

Balancing Aesthetics and Performance: An RGB-Based Coloring Strategy for Building-Integrated Photovoltaics

Xavier L. Pinheiro, António J.N. Oliveira, André F. Violas, Enzo J. Ribeiro, José Fernandes, Mauro Costa, Paulo A. Fernandes, Rute A.S. Ferreira, Pedro M.P. Salomé, and Jennifer P. Teixeira*



Cite This: *ACS Appl. Mater. Interfaces* 2026, 18, 54991–55007



Read Online

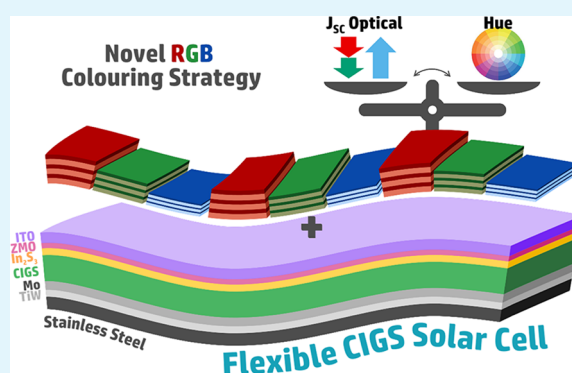
ACCESS |

Metrics & More

Article Recommendations

ABSTRACT: Building-integrated photovoltaics (BIPV) represents a promising approach for energy generation in urban environments, although balancing aesthetics and photovoltaic performance remains challenging. This work presents and validates a novel tunable coloring strategy for flexible Cu(In,Ga)Se₂ (CIGS) solar cells that allows to balance optical induced losses with gains while reducing color angle dependence. Inspired by the light-emitting diode display technology, the strategy combines micropatterned Red, Green, and Blue Bragg reflector (BR) coatings in adjustable proportions to achieve tailored colors. Two line-based micro-architectures were fabricated on soda lime glass and flexible CIGS solar cells. White coloration was selected due to its compatibility with common building facades, with patterns designed to appear visually uniform at distances higher than a 1 m viewing distance. The developed process demonstrated reproducible defect-free microfabrication and successful color perception. Compared to conventional uniform BRs, the RGB pixel coloration strategy significantly reduced color angle dependence and improved optical performance, limiting short-circuit current density losses to below 1.5 mA·cm⁻². Moreover, individual color BR led to a short-circuit current loss of 1% to 4% or an enhancement of nearly 10% depending on the final color. The proposed strategy demonstrates strong potential for efficient, aesthetically integrated colored BIPV applications.

KEYWORDS: aesthetic, RGB, color filter, flexible, CIGS, thin film, BIPV



1. INTRODUCTION

In the past years, the world has faced intense instability and uncertainty, marked by the most severe pandemic since the 1920s, the most significant energy crisis since the 1970s, swift technological advancements within and beyond the energy sector, more evident impacts of climate change, and a growing complexity in global geopolitics.¹ Globally, the energetic challenge is fought in different ways; however, affordability, competitiveness, self-sustenance, and energy security are common desires.¹ To reach these goals, a shared approach is the installation of clean energy technologies. Report numbers show the addition of 685 GW in renewable electricity capacity, a 22% growth over 2023,² and in 2025, it reached 800 GW.³ Within these numbers, photovoltaics (PV) keeps its dominance, being around 80% of the newly installed capacity, the majority being utility scale (large-scale PV power plants),² although its electricity generation only accounts for 7% of the global electricity production.⁴ Therefore, for PV to have a significant impact in the global electricity production, its deployment must increase drastically, and utility scale cannot be the only option.

Beyond technological barriers, the deployment of decentralized PV systems also faces sociological challenges, notably the

NIMBY (Not In My BackYard) syndrome, the widespread tendency of communities to support renewable energy in principle while opposing installations near their homes.⁵ Research suggests that this resistance can be substantially mitigated through public consultations and transparent communication by local leaders and media, addressing climate benefits, financial impacts, and project scope.^{5,6} On the technical side, traditional ground-mounted PV plants carry significant land-use drawbacks, including biodiversity loss and deforestation.⁷ Building-integrated PV (BIPV) and building-applied PV (BAPV) emerge as compelling alternatives for urban and residential contexts, enabling buildings to function as on-site energy generators.⁸ While both approaches share inherent PV limitations such as efficiency and aesthetic constraints, they differ in architectural

Received: August 11, 2026
Revised: September 17, 2026
Accepted: September 22, 2026
Published: October 5, 2026



integration: BIPV is incorporated into the building's structure from the design stage, whereas BAPV is retrofitted onto existing buildings.⁸ Critically, ground-mounted PV can present a carbon payback period 378% to 428% higher than BIPV/BAPV when comparing equivalent modules, highlighting the latter's superior environmental profile.⁹ Despite these advantages, BIPV adoption remains uneven across Europe, with new installations accounting for less than 1% of distributed PV capacity in 2024.⁴ However, countries like Switzerland have achieved 5–10% market share, reflecting the strong influence of local policy and regulatory context. In response, the European Union has issued several directives aimed at accelerating broad PV and BIPV deployment.^{4,10–14}

A further challenge shaping BIPV adoption is architectural suitability. Module aesthetics, encompassing color, pattern, shape, and transparency, are central to public acceptance, yet these features invariably affect power output, requiring a trade-off between visual appeal and performance.¹⁵ Nonetheless, there is broad consensus that BIPV modules should be customizable and colorful to complement building design even at the cost of reduced efficiency and higher expense.¹⁶ Several glass-applied coloring strategies exist across PV technologies, mostly employing absorption or interference pigments or interference coatings using Bragg reflector (BR) multilayers.¹⁷ While most approaches introduce an efficiency loss of 10–30%, multilayer dielectric structures can achieve performance losses below 5%.¹⁷ The high parasitic absorption of opaque pigments significantly limits light transmittance, and interference pigments can, in principle, be designed to minimize performance losses; however, that requires custom-made formulations (commercially available solutions exhibit significant NIR reflectance), which are a considerably complex task.¹⁸ Furthermore, BRs of inorganic layers are photostable and robust under harsh outdoor conditions, being stable over the module lifetime,¹⁹ and a large range of customizable and *a priori* predictable colors are available²⁰ with achievable vivid and saturated colors if a large refractive-index contrast (Δn) between the stack materials is used.²¹ Moreover, a high Δn produces a narrow bandwidth that is less sensitive to blue shift with increasing angle of incidence.^{18,20,21} The available literature on the application of BRs on CIGS-based solar cells clearly shows the aforementioned advantages with vivid colors attainable with narrow and intense (>60%) reflectance peaks at 445, 502, and 693 nm.²² In a similar study, Red, Green, and Blue BR filters developed on CIGSSe had a minimal loss of 1.22% and 3.2% on power conversion efficiency (PCE) and 0.5% to 7% of the short-circuit current density (J_{SC}), for Green and Red, respectively, and a 1.1% PCE increase for Blue.²³ Expanding to other colors, Blue, Green, Yellow, Orange, and Violet BR stacks that induce a J_{SC} loss between 16% and 33% and have a high color purity (reflectance between 30% and 45%) have been shown.²⁴ For a direct integration, a careful selection of the conductive dielectric materials allows to develop color BRs that can be integrated in the window layer without electrical performance degradation.²⁵ Concerning scaling up, colored minimodules with BRs had a PCE decrease of 10% to 50% when applied on top of the solar cell but an increase of up to 10% when applied to the glass substrate rear side.²⁶ Furthermore, leading commercial solutions, such as Fraunhofer ISE's MorphoColor,²⁷ Swissinso's Kromatix,²⁸ and Solaxess,²⁹ are based on interference coatings. Generally, BRs have well-proven benefits, although most coloring has been

applied to the cover glass with a large number of layers and thus a high total thickness, making them incompatible with flexible module formats. Moreover, the critical angle dependence is rarely explored.

Concerning the PV technology to be used in BIPV, thin-film technologies are a key player despite the wafer-based crystalline silicon (Si) dominance, with over 97% of the PV market in 2024.³⁰ Within the thin-film branch, Cu(In,Ga)Se₂ (CIGS) solar cells have key advantages, such as great thermodynamic stability,³¹ high optical absorption coefficient,³² mature commercialization in flexible substrates,³³ and low energy payback time.³⁴ Furthermore, the world record efficiency is at 23.6% considering the thin-film range (approx. 2000 nm thick absorber).^{35,36} If, instead, the ultrathin-film range (≤ 750 nm) is considered, the production costs and time can be reduced, increasing throughput, reducing the usage of critical raw materials, and meeting sustainable goals.^{37,38} However, as for the color/performance compromise, the thickness reduction induces an efficiency loss: from 23.6% to 16.2% for 750 nm and to 15.2% for 490 nm.^{39,40} Hence, the integration of thin-film-based BIPV with low material usage, high efficiency, lower energy payback time, and improved conscious aesthetics can significantly mitigate buildings' lifecycle emissions and increase the BIPV deployment.

This work tackles the coloration of flexible CIGS solar cells, deposited in an in-line industrial sputtering equipment, by means of interference coatings in a novel scheme to reach a versatile and performance-friendly alternative. Taking inspiration from LED-based displays, a combination of three distinct BR coatings was devised. By combining side-by-side Red, Green, and Blue coatings with different proportions, it is possible to tailor the perceived final color and balance the optically induced losses and gains. The development of an efficient pseudo-White coloration with this novel strategy was reproducible through a microfabrication process, both on soda lime glass (SLG) and flexible CIGS solar cells, with no pattern defect and not visible to the naked eye, and the desired color is perceived. Despite the expected optical behavior being attained, all the devices still had a lower performance than the reference bare device because the fabrication processes may have affected the solar cell layers/interfaces and create defects that increase recombination. Although if only the short-circuit current density is considered, compared to a reference, the Red devices had no significant loss, the Green ones had a decrease of around 0.5 mA·cm⁻², while the devised pseudo-White architectures had a decrease of less than 1.5 mA·cm⁻². The Blue coating had a significant increase of 3.3 mA·cm⁻². Hence, the novel coloring strategy has a proven viability and applicability not only on flexible devices but also on cover glasses, and once the fabrication issue is resolved, it will be possible to produce colorful flexible CIGS solar cells with a low optical loss (from 1 to 4% rel.) and even an optical gain (+10% rel.).

