as shown in Figure 7b) and, consequently the PCE also increases. On the other hand, the LUE shows a more complex behavior since it balances transparency with photovoltaic

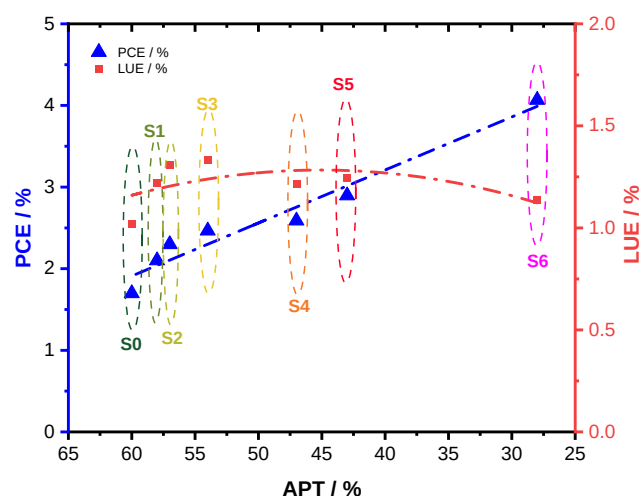


Figure 6. PCE and LUE versus APT, for photovoltaic devices of different absorber thicknesses.

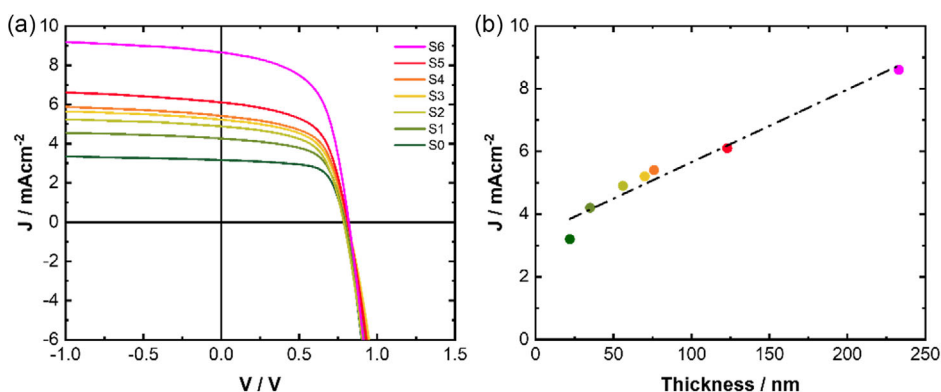


Figure 7. a) *J-V* curves taken at standard test conditions (AM1.5G spectrum, 100 mW cm^{-2} , 25°C) illumination; b) J_{sc} as a function of absorber thickness.

performance. The LUE initially increases with the absorber thickness, showing a maximum value in the range of $\text{LUE} \approx 1.3\%$ for thicknesses in the range of 56–70 nm, and decreases for higher thicknesses. On the other hand, it is interesting to remark on the relatively small changes of the LUE in the range of thicknesses between 35 and 123 nm (S1–S5), with LUE values typically between 1.21 and 1.33%. This indicates an optimal absorber thickness range between 35 and 123 nm where PCE and transparency are well balanced. Beyond this range, further increases in thickness enhance PCE but drastically reduce transparency, causing a higher decrease in the LUE. In addition, we also observe a decrease in the fill factor (FF) for the thicker absorbers, which is likely related to increased internal resistance and recombination losses.

On the other hand, it is also interesting to remark on the relevant values of V_{oc} that are achieved through the whole device series, with values in the range 785–815 mV (with a record value of 817 mV for the thicker absorber layer). These values are close to the record V_{oc} around 900 mV that has been achieved in standard (opaque) a-Si:H solar cells.