2. CONCEPTUALIZATION

When designing colored PV applications, a distinct coating must be developed for each desired hue, which can be a demanding task. A BR strategy, a fundamental optical construction consisting of alternating layers of materials with different refractive indices,⁴¹ is used in several commercial colored rigid PV modules, but its inherent considerable weaknesses are still unmitigated. Such a configuration acts as a highly reflective

structure over a specific wavelength range,^{42,43} however, for each color across the visible spectrum, it requires precise calculation and control of the multilayer thicknesses. As the number of layers increases, the overall thickness, reflectivity, and fabrication complexity also increase. Small fluctuations of the layers thicknesses can lead to degradation of its reflectivity and spectral bandwidth.^{44–46} Regarding device integration, as each produced color exhibits a distinct reflectance spectrum, the resulting optical losses and overall device performance can vary significantly. Furthermore, since the reflectivity of BRs is interference based, the light-to-matter interaction is highly wavelength- and angle-dependent, resulting in a high angular sensibility that shifts the spectrum to shorter wavelength values for oblique angles of incidence.⁴⁷ It is therefore essential to develop a versatile and easily customizable coloring strategy capable of compensating for the optical losses inherent in any coloring strategy so as to minimize the optical impact on performance and reduce color angle dependence.

In residential and urban environments, building facades typically adopt neutral or low-saturation color palettes due to both cultural preferences and functional considerations, including thermal management and solar reflectivity. The most common options are White or grayish tones, which can be obtained through several ways. With pigments, specifically silica-based pigments, a bright grayish coating with approx. 15% induced performance loss was created; however, the majority of visible spectra is still lost through reflection.⁴⁸ Moreover, the development of a White coating with mica/TiO₂ pearlescent interference coatings yielded a performance loss between 10% and 18%. In this case, despite the bright color obtained, the visible reflectance was below 40%.⁴⁹ Similarly, a White inkjet coating of commercial pigments was applied in superstrate perovskite solar cells with an average 25% performance loss.⁵⁰ In regard to BR structures, an optimized simulation procedure shows that a large BR multilayer structure of TiO₂ and Si₃N₄ can produce a significantly pure White that will, however, induce a near 35% loss to the solar cell device.⁵¹ Thus, achieving a White coloration with minimal performance loss is a real challenge since it typically requires broadband and relatively uniform reflectance across the visible spectrum or multiple peaks arranged within the visible spectrum,⁵² inherently leading to increased optical losses. Consequently, this paper proposes and develops a new BR-based concept of color inspired by the fundamental principles underlying modern display technologies, in which color generation is based on a controlled combination of different light sources to create the visible spectrum through the additive color theory with the aim of producing white. Most

displays use three primary light-emitting diodes (LEDs)—emitting in the red, green, and blue spectral regions—that are arranged in a defined subpixel geometry. There are many available LED pixel configurations that can combine subpixels with different shapes, e.g., rectangular and even circular, with varying area percentages, typically red–green–blue (RGB) but also red–green–blue–white (RGBW), in a periodic array.^{53–57} Thus, the relative area and intensity of each subpixel determine the final perceived color. Therefore, the concept of this novel color strategy explores the combination of three distinct color coatings, i.e., Red, Green, and Blue, in the same pixel area. The final perceived color of the structure depends solely on the area fraction of each constituent color, thereby enabling customized color tuning. Furthermore, in theory, this strategy can mitigate color-induced optical losses compared to a broadband spectrum since, to attain it, a White coloration is only needed to have narrow reflection in the Red, Green, and Blue spectral regions; additionally, combining these three color coatings, each associated with either an optical loss or gain, may help minimize the decrease on device performance, as their effects can compensate for one another.

To develop the individual coloring components responsible for color generation within the proposed RGB pixel coloring strategy, BR architecture was adopted as the platform. Silicon oxide (SiO_x) and silicon nitride (SiN_x) were selected as the constituent materials due to their suitable refractive index contrast (approximately 1.5 and 2.0 at 550 nm literature values, respectively),^{58,59} enabling effective spectral tuning of the reflected color, industry availability and high usage, and encapsulation properties.^{60,61} The number of SiO_x/SiN_x bilayers was fixed at three, for a total of six layers, to minimize optical losses and process complexity, to maintain the flexibility of the device, and to prevent delamination concerns when actively bent since plasma enhanced chemical vapor deposition (PECVD) has inherent stress.^{62,63} A visual representation of this work conceptualization, the RGB pixel coloration strategy, is represented in Figure 1, where BRs of SiO_x and SiN_x that provide a Red, Green, and Blue coloration are combined on top of the flexible CIGS solar cell: (from bottom to top) stainless-steel substrate, titanium tungsten (TiW) diffusing layer, molybdenum (Mo) rear contact, CIGS absorber, indium sulfide (In₂S₃) buffer layer, magnesium-doped zinc oxide (Mg_xZn_{1-x}O-ZMO), and tin-doped indium oxide (Sn:In₂O₃-ITO) window layers.⁶⁴

The multilayer scheme for the individual color coatings was achieved via optical simulations under the OpenFilters software.⁶⁵ Each color multilayer scheme was optimized by calculating the spectral response of the system, solar cell + multilayer, using

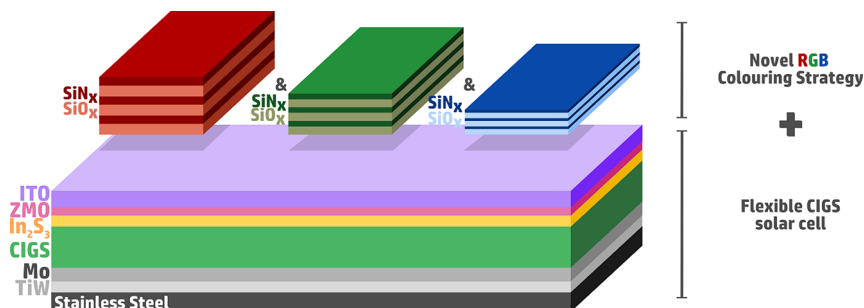


Figure 1. Schematic representation of the novel RGB pixel coloration with Red, Green, and Blue BR-based coatings side-by-side, on top of a CIGS solar cell.

the transfer matrix method. This framework allows for the precise tuning of the layer thickness value to achieve the targeted hue. The target colors were defined considering the R–G–B code for Red, Green, and Blue: (255,0,0), (0,255,0), and (0,0,255), respectively, and converted into the CIE 1931 color space (the standard colorimetric observer) to obtain the correspondent chromatic coordinates: (21.26, 0.64, 0.33), (71.52, 0.30, 0.60), and (7.22, 0.15, 0.06). As a first step, a quarter-wave optical thickness condition was established for the multilayer schemes to match the desired reflection wavelength values. Each layer is described by its complex refractive index (n , k) and thickness. The propagation of electromagnetic waves through the multilayers is treated by solving Maxwell's equations under planar boundary conditions. Subsequently, an internal optimization routine was employed to tune the thickness of each layer, minimizing the deviation between the obtained color, calculated from the simulated reflectance spectra, and target color (Y, x, y). The resulting chromaticity coordinates in comparison with the target colors and layer thickness values are summarized in Table 1. To obtain quantitative values that represent the differences between the target and obtained color, the following parameters were determined: total difference (ΔE), chroma difference (ΔC), and hue difference (ΔH).^{66,67} The ΔE parameter indicates if an observer can distinguish both colors when compared side by side, the ΔC shows a change in saturation, while ΔH values reveal if the colors have shifted to a different color region.⁶⁷ The ΔE values indicate that the obtained and target colors are seen as different since the values are over the maximum limit of 5 from which two different colors are observed; concerning ΔC , the negative values indicate a decrease in saturation. The same conclusions can be reached by comparing the target and obtained color insets in Table 1, where the obtained colors are more pastel and less vivid. Finally, regarding ΔH , in Red and Blue, there is no significant hue difference, but for Green, there is a slight shift, but the obtained color is still in Green's region. This significant difference in the Green optimization arises from the limited number of layers in the BR, which makes it challenging to achieve a narrow reflectance band while simultaneously suppressing the interference fringes on either side of the main reflection peak.^{68–70} In contrast, the Red and Blue cases are less restrictive, as their target reflectance profiles primarily require long- and short-wavelength stopbands, respectively. Therefore, a broader reflectance band has a less pronounced effect on the resulting color provided that reflection remains confined to the desired region of the visible spectrum. Nonetheless, in all of them, it is very challenging to reach the highly saturated and vivid color defined as the target, and the small number of layers is the most probable limiting factor. In contrast to conventional periodic BRs, the obtained multilayer

schemes are nonperiodic. This results from the incorporation of the solar cell under the multilayer scheme in the optical model, where absorption and interference from the underlying layers will impact both amplitude and phase of the reflected light. Consequently, each layer thickness is individually tuned to compensate for these effects and to reach the defined target hue. Note that as the number of layers in BR increases, the substrate reflectance impact is gradually reduced. After thickness optimization, each reflectance spectrum was calculated and are displayed in Figure 2A. In all three Red, Green, and Blue spectra, a broad reflection peak in the required spectral region values is observed (at approx. 700, 550, and 400 nm, respectively). Despite the broad reflectance peaks, the obtained colors closely match their corresponding color target, with a maximum chromaticity difference of 0.14. However, the light luminance (Y) remains lower than the nominal target due to the small number of layers.

The internal quantum efficiency (IQE) plotted in Figure 2A alongside the individual coatings' reflectance spectra shows that the CIGS solar cells exhibit a steep decrease near 350 nm due to parasitic absorption of the top layers, it is more or less constant within the remaining visible spectra, reaching 90%, and then slowly decreases until it reaches the band gap value. An assessment of the optical performance impact of coloring strategies is possible by considering the present IQE and comparing the reflectance spectra of the individual Red, Green, and Blue with the Bare counterpart, a reference flexible solar cell with no color coating. The Red and Green coatings exhibit intense reflection peaks in the spectral region of CIGS maximum absorbance from 500 to 800 nm, and in the remaining spectrum, they have a similar or slightly higher reflectance than the Bare reference, leading to lower-performance devices. In contrast, for the Blue device, the reflectance peak lies outside the region of maximum absorbance. Moreover, in the remaining spectral region, it has an antireflective behavior decreasing reflectance, which can lead to performance enhancement. These optical behaviors are consistent with the theoretical expectations, whereby the selective spectral positioning within the visible range leads to distinct impacts on device performance. When combined within the proposed RGB pixel coloring strategy, these individual losses and gains can be balanced while simultaneously achieving the desired perceived color.

Among distinct pixel configurations, a simple rectangular shape in an RGB layout was chosen as a baseline. Two distinct architectures were designed as presented in Figure 2B,C, respectively: (i) Lines, in which the three RGB rectangular color coatings are placed side-by-side across the sample area, with their length spreading from top to bottom, in the centimeter range, much larger than their width, in the micrometer range,

Table 1. Target Chromaticity Coordinates in the CIE 1931 Color Space with Interval ($Y \pm 1$, $x \pm 0.01$, $y \pm 0.01$) Used for the Optical Optimization of Red, Green, and Blue Coatings, along with the Corresponding Optimized Layer Thickness Values from Bottom to Top; Resulting Simulated Chromaticity Coordinates; and the Total Color, Chroma, and Hue Differences

Color Target (Y, x, y)	Layer Thickness in nm ($\text{SiO}_2/\text{SiN}_x$) ³	Color Obtained (Y, x, y)	ΔE	ΔC	ΔH
21.26, 0.64, 0.33 	16/103/125/82/89/119	14.38, 0.57, 0.35 	39	-38	1
71.52, 0.30, 0.60 	39/72/92/74/94/74	49.83, 0.36, 0.46 	73	-68	24
7.22, 0.15, 0.06 	70/31/70/67/90/22	3.67, 0.17, 0.09 	58	-57	4

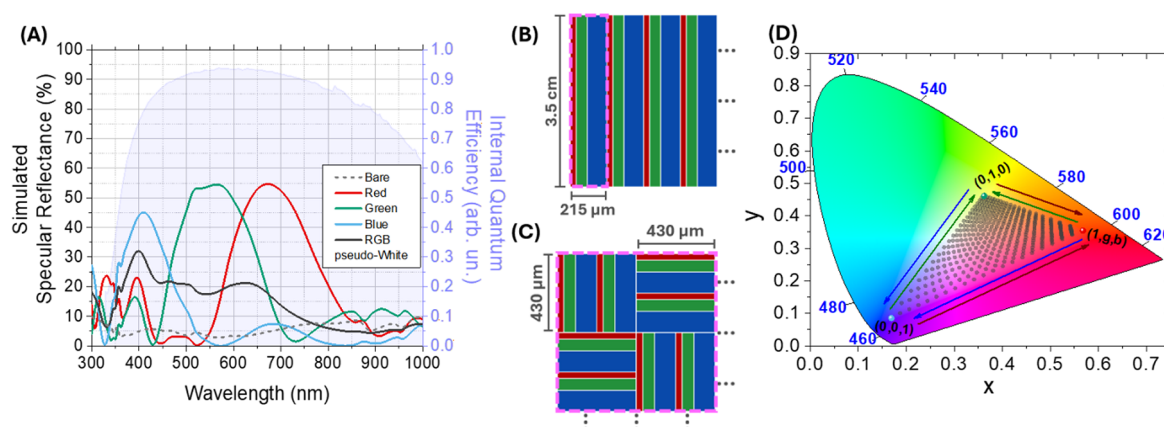


Figure 2. Simulated specular reflectance for a flexible CIGS solar cell with (A) Red, Green, and Blue coatings. The Bare and the expected spectrum for the combination of the three in the RGB pixel coloration strategy considering the calculated color ratio, alongside the cell internal quantum efficiency (IQE) spectrum. (B and C) A representation of the Lines and CrissCross architectures, respectively. The pattern “unit cell” is delimited by the dashed pink rectangle in each architecture representation. In the (D) CIE 1931 color space diagram, the color hues achievable with this work novel strategy are shown. The arrows represent each of the subarea percentage increase and how that leads to the original vertices’ colors (dark-red arrow for r , green arrow for g , and dark-blue arrow for b).

and (ii) CrissCross, in which the two sets of RGB rectangular color coatings are placed side-by-side to form a “subpixel”, with the length and width now both in the micrometer range, and while one “subpixel” is vertically aligned, the adjacent ones are horizontal, and vice-versa. With only parallel lines in the first geometry and both parallel and perpendicular in the second, it may be possible to probe distinct light–matter interaction and see what the color impact is. Moreover, as the patterned arrangement of RGB subareas has different total thickness values, the final pixel concept results in a non-fully planar coating. Thus, diffuse light can be significant, which can impact the cell performance.

To calculate the necessary individual color subareas, the White color was defined as the chromaticity coordinates $x = 0.31$ and $y = 0.33$, which is the center color of the CIE 1931 color space under a D65 illumination. The color luminance was not considered in the optimization since its incorporation tends to favor greenish color due to the high human eye sensibility in this spectral region even when a lower weighting factor was applied to this parameter. The subarea calculations were performed over an arbitrary area unit using two-parameter sweeps, accounting for all possible combinations of Red, Green, and Blue. Knowing the color subarea proportions, the perceived reflectance spectrum can be calculated with a weight average and the corresponding chromaticity coordinates. The optimum solution having the closest Euclidean distance to the color target resulted in subareas of $r = 0.15$, $g = 0.3$, and $b = 0.55$, which lead to the exact chromaticity coordinates of White. The reflectance spectrum of White RGB pixel coloration is found on Figure 2A where the individual coating characteristic color peaks can be identified. The reflectance spectrum clearly evidences the combination of the three individual spectra; in the 400 nm spectral region, the combination of the main Blue reflectance peak and secondary peaks of the Red and Green results in a major reflectance peak in the final spectrum, and in the 500 to 800 nm spectral region since the Blue coating exhibits a very low reflectance and the Red and Green peaks have a slight overlap, the resulting spectrum has a broad plateau like reflectance. Since the optimized parameters were only the chromaticity coordinates, the resulting color does not have a

high luminance and will not be perceived as “bright”, so the RGB pixel coloration designed will be called pseudo-White from now on.

While a White coloration was chosen to prove this novel concept, there is a large span of colors that can be achieved. To showcase which colors are possible, a procedure equal to the subarea color calculation was performed with 20 points per color, and the reflectance spectra and corresponding chromaticity coordinates were calculated for each combination. The determined color coordinates are plotted in the CIE 1931 color space of Figure 2C alongside the original individual colors Red, Green, and Blue. This result clearly shows that a large part of the color space is attained with the RGB structure, mostly parts of blue, purple, pink, red, orange, yellow, green, and white. While a significant range is possible, it seems that to allow a more complete coverage of the color space instead of Red, Green, and Blue, edge colors such as purest Red, Greenish-Cyan, and Purple would be preferred.

At this point, the fundamental design parameters, including the optical strategy, the color coatings multilayers, and their corresponding area fractions, were established. Then, the pixel size parameter is the only missing piece, which must be optimized considering the human visual perception constraints. To ensure that the RGB pattern is not spatially resolved, being instead perceived as a homogeneous color, the pattern dimensions must fall below the angular resolution limit of the human eye. So, by considering a distance of 1 m to the solar cell and the defined standard human eye resolution (θ) of 1 arcmin⁷¹ and using the small angular approximation ($d = \frac{\theta \cdot s}{3438}$, where d is the minimum feature size and s the viewing distance), the maximum dimension must be smaller than 200 μm . Thus, this value was therefore selected as the total size of the RGB lines; considering the individual color coatings area percentages, the individual color line’s lateral dimensions are 30 μm for Red, 60 μm for Green, and 110 μm for Blue, with a 5 μm spacing to avoid overlap, ensuring compatibility with lithographic fabrication constraints. There are two architectures considered: in the Lines scheme, the three-line “unit cell” (delimited in Figure 2B by the dashed pink rectangle) has a 215 μm width, accounting for the spacing, and the length of the lines is approx. 3.5 cm

to have a complete coverage of the sample's active area (25 mm^2 in a 6×6 solar cell grid); for the CrissCross architecture, the "subpixel" that contains the two sets of RGB lines has both a width and length of $430 \text{ }\mu\text{m}$, and its repeated four times with the rotational component forming a $1 \times 1 \text{ mm}$ "unit cell". Both patterns' unit cells are periodically replicated to form an approx. $3.5 \times 3.5 \text{ cm}$ coverage of the active area.

3. RESULTS AND DISCUSSION

3.1. Transparent SLG

The color concept was first developed and evaluated on SLG substrates. From an optical perspective, this strategy isolates the intrinsic response of the multilayer coatings, decoupling it from the complex interference and absorption effects of the underlying solar cell architecture. With SLG being a very well-known optical platform, this approach enables validation of the spectral response and color performance under well-defined optical conditions before integration into the full CIGS solar cell architecture. Thus, the usage of SLG substrates allows direct validation of the spectral response and provides a reference for the integration into the solar cell. In addition, the use of SLG substrates facilitates the exploitation of micro-fabrication procedures to validate both design and fabrication. This includes assessing feature resolution, pattern fidelity, and their impact on optical behavior before transferring the concept to the solar cell stack. Therefore, this intermediate step allows both optical validation and the assessment of microfabrication prior to integration into the CIGS device architecture. Moreover, it allows to transfer this new strategy to other technologies and applications since SLG or other glass substrates are widely used.

3.1.1. Microfabrication Procedure. At the moment, the multilayers BR structures for the Red, Green, and Blue coatings are simulated, and the expected optical behavior is known. Notwithstanding, depositing these complex structures is challenging since precise control and accuracy are required to obtain the optimized optical properties. Each individual color coating was deposited, and its total reflectance spectra were characterized and compared with simulation. If a spectral shift exists, the deposition rate of either material can be adjusted and the spectral response corrected considering that the deposition rate of each material was individually calibrated beforehand. For the individual color samples, the fabrication process is only composed of the deposition of the $\text{SiO}_x/\text{SiN}_x$ multilayer by PECVD. Afterward, the developed fabrication process of the herein presented RGB pixel coloration was established and is

presented in Figure 3. It is composed of several steps: (a) deposition of the BR individual color coatings by PECVD and stopping layer by magnetron sputtering, (b) lithography, (c) wet etch of the stopping layer, (d) reactive ion etching (RIE) of the color coatings, and (e) plasma ashing of the photoresist. Chromium (Cr) was the chosen stopping layer since it provides a high etch selectivity relative to SiO_x and SiN_x . As the individual color coatings are sequentially deposited and etched, the purpose of the stopping layer is to prevent the previous individual color coating to be etched in the following cycle, acting as a barrier during the RIE and ensuring the integrity of the patterned region during the processing of subsequent color coating region (e.g., so that the Red pattern is not etched during the Green cycle RIE step). The fabrication processes are repeated in three sequential cycles for each of the three-color coatings that compose this RGB pixel coloration. The major differences between each cycle are the deposition thickness in step a, the photolithography masks in step b, and the etching times in steps c and d. At end of the three cycles, one extra step must be taken to remove all stopping layer remnants.