3.2.2. *VIM Analysis*

The measurement of the *J(V)* curve under variable illumination (VIM)^[24] has proven to be an effective method to identify the mechanisms limiting the efficiency of amorphous silicon p-i-n solar cells and is expected to be equally effective in our devices, whose structure is very similar. As in p-i-n devices, the collected photocurrent depends on the drift of carriers by the internal electric field generated by the contacts, and consequently, the collection efficiency (χ_c) must be a function of the applied voltage.^[25]

For devices with voltage-dependent photocurrent, it is common to observe a range of illumination where the slope of the *J(V)* curve under short-circuit conditions (G_{sc}) is proportional to the short-circuit current (J_{sc}). Consequently, the product of J_{sc} and the dynamic short-circuit resistance ($R_{\text{sc}} = 1/G_{\text{sc}}$) is constant and is referred to as the collection voltage (V_C).^[26,27]

$$V_C = J_{\text{sc}} R_{\text{sc}} = \chi_{c0} \left(\frac{d\chi_c}{dV} \right)^{-1} \bigg|_{V=0} \quad (3)$$

where χ_{c0} is the value of χ_c in the absence of an applied voltage, that is, under short-circuit conditions, commonly referred to as

the collection efficiency of the solar cell ($\chi_{c0} = J_{sc}/J_{ph}$, where J_{ph} is the total photocurrent).

Figure 8a shows G_{sc} as a function of J_{sc} for the different devices. It can be seen that, indeed, in all cases, G_{sc} is proportional to J_{sc} , indicating that the slope of the $J(V)$ curve under short-circuit conditions is controlled by the collection function $\chi_c(V)$ over a wide range of illumination levels. Only at very low illumination ($J_{sc} \gg 1 \text{ mA cm}^{-2}$) would one expect to observe the leakage effect due to possible shunt parasitic resistance.^[24] **Figure 8b** illustrates how V_c controls the short-circuit behavior of $J(V)$ for two of the devices.

Applying the uniform field model developed for amorphous silicon p-i-n devices, it is possible to derive simple expressions to calculate χ_{c0} and the effective $\mu\tau$ product ($\mu\tau_{eff}$) from the experimental measurement of V_c . Additionally, the absorber thickness (d) and the built-in potential (V_{bi}) must also be known.^[24,28]

$$\chi_{c0} = 1 - \frac{V_{bi}}{V_c} \quad (4)$$

$$\mu\tau_{eff} = L_{c0} \times \frac{d}{V_{bi}} \quad (5)$$

where L_{c0} is the effective short-circuit collection length, representing the average distance that carriers, driven by the electric field, travel before recombining.^[25]

$$L_{c0} = \left(\frac{V_c}{V_{bi}} - 1 \right) \times d \quad (6)$$

Figure 9 shows the collection voltage V_c derived from the $J(V)$ curves over the illumination range where $J_{sc} > 1 \text{ mA cm}^{-2}$, along with the values of $\mu\tau_{eff}$, χ_{c0} , and L_{c0} calculated from Equation (4–6). An approximate value of V_{bi} of 1 V is assumed, which is expected to be the same for all the devices as the selective contacts are identical. The shaded region represents absorbers with a thickness of less than 100 nm, corresponding to TPV devices with significant transparency (APT > 50%). In this region, a clear increase in the V_c voltage is observed as the thickness decreases. However, the $\mu\tau_{eff}$ value derived from Equation (5) deteriorates significantly, which would typically be interpreted as a significant decrease in the absorber quality.^[24]

This is not the case for the collection efficiency, which, despite the deterioration of $\mu\tau_{eff}$, improves as the thickness decreases. It should be noted that the reduction in thickness favors carrier collection, both because the distance they must travel to be collected

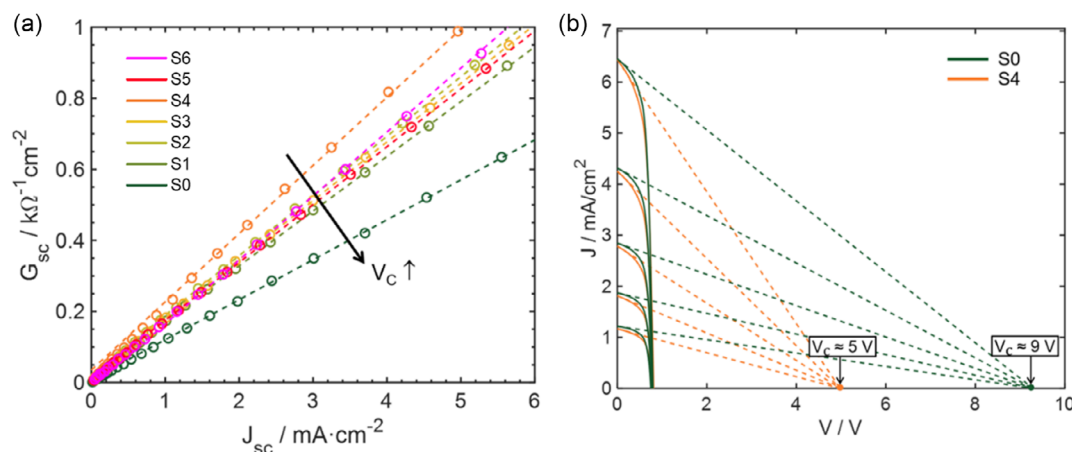


Figure 8. a) Slope of the $J(V)$ curve under short-circuit conditions (G_{sc}) as a function of the short-circuit current density (J_{sc}). The slope of the lines is equal to $1/V_c$. b) Graphical interpretation of the meaning of V_c .

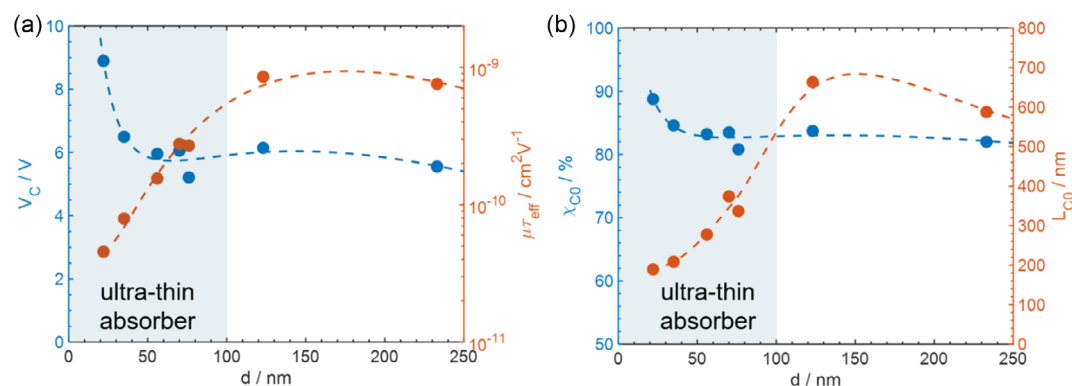


Figure 9. a) Collection voltage V_c and effective $\mu\tau$ as a function of thickness. b) Collection efficiency χ_{c0} and collection length L_{c0} as a function of thickness.

is shorter, and because the intensity of the internal electric field increases. These effects more than compensate for the apparent degradation in absorber quality. In fact, the device with the highest collection efficiency ($\approx 90\%$) is the one with the lowest thickness (S0, 22 nm). For this device, the value of $\mu\tau_{\text{eff}}$ is $\approx 3 \times 10^{-11} \text{ cm}^2 \text{ V}^{-1}$, which is more than two orders of magnitude lower than values previously reported for thicker standard a-Si:H p-i-n cells.^[24] On the other hand, it is interesting to remark on the relevant collection efficiency values in the range between 80 and 90% that are achieved for the whole device series, which is directly related to the optimized HTL and ETL selective contact configurations.

It is important to note that the low value of $\mu\tau_{\text{eff}}$ is most likely related to the increased influence of charged defects at the interfaces near the contacts as the thickness decreases.^[28] As the thickness increases, $\mu\tau_{\text{eff}}$ rises significantly, saturating at values above $10^{-9} \text{ cm}^2 \text{ V}^{-1}$, for absorber thicknesses $\geq 150 \text{ nm}$. This is comparable to the values found in conventional p-i-n devices. Regarding the voltage and collection efficiencies, there is a critical thickness of about 70 nm beyond which these parameters tend to increase and saturate for a thickness of about 123 nm, remaining almost constant beyond this value.

Finally, the VIM analysis was extended to study the series resistance R_s of the devices. According to the equivalent circuit of the device, the derivative dV/dJ as a function of $1/J$, both in the dark and under illumination,^[25] forms a straight line, where the slope is nkT/q (with n being the diode's ideality factor) and the intercept corresponds to R_s .

Figure 10 shows the results of this study. In the dark, the value of R_s increases with thickness, reaching nearly $100 \Omega \text{ cm}^2$ for the thickest device; see Figure 10a. However, under illumination, R_s decreases drastically to a value of $4\text{--}6 \Omega \text{ cm}^2$, which is virtually the same for all devices. This result suggests that the electrode resistance (AZO + FTO) is the limiting factor for R_s under illuminated conditions, while the effect of internal resistance, though significant in the dark, has little influence under illumination.