Optimizing the complete fabrication process involved work individually in each step to ensure that the necessary processes were carried out and there was no interference with subsequent steps. As previously stated, the deposition times of each color coating layer were carefully calibrated; then, the Cr wet etch and RIE times were also calibrated to guarantee a correct etch. In the first attempts, the Green and Blue coatings started to delaminate after the RIE step due to the accumulation of carbon fluoride specimens (CF_x) on the SLG surface. An ultraviolet and oxygen (UVO) surface treatment was used to remove the contamination. Afterward, the RGB pixel coloration process was optimized, and it was reproducible.

3.1.2. Characterization. The successful fabrication of colored SLG substrates, including both individual coatings and the RGB pixel colorations, is first qualitatively assessed. To systematically convey this observer-dependent perceptions, photographs of the samples were acquired under outdoor conditions, specifically at noon on a clear sunny day. In Figure 4A–E, two photographs per sample are presented: (top) with an opaque optically graded black cardboard immediately behind the sample to solely access the reflected color and (bottom) without any optical rear obstruction to observe the transmission capabilities of the substrates. Furthermore, an inset on the top right corner presents the obtained color calculated from the measured normal incidence total reflectance spectrum. First, concerning the individual colors' reflectance (Red, Green, and Blue in Figure 4A–C, respectively), it is possible to observe a uniform coloration of the $5 \times 5 \text{ cm}$ substrate with small defects

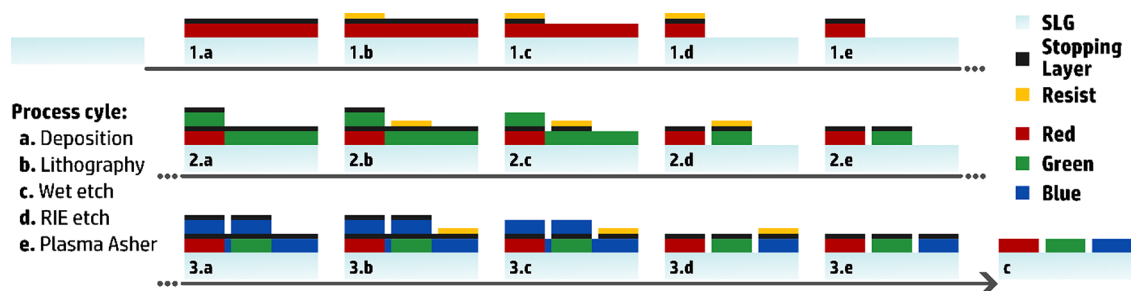


Figure 3. Schematics of the flow of the RGB pixel coloration on SLG, in which the process cycle from a to e is repeated three times for each color (e.g., step 1.a represents the process a of the first cycle).

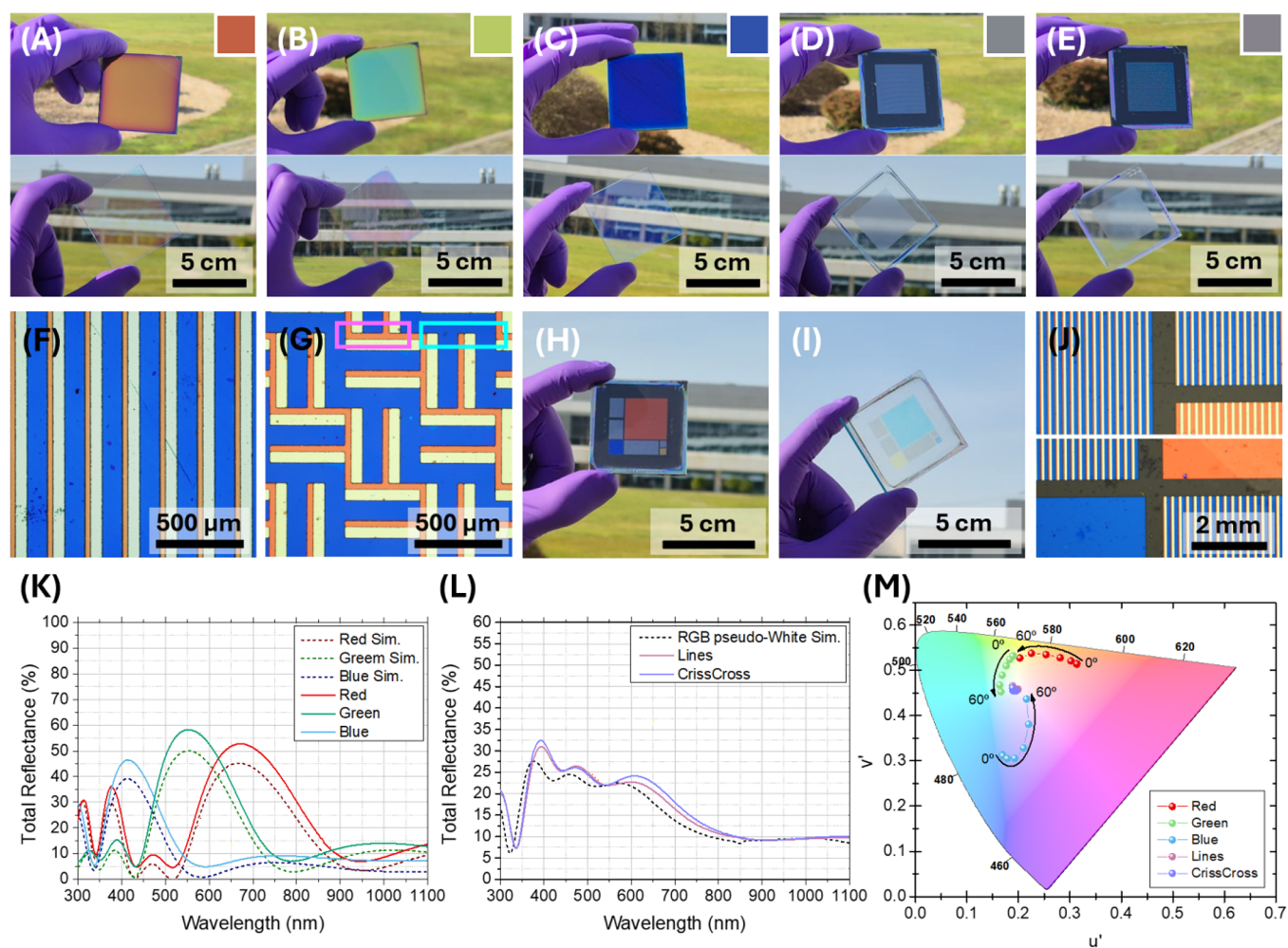


Figure 4. Photographs of the (A) Red, (B) Green, (C) Blue, (D) Lines, and (E) CrissCross coated SLG substrate ($5 \times 5 \text{ cm}^2$) taken at noon in a sunny day. The top photograph shows each sample with an opaque background (optically graded black cardboard) and the bottom without any rear optical obstruction; also, an inset color square on the top right corner shows the obtained color with normal incidence. The optical microscope images display the microfabricated architecture of the (F) Lines and (G) CrissCross architectures. On panels (H) and (I), the fabricated Mondrian's *Composition II in Red, Blue, and Yellow* photographs are shown in the same conditions, and in panel (J), optical microscope images of the lines on the Mondrian painting are shown. Plots (K) and (L) display the reflectance spectra for all fabricated samples with the corresponding simulation, and panel (M) shows the color space plot with the coordinates for all samples at different angles of incidence.

on the edges, originated by the rough SLG/carrier wafer interface that may create SiO_x and SiN_x precursor accumulation or depletion, leading to thickness differences. For the Red and Blue coatings, the photograph observed coloration matches the inset color, but in Green, there is a slight blue shift possibly due to illumination and viewing at a not zero angle. Regarding the transmission capabilities, it is possible to distinguish the far background with some detail through the colored substrate with just a small tone. Hence, the transmission is not being significantly affected. Regarding the pseudo-White samples, both Lines and CrissCross architectures shown in Figure 4D,E, respectively, have the expected color, at least in the normal incidence coloration (square inset), seeing that, in the photographs, the observed color has a bluish tone. The obtained normal incidence color is of a grayish tone and not White, agreeing with the expected pseudo-White. Although chromaticity coordinates are located in the required spectral region, the color luminance Y is low as a result of the median intensity color reflection peak of the individual coatings (Red, Green, and Blue) and the

combination in the RGB pixel coloration concept; also, in the subarea calculation, the Y parameter was excluded, so it was not maximized. To increase the Y value and switch from a grayish tone to the purest White, the number of layers should be increased, in that way having a higher maximum reflection value, but that could impact flexibility, increase chances of delamination under load, and may also induce higher losses in the solar cell photocurrent generation. In both top and bottom photographs, a translucent effect of the coloration can be seen, which is more evident in the clear background. As expected, the combination of coatings with different thicknesses in a micro-pattern seems to increase the diffusivity of the reflected and transmitted light. By close analysis of the microfabricated patterns with an optical microscope (OM) (Figure 4F,G for the Lines and CrissCross architecture, respectively), in both cases, the lines are well separated and defined. In the Lines architecture, the individual lines are parallel to the adjacent ones, and there is no clear superposition or fabrication defects; in the CrissCross architecture, each individual "subpixel" composed

of two sets of the three distinct coatings is also well defined, and the 90° rotated adjacent “subpixel” has perpendicular lines, as expected. In this case, there is no line overlapping either between lines of different coatings; however, some Red and Blue lines have fused at the extremities, highlighted in Figure 4G by neon pink and blue rectangles, respectively. This has occurred because the opaque lithography mask (for the negative resist) separation in the “defect” location is at the limit of the mask aligner resolution. Nevertheless, this is not critical since, without such defects, those areas would have no coating. In both images, the width differences between the Red, Green, and Blue lines are clear, the nominal value being 30 μm for Red, 60 μm for Green, and 120 μm for Blue.

To further test and showcase the potential of the RGB pixel coloration, the development of a simple artwork was tested: *Composition II in Red, Blue, and Yellow* by Piet Mondrian. This painting is composed of four colors, i.e., Red, Blue, Yellow, and White, and the objective was to cover the Red and Blue areas with the respective uniform individual color coatings and, on the White and Yellow, apply the novel coloration strategy. For the pseudo-White subareas, the already calculated color proportion $r = 0.15$, $g = 0.3$, and $b = 0.55$ were used, but for Yellow, new calculations were needed. Therefore, the defined Yellow targets $x = 0.45$ and $y = 0.45$ lead to new color proportions $r = 0.62$, $g = 0.38$, and $b = 0$ and simulated chromaticity coordinates $x = 0.44$ and $y = 0.44$, which has an insignificant chromaticity difference. For simplicity, the pseudo-White and Yellow component was made with the Lines architecture. The replica of Mondrian’s painting on SLG is shown in Figure 4H,I, considering an opaque and clear background, respectively, and it is very simple to distinguish the individual color sections in Figure 4H. Looking at the OM images in Figure 4J, it is possible to observe the Red and Blue square areas, where the individual lines are not superimposed, and the difference between the pseudo-White and Yellow architecture, with no Blue lines. This proof of concept not only pushes the possibilities of this novel coloring strategy but also proves its tailoring capabilities.

Considering a quantitative result, by analyzing the measured and simulated reflected spectra of the individual Red, Green, and Blue coatings (Figure 4K), a good match between the simulated (dashed curves) and the measured (solid curves) can be observed. The maximum reflectance peaks are centered around the expected wavelength, although with a slight red shift that could have occurred due to a small difference in some layers’ thickness, and there is an intensity difference between the simulated and measured spectra across all spectral regions that

arises because the simulation only accounts for the specular reflectance. By doing the same analysis on the Line and CrissCross samples (Figure 4L), it is possible to arrive at the same conclusions, observing the same small spectral red shift and a proportional intensity difference. Before, it was speculated that the perpendicularity of the “subpixel” lines of the CrissCross architecture could induce a higher light diffusion, although since the Lines and CrissCross samples have equal total reflectance spectra, it can be seen that, in the SLG, no effect was detected. To study the angle dependence of the color coatings, the specular reflectance of each sample for different angles of incidence from 0° to 60° was determined. Afterward, the chromaticity coordinates (u' , v') were calculated and plotted in the 1976 CIE color space. Despite the CIE 1931 color diagram being widely used, it does not provide a perceptually uniform representation of hue; that is, equal distances within the diagram do not correspond to equal perceived differences between color stimuli. To address this limitation, the CIE 1976 color diagram was presented, in which the coordinate system is defined by nonlinear transformations of the tristimulus values, resulting in a more nearly perceptually uniform color space. The data show a high variation of the chromaticity coordinates for the individual Red, Green, and Blue coatings, as expected since the BR strategy is based on the interference phenomenon. However, for the Lines and CrissCross strategies, the points are almost completely overlapping, showing a clear reduction on the color angle dependence.

The development on SLG served as a proof of concept before the development on CIGS solar cells; nevertheless, when considering other types of PV technologies, the implementation of this novel color strategy is still viable. It can be implemented on any SLG-based substrates, for example, to fabricate superstrate PV solar cells. Additionally, considering a more scalable option, this novel strategy can be directly implemented on the cover glass of PV modules independently of the PV technology, showcasing the versatility and applicability of the RGB pixel coloration.

3.2. Flexible CIGS Solar Cells

3.2.1. Microfabrication Procedure. A similar optimization to the one performed on SLG substrates was adopted on flexible CIGS solar cells. Before any device fabrication, the Red, Green, and Blue coloring coating depositions were recalibrated by depositing them on flexible CIGS solar cells and characterizing the optical response. In Figure 5A, the complete microfabrication procedure is depicted, with all its individual processes: (a) color coating deposition, (b) lithography, and

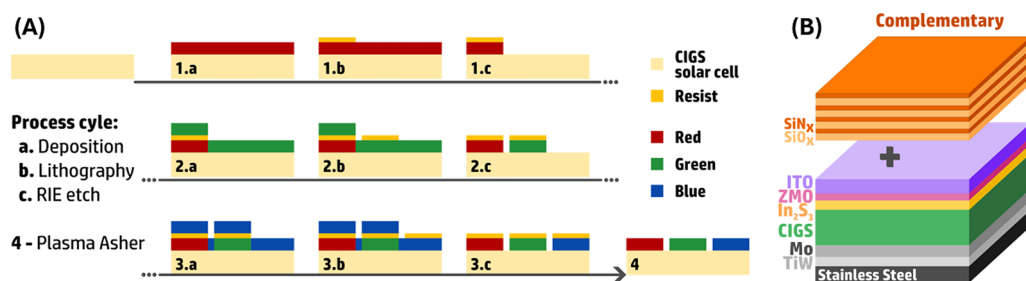


Figure 5. (A) Schematic of the process flow of the RGB color strategy on flexible CIGS solar cells, in which the process cycle from *a* to *c* is executed three times for each color (e.g., step 1.a represents the process *a* of the first cycle), plus a concluding plasma ashing step (4). (B) Representation of the Complementary coating eight-layer structure.

(c) RIE etching, which are sequentially executed three times, and the last step is a plasma ashing removal of the photoresist (numbered 4). By simple comparison of the optimized process flows in Figures 3 and 5A, the schematic that represents the optimized process on CIGS solar cells is much simpler. With the optimization process, the RIE process optimized for SLG substrates proved to be incompatible with the SS substrate, most probably due to the high plasma power and the significant temperature difference between the chamber and the substrate holder. Thus, this processing step was swapped for a similar low-thermal-budget RIE process. Moreover, because of the Cr's etch process incompatibility with the solar cell structure and the RIE etch selectivity to SiO_x and SiN_x , the stopping layer was removed from the process, and the photoresist served as patterning mask and stopping layer for the following process cycles. Notwithstanding, the photoresist was changed for one capable of enduring the repetitive process conditions due to its enhanced chemical stability, plasma etching resistance, and temperature stability up to 220 °C. Also, besides the similar chemistry previous and new etches, C_4F_8 and CF_4 , respectively, in the solar cell processing, the UVO surface treatment was no longer necessary since the SiO_x and SiN_x had the proper adhesion to the ITO front contact. At this point, the process was considered optimized and reproducible. Note that this can also be employed on the SLG substrate, and the process can benefit from the optimized updates.

To accurately access the benefits and disadvantages of this work of a novel RGB coloring strategy, a counterpart was established, developed, and called Complementary. This coating is of a simple BR alternating structure that provides the same color as the Lines and CrissCross RGB samples: pseudo-White. In Table 2, the OpenFilters simulation parameters are presented; the color target was set with the same chromaticity coordinates as the previous color proportion calculation and with the initial thicknesses defined as quarter wave thick at 500 nm. In this case, luminance Y was defined as 30 to obtain the pseudo-White tone. Initially, the number of layers was set to six, as for the previous individual color coatings, but all the tests with different initial conditions (center wavelength at different wavelength values) did not lead to the required result, always shifting to green or purplish tones. Then, the number of layers was increased to eight to produce a Complementary sample that could be compared with the pseudo-White RGB pixel coloration samples. The optimized layer thickness and the obtained color are listed in Table 2, and the final BR structure of the Complementary coating is shown in Figure 5B. For this BR structure optimization, the color differences indicate no significant change in saturation or hue, although the ΔE value still tells that the colors are easily distinguishable.

Regarding the fabrication of the individual color coating (Red, Green, Blue, and the Complementary), since part of the ITO of each cell must be exposed to allow an electrical contact,

a microfabrication cycle (a–c) plus the resist removal had to be done to complete a device.

3.2.2. Characterization. In Figure 6A–G, photographs of Bare, Red, Green, and Blue; the novel strategy with Lines and CrissCross patterns; and Complementary samples are presented, respectively. First, concerning the Bare solar cell, it is possible to observe a very dark blue, especially in the top right corner color inset. The Red, Green, and Blue have the expected coloration, agreeing with the simulated color. Regarding the pseudo-White RGB pixel coloration samples, Lines and CrissCross, both samples show the required whitish coloration; only the active middle area of the sample was covered with the novel coloring strategy, contrary to the individual color coatings where all $5 \times 5 \text{ cm}^2$ areas were covered. The perceived color is uniform within the covered area, the distinct pattern is not distinguishable, and the measured color is similar in both cases. Analogous to the development on SLG, the microfabrication pattern obtained presents no defects or superposition of adjacent lines, seen through OM. Comparing this samples with the Complementary coating in Figure 6G, it seems that this one has a more intense specular reflectance; also, in the color inset, the grayish tone is indeed brighter but also appears to have a pink tone. Although with a brighter color, the Complementary coating still has a slight color deviation to what is desired even with the increase of the number of layers from six to eight.

The measured total reflectance spectra for Bare and individual colors samples (Red, Green, and Blue) and corresponding simulation are plotted in Figure 6H, in which the extremely low reflectance of Bare is seen even without an antireflective coating (ARC). For the three individual color samples, the measurements have a maximum reflection intensity difference to simulation of about 20–25% absolute value. Such difference may be due to the higher simulation complexity of the CIGS solar cell's optical system compared to SLG substrates. Nevertheless, the intended dominant reflection peaks are located in the appropriate spectral region, and the expected color is obtained. Figure 6I has the reflectance spectra corresponding to the pseudo-White samples, the RGB pixel coloration with Lines and CrissCross (left), and the Complementary coating (right). Like in SLG substrates, the Lines and CrissCross strategies have identical reflectance spectra providing the same color, holding similar conclusions about the diffuse properties. Comparing it with the simulated spectrum, the curve trend is the same, but once again, there is a slight intensity difference, possibly arising from the same cause as for the individual color coatings. In the Complementary coating, the intensity of the measured and simulated spectra is in the same range; however, there is a slight ($\sim 20 \text{ nm}$) blue-shift in the measured spectra. The intensity difference could have been minimized due to the increase from six to eight layers; nonetheless, with more layers, the structure can have a higher thickness

Table 2. Optical Simulation Color Target with Interval ($Y \pm 1$, $x \pm 0.01$, $y \pm 0.01$) Defined to Optimize the Thickness of the Complementary Coating; the Obtained Thickness Values; the Simulated Final Color; and the Total Color, Chroma, and Hue Differences

Color Target (Y, x, y)	Layer Thickness in nm ($\text{SiO}_x/\text{SiN}_x$) ^a	Color Obtained (Y, x, y)	ΔE	ΔH	ΔC
30, 0.31, 0.33	48/136/126/100/127/83/73/60	26.83, 0.33, 0.33	8	5	5