The difference ΔR_s between R_s and its saturation value at high illumination can be interpreted as the internal resistance of the absorber and $1/\Delta R_s$, therefore, as the photoconductance of the absorber. Figure 10b shows the dependence of $1/\Delta R_s$ on illumination. Assuming that J_{sc} approximates the photocurrent

generated optically in the absorber, it is possible to estimate the $\mu\tau$ product associated with the photoconductivity. The values obtained are in the range of $10^{-8}\text{--}10^{-7} \text{ cm}^2 \text{ V}^{-1}$, which are very similar to those found in a-Si:H using conventional techniques.^[29] In a sense, the discrepancy with the values obtained from the VIM analysis highlights the limitations of the assumptions in the model used to interpret the measurements, particularly regarding the real meaning of the effective $\mu\tau$ derived from these measurements.

3.2.3. Spectral Response Measurements

Spectral response measurements are valuable to characterize the photocurrent and are commonly used to determine the losses responsible for reducing the measured J_{sc} from the maximum achievable photocurrent. EQE is a dimensionless parameter given by the number of electrons which exit the device per incident photon at each wavelength. The photocurrent is the integral over wavelength of the product of the measured EQE with the illumination spectrum, AM1.5G for terrestrial standard solar cells.^[30] The IQE for transparent solar devices was calculated using Equation (7).

$$\text{IQE} = \frac{\text{EQE}}{1 - R - T} \quad (7)$$

As the absorber thickness increases, EQE initially improves but then decreases or broadens, particularly around the 400 nm peak. Thinner absorbers may not fully capture incident light, while thicker absorbers face increased recombination losses. Additionally, significant reflection losses, particularly at the 450 nm peak, further reduce efficiency. Beyond 600 nm, EQE declines across all samples, with this decrease corresponding to the absorber bandgap, which limits the ability of the material to convert lower energy photons into electron flow (Figure 11).

A comparison between the EQE and IQE curves suggests that while internal losses can be well managed, further optimization of the antireflection coating would increase both PCE and LUE values. In any case, we can estimate that by reducing reflection losses in the wavelength range 350–500 nm, values of LUE beyond 1.6% are possible. Additionally, as a routine check, we

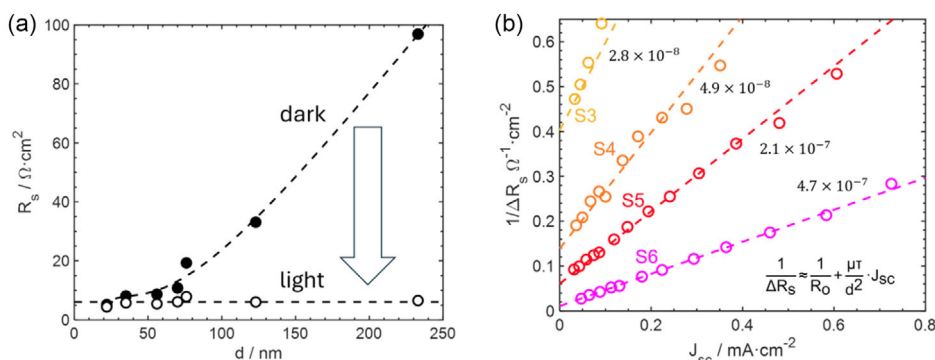


Figure 10. a) R_s in darkness and saturation value at maximum illumination as a function of thickness. b) Photoconductance $1/\Delta R_s$ as a function of J_{sc} for the thicker devices (S3, S4, S5, and S6). The linear fit allows us to obtain the $\mu\tau$ product associated with the photoconductivity of the absorber. The $\mu\tau$ values, in $\text{cm}^2 \text{ V}^{-1}$, are presented in the figure.