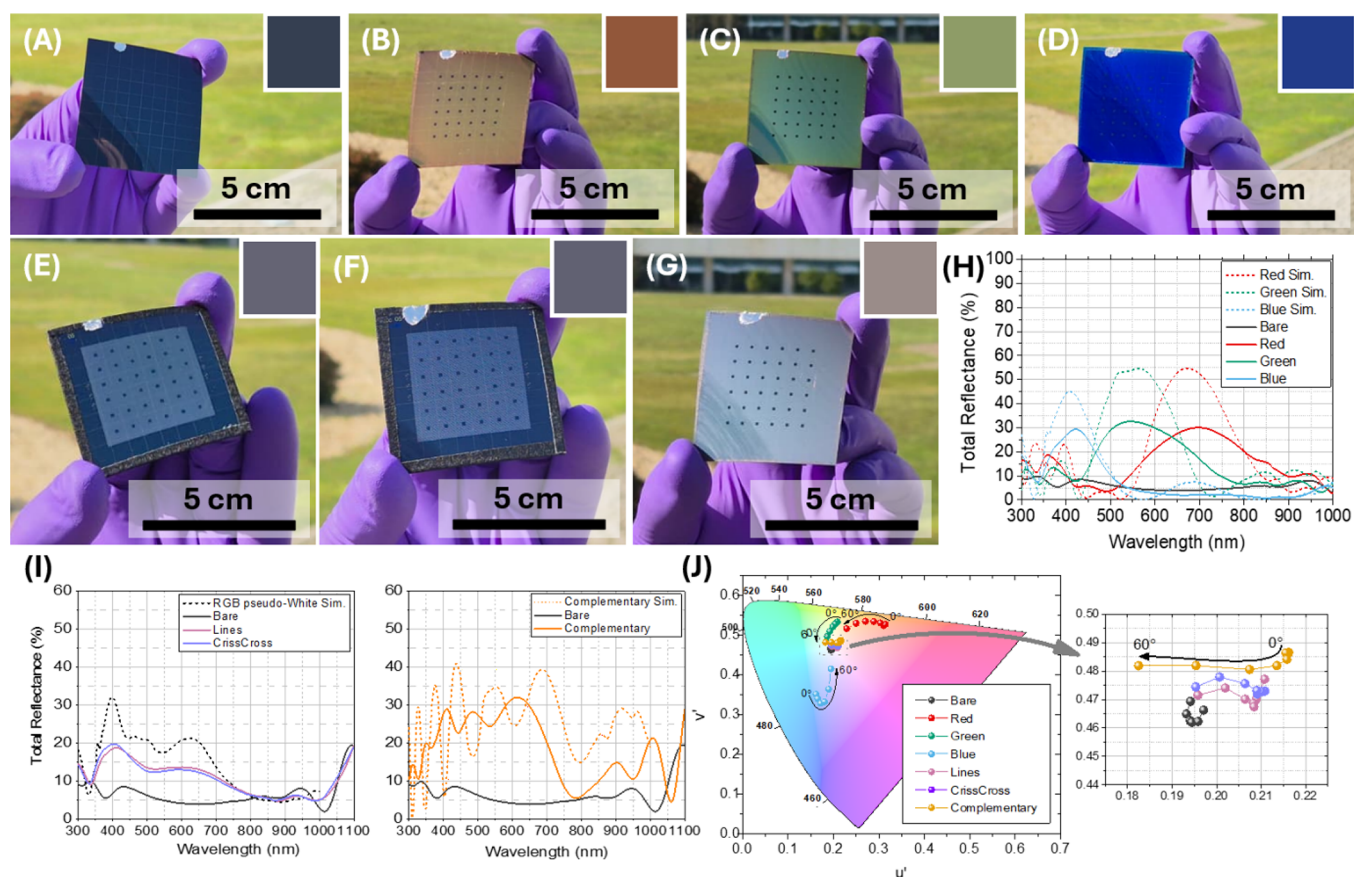


Figure 6. Photographs of the (A) Bare, (B) Red, (C) Green, (D) Blue, (E) Lines, (F) CrissCross, and (G) the newly defined Complementary coated flexible CIGS solar cells ($5 \times 5 \text{ cm}^2$) taken at noon in a sunny day. Plots (H) and (I) display the reflectance spectra of the individual color coatings and the pseudo-White strategies, respectively, and panel (J) shows the color space with the coordinates for all samples at different angles of incidence; the inset presents a close-up of the white color region.

sensitivity, which can explain the shift. The color diagram in Figure 6J shows the color angle dependence for all fabricated colorful solar cells. As expected, the Red, Green, and Blue samples have a large spread, although smaller than in the SLG samples. The remaining samples (Bare, Lines, CrissCross, and Complementary) have their chromaticity coordinates located at the center region of the color diagram, and by careful inspection, it can be seen that the Complementary coating has a higher color angle dependence than its counterparts (Lines and CrissCross). To have a clearer analysis, a zoom-in inset of this region is provided. While the v' variation is similar, in the u' axis, the Complementary coating spreads from 0.185 to 0.215, while the Lines and CrissCross only do from 0.195 to 0.210. Considering the reflectance spectra and that the color angle dependence is reduced by half with this work strategy in comparison to the Complementary, optically, the Lines and CrissCross samples prove to be a better alternative to develop a pseudo-White coloration.

After the sample's optical characterization, the flexible CIGS solar cells' optoelectrical performance was studied to assess the coloring impact. External quantum efficiency (EQE) spectra and standard current density vs voltage (JV) characteristic curves were measured. In Figure 7A,B, EQE spectra of samples of the individual color coatings and the pseudo-White strategies, respectively, are presented. Comparing the Red, Green, and Blue coatings in Figure 7A with the Bare sample EQE, the color

reflection peaks at 700, 550, and 420 nm can be seen as valleys in their respective spectrum. In the remaining spectral region, from 330 to below 400 nm, the three coatings follow the Bare sample behavior, and from 800 nm and above, these act as ARC, decreasing the surface reflectance and increasing the light that reaches the absorber. Within the visible spectral region and outside the higher-intensity reflection peak, the Blue has a higher EQE, while the Red and Green have lower EQE, similar to the tendencies shown on the reflectance spectra. Concerning the pseudo-White samples (Lines, CrissCross, and Complementary) in Figure 7B, the reflectance peaks that originate color in the 350 to 750 nm region are translated to a lower EQE compared with the Bare reference, and from 800 nm forward, the three EQE spectra follow the Bare sample behavior since the decrease in reflectance, the antireflective effect, is not significant. Note that the difference in reflectance intensity between the Lines and CrissCross and the Complementary is also evident in the EQE.

In Figure 8A,B, the JV representative curves for samples of the individual color coatings and the pseudo-White strategies, respectively, are presented. A diode-like JV behavior is observed in all devices, with no evidence of considerable shunting. One common aspect for all curves is the crossover effect between the AM1.5G (solid lines) and Dark curves (dashed lines), which has been associated with a barrier at the front or rear interface.^{72,73} Then, in the box plots of Figure 8C–F,

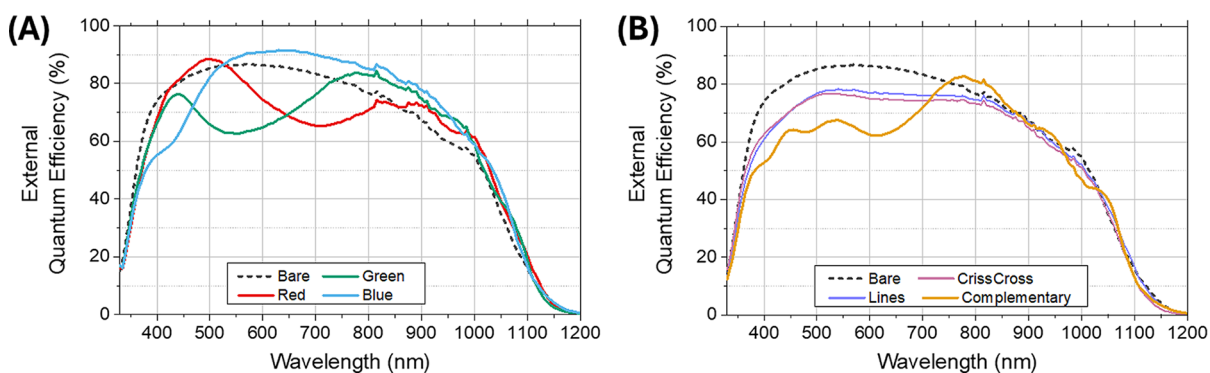


Figure 7. EQE spectra of representative devices in (A) the Bare, Red, Green, and Blue devices and (B) for Bare, Lines, and CrissCross strategies and the Complementary coating.

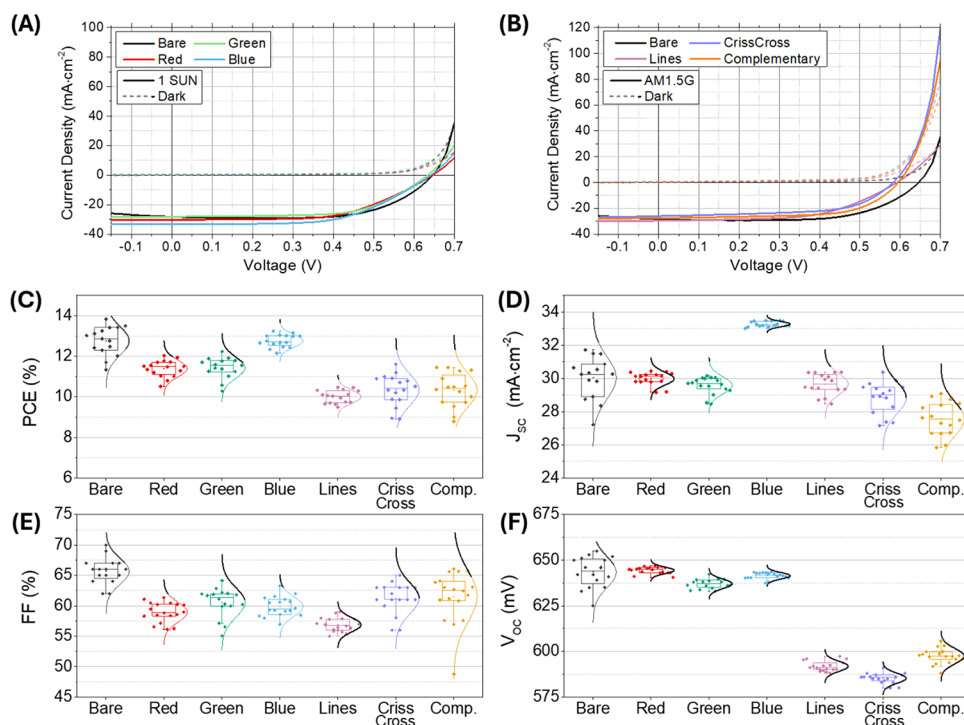


Figure 8. Current–voltage characteristic curve of the representative cell for (A) the individual colors and (B) the pseudo-White coatings. Box plots of the figures of merit: (C) power conversion efficiency, (D) short circuit current, (E) fill factor, and (F) open circuit voltage from 18 solar cells per device, based on JV data. The J_{SC} was determined with EQE, and the PCE was corrected with it.

the performance of all measured cells per sample is summarized with the four main figures of merit: PCE, J_{SC} determined through EQE, open-circuit voltage (V_{OC}), and fill factor (FF), respectively. In terms of the overall PCE in Figure 8C, the higher average value is from the Bare samples, without any color coating, followed by the Blue, then Red and Green with approximately the same value, and last the pseudo-White strategies (Lines, CrissCross, and Complementary), as expected. This result is anticipated since the addition of a coloration strategy by default induces optical losses; nevertheless, there are other unexpected factors that also affected performance. The J_{SC} analysis in the JV plots of Figure 8A shows that while the Bare, Red, and Green samples are around the same value, less than $30 \text{ mA}\cdot\text{cm}^{-2}$, the Blue sample clearly stands out with the higher value; in Figure 8B, the three pseudo-White coatings

show a slight reduction of J_{SC} when compared to the Bare. Comparing the average J_{SC} values obtained from EQE in Figure 8D, Red has no significant loss, and the Green sample loss is nearly $0.5 \text{ mA}\cdot\text{cm}^{-2}$ (in comparison with the Bare) despite the broad reflection peaks; the higher EQE from 800 nm and above probably allows to compensate for the losses induced in the visible range. For Blue, a considerable $3.3 \text{ mA}\cdot\text{cm}^{-2}$ increase is obtained, which means that the antireflection behavior produced in the majority of the spectral range of interest overshadows the loss induced by the main reflectance peak. In the novel coloring strategy, although these have similar reflectance spectra, the average J_{SC} loss is lower for the CrissCross (approx. $1.2 \text{ mA}\cdot\text{cm}^{-2}$) than for the Lines pattern (approx. $0.5 \text{ mA}\cdot\text{cm}^{-2}$), possibly due to resistive or recombinative losses, as the CrissCross sample also demonstrated the

lowest V_{OC} . The Complementary coating induces higher J_{SC} losses, $2.5 \text{ mA}\cdot\text{cm}^{-2}$, agreeing with the low EQE from 350 to 800 nm. Comparing the curves in Figure 8A,B, FF seems higher for the Bare sample, and the same is observed in the box plot of Figure 8E. While the Bare sample has an FF value over 65%, the remaining samples have similar values, around 60%. The slight FF degradation might have resulted from the plasma ashing step in the microfabrication procedure. The photoresist is removed by using an oxygen (O_2) generated plasma, and the high concentration of O_2 can induce changes in the ITO that decrease its conductivity and, consequently, the solar cells' FF.^{74,75} Regarding V_{OC} , two distinct values can be spotted. From the average values in the box plot of Figure 8F, Bare, Red, Green, and Blue samples have the same V_{OC} of around 640 mV, while the pseudo-White coloration samples suffered a significant decrease to approximately 590 mV. The Lines and CrissCross samples have a distinct three-cycle process that can be the cause of the V_{OC} decrease, but the Complementary coating has the same fabrication process as Red, Green, and Blue samples. The only common fabrication aspect between the RGB pixel coloration and Complementary samples is the cumulative RIE etch time, which for the Lines and CrissCross is the sum of three separate etch procedures and for the Complementary is a long single etch, being over 9 min for all three. Moreover, although the total duration is the same, in a longer continuous process, the thermal budget might be higher due to heat accumulation. Thus, besides the optical impact of the coloring strategies, there is unexpected process damage to the performance that somehow decreases FF and V_{OC} , possibly arising from the RIE and the photoresist removal processes.

Common plasma-induced damage in RIE processes arises from ion bombardment and/or UV radiation, leading to carrier recombination in Si technologies, reversible or irreversible depending on the affected area, i.e., deep Si substrates or Si-based layer (e.g., SiO_x and SiN_x), respectively.^{76,77} Similarly, group III–V compounds are also prone to this type of degradation,^{78,79} leading to crystal amorphization and defect generation, which will also increase recombination and leakage current.⁷⁹ Therefore, there is a high probability that the prolonged exposure in the RIE process of the pseudo-White samples, even though for the Lines and CrissCross it was divided in three distinct moments, degraded the CIGS solar cell, absorber, or interfaces, which led to increased recombination centers. Consequently, this might have led to the approx. 60 mV reduction in V_{OC} . To further verify the aforementioned assumptions, a one-diode model analysis⁸⁰ was done to the dark characteristic JV curves of the samples with highest and lowest V_{OC} , i.e., Bare and CrissCross, respectively. The advanced cell parameters were obtained: shunt resistance (R_{shunt}), series resistance (R_{series}), ideality factor (A), and saturation current density (J_0), and summarized in Table 3.

The increase in the ideality factor from the Bare with 1.3 to 1.9 for the CrissCross indicates a transition from an almost

ideal one-diode JV behavior to a less ideal regime, suggesting an increase in recombination losses. Since A approaches a value of 2, the dominant recombination mechanism is likely associated with the space-charge region (SCR).⁸¹ Both values show that recombination mechanisms can be described by Shockley–Read–Hall (SRH) model: deep defect states.⁸¹ The R_{series} value increase by 1 order of magnitude may have been caused by the ITO surface damage in the photoresist removal process, which led to a lower layer conductivity. The R_{shunt} is similar, so the RIE did not create more shunt paths that could damage performance. Finally, a 2 order of magnitude increase is seen in J_0 , which can be associated with an increase in recombination rate, probability caused by RIE. Hence, besides the optical changes that affected the performance of the solar cells, there are two main fabrication factors that induced losses: (i) the RIE damage, which led to an increased recombination rate, decreasing the V_{OC} , and (ii) the plasma ashing process for photoresist removal, which decreased the ITO conductivity, leading to an FF reduction. These issues, although critical, can be mitigated by finding alternative processes. For instance, the CF_4 -based etch can be replaced by a purely physical etching, although that will come with its own challenges. For once the selectivity is negligible, the etching times must be precisely calibrated, and the photoresist thickness values must be adjusted. Another issue is the possible formation of not negligible texturization and/or reduction of the ITO front contact layer, which can cause unexpected optical behavior and charge extraction issues, respectively; nonetheless, the ITO front contact can be optimized to tackle these if such issues arise. Another alternative is tuning the CF_4 -based RIE conditions to a lower RF power. Some research has been carried out to adapt the RIE process or plasma treatments, minimizing solar cell degradation.^{78,82–84}

This demonstration proves that the combination of distinct individual color coatings in the same microsize structure, RGB pixel coloration, based on the physical principle of the additive color theory, is a viable and meaningful strategy to color flexible CIGS solar cells. A uniform pseudo-White coloration with the desired hue was reached with two distinct architectures, i.e., Lines and CrissCross, by tailoring the individual color proportions. The microfabrication process flow was optimized to obtain reproducible results, but microfabrication processes fully compatible with CIGS solar cells must still be found. Optically, the RGB pixel samples' behavior is as expected, with relative total reflectance trends being seen in the EQE and a significant improvement in color angle dependence. Considering the pseudo-White RGB pixel coloration samples, these have a significant lower J_{SC} loss, emerging from the basic concept of this work. Comparing the Lines and CrissCross samples, while both have equal optical behavior, their device FoMs are inconclusive due to the fabrication setbacks affecting V_{OC} and FF and small variations arising from possible CIGS solar cell differences. Thus, a final appreciation of the preferred architecture will tend to the Lines because of its simplicity and the pattern being less distinguishable by the naked eye at higher proximity. In general, the optical J_{SC} loss is as high as 4%, while enhancements reach 10%.

4. CONCLUSIONS AND OUTLOOK

In this work, a novel coloring strategy capable of color tunability, reduced optical losses, and mitigated angle dependence

Table 3. Mean and Associated Uncertainty of the Advanced Parameters R_{shunt} , R_{series} , A , and J_0 Derived through a One-Diode Model Fit

	A	$R_{series} (\Omega\cdot\text{cm}^2)$	$R_{shunt} (\text{k}\Omega\cdot\text{cm}^2)$	$J_0 (\text{nA}\cdot\text{cm}^{-2})$
Bare	1.3 ± 0.1	0.3 ± 0.1	1.6 ± 0.4	1.6 ± 0.7
CrissCross	1.9 ± 0.1	2.4 ± 0.1	1.4 ± 0.2	214.9 ± 131.7

was proposed and experimentally demonstrated. Inspired by LED-based display technologies, the concept relies on the side-by-side combination of three distinct BR coatings corresponding to Red, Green, and Blue (RGB). By varying the relative area fraction of each coating, the perceived final color can be tailored while simultaneously balancing performance losses and gains associated with the individual color components. Two microscale line-based architectures were initially developed on SLG substrates to directly validate their spectral response and were subsequently implemented on flexible CIGS solar cells, the targeted platform. White coloration was selected as the primary demonstration due to the predominance of neutral and low-saturation tones in building facades. However, the capability to achieve a broader range of colors was also demonstrated. The results confirmed a reproducible microfabrication process on both SLG and flexible CIGS solar cells, yielding visual defect-free patterns while successfully producing the desired optical response. Furthermore, the proposed RGB pixel coloration strategy significantly reduced color angle dependence when compared with conventional uniform BR structures. In terms of photovoltaic performance, all colored devices exhibited equal or lower power conversion efficiency values than the bare reference cell. Both the fill factor and open-circuit voltage were affected by specific microfabrication steps, namely, resist removal, which may have increased the ITO resistance, and reactive ion etching, which likely enhanced recombination within the device. Nevertheless, these limitations are attributed to process-related issues and can be addressed through further process optimization and engineering. Regarding the optically induced variations in short-circuit current density, the Red coating exhibited negligible losses, while the Green coating showed a reduction of approximately $0.5 \text{ mA}\cdot\text{cm}^{-2}$. In contrast, the Blue coating produced a substantial enhancement of $3.3 \text{ mA}\cdot\text{cm}^{-2}$. The proposed RGB pixel coloration resulted in a current density reduction of less than $1.5 \text{ mA}\cdot\text{cm}^{-2}$, whereas a conventional uniform BR designed to achieve a similar White appearance exhibited a decrease of approximately $2.5 \text{ mA}\cdot\text{cm}^{-2}$. Overall, the proposed coloring strategy demonstrates strong potential and practical applicability not only for flexible photovoltaic devices but also for colored cover glass applications. Once the identified fabrication-related issues are resolved, this approach may enable the realization of colorful solar cells with minimal efficiency penalties (1% to 4% relative) and, in specific cases, even enhancements of up to 10%.