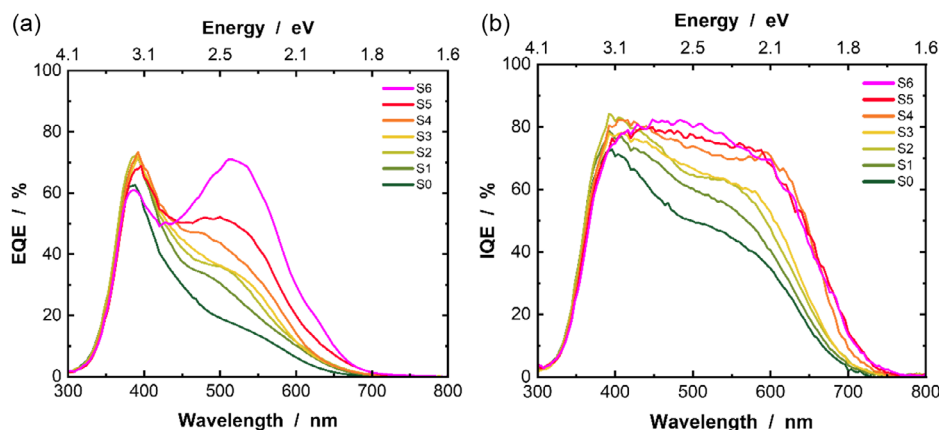


Figure 11. a) EQE. b) IQE characteristics of the studied devices.

have made a photon balance check to ensure that $T + R + EQE < 100\%$ ensuring no overestimation in photocurrent and device efficiency (Figure S2, Supporting Information).

4. Conclusion

In this work, the limits of device efficiency, transparency, and LUE have been studied in TPV devices based on the integration of a nano a-Si:H layer between optimized selective contacts. The study performed corroborates that the thickness of the absorber layer is crucial to the overall performance of TPV devices. As absorber thickness increases, transparency and color accuracy decrease. This tradeoff is essential for applications like BIPV, where both energy efficiency and esthetic considerations are important. Thicker absorbers improve energy conversion at the expense of transparency and potential color distortion. There is an optimal thickness range, between 50 and 150 nm, where a suitable balance between PCE and transparency is achieved, yielding maximum LUE values in the range of $LUE \approx 1.25\text{--}1.33\%$, corresponding to devices with PCE values up to 2.9% and transparency (APT) in the range of 40–60%. These constitute world-record LUE values for inorganic TPV devices. On the other hand, devices are characterized by good V_{oc} values (in the range of 788–817 mV) and collection efficiencies (in the range of 80–90%) for the whole device series, which can be related to the optimized selective contacts implemented in these devices. The highest carrier collection efficiencies of 90% are achieved within the thinner absorbers (thickness ≈ 22 nm) and this partially compensates for potential efficiency losses related to the deterioration of $\mu\tau_{eff}$ observed at these very low absorber thicknesses, likely related to the influence of charged defects at the interfaces.

Finally, reflection and EQE/IQE measurements indicate the presence of reflection losses mainly located in the 450 nm spectral range, with the 220 nm AZO layer notably contributing to these losses. Correction of these losses by suitable adjustment of TCO thickness and/or implementation of suitable antireflective coatings could allow for a relevant increase of LUE beyond values in the range of 1.6%.

5. Experimental Section

Sample Preparation: Transparent solar cells fabricated in this work presented the structure $SLG/FTO/AZO/a\text{-Si}_x\text{H}_y(n)/a\text{-Si:H}/V_2O_5/AZO$. Commercial SLG/FTO substrates (Merck; $R_{sh} = 10 \Omega \text{ sq}^{-1}$) were used as substrate and transparent back contact. Prior to deposition, substrates were rinsed in distilled water, dried in Ar flux, and afterward cleaned by subsequent 10 min ultrasonic baths in isopropanol and ultrapure H_2O at room temperature, followed by a drying step in Ar flux. A 45 nm AZO film was grown in an ALD system (Savannah S200, Cambridge Nanotech) at 200°C , using precursors diethylzinc (DEZ 95%, STEM), ultrapure H_2O , and trimethylaluminum (TMA 99%, STEM) and using N_2 as purging gas. Sixteen supercycles at a 19:1 DEZ:TMA ratio were performed, with 19 $H_2O/N_2/DEZ/N_2$ (20 ms/5 s/15 ms/5 s) cycles and 1 TMA/ N_2 (s/20 ms/5 s) cycle. After the AZO, the following step consisted in depositing an ETL film of 12 nm, deposited by PE-CVD (Elettrovava) with an RF power supply of 13.56 MHz at 6 W. Substrate temperature was measured at $148\text{--}150^\circ\text{C}$ during deposition, with a mixed 36/12/30 sccm $SiH_4/CH_4/SiPH_3$ atmosphere and with deposition time of 3 min. Afterward, intrinsic a-Si:H ultrathin films of 24, 38, 56, 74, 80, 129, and 288 nm were deposited by PE-CVD (Elettrovava) with an RF power supply of 13.56 MHz at 6 W. Substrate temperature was measured at $148\text{--}150^\circ\text{C}$ during deposition, with a mixed 36/12 sccm SiH_4/CH_4 atmosphere and with deposition time of 3, 5, 7, 9, 11, 17, and 34 min, respectively. To finish the solar cells, the HTL and front contact were deposited in a single sequential ALD process without breaking vacuum. V_2O_5 was grown at 125°C , using tetrakis(ethylmethylamino)-vanadium (IV) ($C_{12}H_{32}N_4V$) (TEMAV 99%, STEM) and ultrapure H_2O using again N_2 as a carrier and purging gas. Two hundred supercycles of $H_2O/N_2/TEMAV/N_2$ (2 s/5 s/5 s/5 s) were carried out. AZO was deposited at a 19:1 ratio for 75 supercycles at $T = 175^\circ\text{C}$. Once the sample was fully grown, the active area cells were isolated using a photolithographic process followed by a wet chemical etching process that effectively isolated the cells from each other. First, photoresist at room temperature was spread on the surface of the samples and was statically spin coating for 30 s at 30.000 rpm. Immediately after, it was taken to a furnace at 105°C for 20 min in order to evaporate the residual solvent. Then, UV photolithography was performed with a positive mask with square patterns defining a cell active area of 0.25 cm^2 . Afterward, an etching process was performed using an isotropic etching solution of $HF + HNO_3$ to attack and remove the thin films down to the FTO, which remained unaffected. As a result, the active area protected with the resin would remain and the subcells would be effectively isolated from each other allowing for J–V characterization without the need for a mask to define the active area during measurements (Figure 2).

Characterization: Spectrophotometry measurements were carried out with a UV-VIS-NIR spectrophotometer (Perkin Elmer Lambda L950) with an integrating sphere, in single-beam configuration, in transmittance and

reflectance mode with spectral range from 300 to 800 nm in order to measure the completed device total transmittance and reflectance. This data was also used to calculate the device APT and CRI. $J-V$ (current density–voltage) measurements under illumination were carried out using a AAA class solar simulator with AM1.5G illumination calibrated using an NREL-certified Si reference solar cell (Abet Technologies Model 15150). Electrical measurements were carried out with a source-measure unit (Keithley SMU 2400) in 4-wire sense mode, remotely controlled by the software Tracer (ReRa solutions) using an IEEE 488 GPIB Instrument Control Device (National Instruments GPIB-USB-HS). Spectral response measurements were acquired using a spectral response system (Bentham PVE300) calibrated with Si and Ge photodiodes. For optoelectronic measurements, the samples have been placed in a dark opaque mat to avoid any back reflections that could alter the characterization of the transparent solar cells.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Gustavo Alvarez-Suarez: data curation (lead); formal analysis (lead); investigation (equal); writing—original draft (lead); writing—review and editing (equal). **Alex J. Lopez-Garcia:** conceptualization (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); supervision (lead); validation (equal); writing—original draft (equal); writing—review and editing (equal). **Pau Estarlich:** data curation (supporting); investigation (supporting); writing—original draft (supporting); writing—review and editing (supporting). **Jose Miguel Asensi:** data curation (supporting); formal analysis (supporting); investigation (supporting); methodology (supporting); writing—review and editing (supporting). **Gerard Masmitjà:** investigation (supporting); supervision (supporting); writing—review and editing (supporting). **Pablo Ortega:** conceptualization (supporting); formal analysis (supporting); methodology (supporting); supervision (equal); validation (equal); writing—review and editing (supporting). **Cristobal Voz:** conceptualization (supporting); investigation (supporting); supervision (equal); validation (supporting); writing—original draft (supporting); writing—review and editing (supporting). **Joaquim Puigdollers:** funding acquisition (equal); investigation (supporting); resources (equal); supervision (supporting); writing—review and editing (supporting). **Alejandro Pérez Rodríguez:** conceptualization (supporting); project administration (lead); resources (equal); supervision (equal); validation (supporting); writing—review and editing (supporting).

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

amorphous silicon, building-integrated photovoltaics, inorganic solar cells, selective contacts, transparent photovoltaics

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