5. EXPERIMENTAL SECTION AND METHODS

5.1. Optical Simulations

Optical Simulations. Optical simulations were performed using the transfer matrix method (TMM), which models light propagation and interference in multilayer thin-film schemes, in the open-source software OpenFilters.⁶⁵ The optical constants (refractive index and extinction coefficient: n and k) of each material were measured through a spectroscopy ellipsometer (J.A. Woollam M-2000 Ellipsometer) with a Cauchy model and then uploaded to OpenFilters. With the determined Cauchy parameters— $A = 1.46$, $B = 0.005$, and $C = -1 \times 10^{-4}$ for SiO_x and $A = 1.82$, $B = 0.012$, and $C = 8 \times 10^{-4}$ for SiN_x —the refractive index values at 550 nm are 1.48 and 1.86, respectively. The optical constants of the remaining solar cell layers were based on already reported values that can be found elsewhere.⁸⁵ The simulated structure considers all the solar cell layers and a BR multilayer of SiO_x and SiN_x on top. The number of $\text{SiO}_x/\text{SiN}_x$ bilayers was

changed between one and four in preliminary simulations and then fixed at three. The initial thickness for each layer was established to be a quarter-wave thick ($d = \lambda/4n$, where d is the layer thickness, λ the center color wavelength, and n is the refractive index of the material at λ). To reach the desired color target (Y, x, y), which is defined in the software, an internal optimization option based on the Levenberg–Marquardt algorithm⁶⁵ was used, in which each layer thickness of the BR was varied and optimized. At any point, the software is able to determine optical physical characteristics (reflectance, transmittance, absorbance, color coordinates, etc.) using mathematical calculations based on the TMM.⁶⁵

5.1.1. Subarea Color Calculation. To cover all possible combinations of the Red, Green and Blue combination in an arbitrary area unit, two sequential sweeps were used. First, the subarea fraction of red (r) varied from 0 to 1 to define the portion of the total area occupied by the Red coating. Following, a second parameter (p), also ranging from 0 to 1, was introduced to determine the fraction of the remaining area (not covered by Red) to be assigned to the Green coating, such that $g = (1 - r)p$. The blue coating occupies the remaining area, given by $b = 1 - r - g$. In this optimization, the effective reflectance spectrum for a pixel was calculated by simply considering an average of the subarea-weighted Red, Green, and Blue simulated reflectance spectra ($R(\lambda) = r \cdot R_{\text{Red}}(\lambda) + g \cdot R_{\text{Green}}(\lambda) + b \cdot R_{\text{Blue}}(\lambda)$). Afterward, the chromaticity coordinates were calculated, and so was the Euclidean distance to define the color target. The optimal solution was defined as the set of parameters (r, g, b) that minimizes this distance.

5.1.2. Substrate Preparation. Substrate Preparation. Prior to the microfabrication process, the SLG substrates were cleaned in a 5 min sequential ultrasonic acetone, isopropanol (IPA), and deionized (DI) water bath and then blow-dried with nitrogen (N_2).

5.1.3. Solar Cell Fabrication. The flexible CIGS solar cells used to develop colorful devices were produced in Midsummer's DUO tool: an in-line vacuum, sputtering-based approach with 25 sputtering stations that uses an 8 in. semisquare stainless-steel plate as substrate. The deposition process is described elsewhere.⁶⁴ The solar cell is composed of different layers, starting with the diffusion barrier of TiW followed by the sodium (Na) source of Na-doped molybdenum (Mo/Na) and the Mo rear contact; then the CIGS absorber layer is formed by sequential layers with different compositions to form the necessary grading, followed by the In_2S_3 buffer layer; to top off the solar cell, the window layer is composed of ZMO and ITO. Since the solar cell deposition was done in wafer size, they were cut in a semiautomatic dicing saw equipment (Disco DAD 3500 with boron nitride blade) to a $5 \times 5 \text{ cm}$ size after being coated with a protective resist; then the device was submitted to 5 min sequential ultrasonic bath of acetone and IPA and blow-dried with N_2 . Afterward, the individual solar cells were mechanically scribed with a diamond tip to a $5 \times 5 \text{ mm}$ size; any residue of this process was removed with IPA and blow-dried with N_2 .

5.1.4. Quasi-Bragg Reflector Deposition. To improve the adhesion of the first layer of the color coating and remove any residue from the subsequent etch procedures used in the process, an UVO surface treatment at 60°C for 10 min, from a NOVASCAN 4" UV/Ozone System, was used in the SLG substrates. Such step was not required in the CIGS solar cell processing. The SiO_x and SiN_x that compose the multilayer coloring coatings were deposited by PECVD using an SPTS PECVD system, with a plasma power of 30 W at 13.56 MHz, a substrate temperature of 200°C , 0.9 Torr working pressure, and a mixture of SiH_4 and N_2O , and SiH_4 and NH_3 precursor gases, respectively.

5.1.5. Lithography Procedure. Before any photoresist coating, the surface was primed with an HMDS (hexamethyldisilazane) at 150°C in a Vapor Prime Oven YES-310TA. Since the optimization process for flexible CIGS solar cell was carried out after completing the optimization on the SLG substrate, some minor differences were implemented. Although both exposures were performed in a 6 in. mask aligner (MA6BA6 from Suss Microtec), for SLG substrates, a $2.2 \mu\text{m}$

positive AZP4110 photoresist was used that required an i-line exposure development in AZ 400 K 1:4, while for flexible CIGS solar cells, the process was carried out with 2.2 μm negative AR-N4340 photoresist exposed with broadband UV light and developed with AR 300-47 4:3. In both cases, after the development, the Lines and CrissCross pattern was transferred to the photoresist.

5.1.6. Etching Procedures. The patterning of the color coatings was physically and chemically etched in two RIE equipment, both from SPTS. The first, used in the SLG substrate process, employs a C_4F_8 chemistry at 100 $^\circ\text{C}$ and a 2000 W at 13.56 MHz and active temperature control on the wafer holder set at 0 $^\circ\text{C}$. The second, used for processing CIGS solar cells, uses CF_4 chemistry at 50 $^\circ\text{C}$ and a 1300 W at 13.56 MHz, with a wafer holder temperature set at 40 $^\circ\text{C}$. The Cr stopping layer deposited via magnetron sputtering in a Kenosistec-A multitarget UHV sputtering system (100 nm for Red, 75 nm for Green, and 45 nm for Blue), used in the SLG process, was patterned and removed with 100 rpm agitated bath of Cr Etchant (*Chrome Etch 18* from Micro Resist Technology) with an approx. etch rate of 1 $\text{nm}\cdot\text{s}^{-1}$. After such wet etch, the samples were rinsed with DI water and blow dried with N_2 . When the resist was to be removed from both SLG and flexible CIGS solar cells, a plasma ashing process was done in a PVA Tepla GIGAbatch 360 M system: the recipe applied a 230 W microwave plasma at 2.45 GHz with an O_2 atmosphere for 6 min; this was repeated a maximum of four times to ensure a complete resist removal.

5.1.7. Characterization. The optical measurements were performed with a Perkin Elmer Lambda 1050 + UV-Vis-NIR system with an integrative sphere module from 300 to 1200 nm. To perform angle-dependent measurements, both the integrative sphere and the Total Absolute Measurement System (TAMS) modules were used. For normal incidence, the specular component was calculated with the total and diffuse reflectance subtraction, both measured in an integrating sphere. For angles of incidence from 10 $^\circ$ to 60 $^\circ$, the TAMS allows to rotate the sample holder and detector in a way that their surface normal forms an angle of α and 2α with the incident beam direction, respectively, ensuring the specular condition. Regarding the color coordinates, they were calculated as described elsewhere considering D65 illumination, meaning an average daylight representation, and were plotted in the 1931 CIE (International Commission on Illumination) with the x and y coordinates. However, when considering angle dependence, the 1976 CIE color space was used instead, with $u' = \frac{4x}{-2x + 12y + 3}$ and $v' = \frac{9y}{-2x + 12y + 3}$, since it provides a more uniform color spacing. The sample's surface was analyzed by optical microscope imaging (Nikon Eclipse L200N) with different external objective magnifications (1 $\times$, 5 $\times$, 10 $\times$, and 20 $\times$). Regarding solar cell characterization, JV measurements were conducted in a standard condition with a home-made system (Sol3A Class AAA solar simulator and Keithley 2040 source-meter with four-wire sense), both in AM1.5G illumination and in the dark. Then, EQE measurements were performed in a QuantaX Oriol 300 system that uses a chopped monochromatic light scan from 330 to 1200 nm with a 5 nm step.

AUTHOR INFORMATION

Corresponding Author

Jennifer P. Teixeira – INL - International Iberian Nanotechnology Laboratory, Avenida Mestre José Veiga, Braga 4715-330, Portugal; Email: jennifer.teixeira@inl.int

Authors

Xavier L. Pinheiro – INL - International Iberian Nanotechnology Laboratory, Avenida Mestre José Veiga, Braga 4715-330, Portugal; Departamento de Física da Universidade de Aveiro, Campus Universitário de Santiago, Aveiro 3810-193, Portugal; CICECO, Aveiro Institute of Materials, University of Aveiro, Campus Universitário de

Santiago, Aveiro 3810-193, Portugal; orcid.org/0000-0001-7786-3638

António J.N. Oliveira – INL - International Iberian Nanotechnology Laboratory, Avenida Mestre José Veiga, Braga 4715-330, Portugal

André F. Violas – INL - International Iberian Nanotechnology Laboratory, Avenida Mestre José Veiga, Braga 4715-330, Portugal; orcid.org/0009-0001-6858-6680

Enzo J. Ribeiro – INL - International Iberian Nanotechnology Laboratory, Avenida Mestre José Veiga, Braga 4715-330, Portugal; Hasselt University, imo-imomec, Martelarenlaan 42, Hasselt 3500, Belgium; Imec, imo-imomec, Thor Park 8320, Genk 3600, Belgium; EnergyVille, imo-imomec, Thor Park 8320, Genk 3600, Belgium

José Fernandes – INL - International Iberian Nanotechnology Laboratory, Avenida Mestre José Veiga, Braga 4715-330, Portugal; Department of Industrial Electronics (DEI) of the School of Engineering of the University of Minho, Campus of Gualtar, Rua da Universidade, Braga 4710-057, Portugal

Mauro Costa – DST Solar, S.A., Rua de Pitancinhos, apartado 208, -Palmeira, Braga 4711-911, Portugal; orcid.org/0000-0003-0601-4166

Paulo A. Fernandes – INL - International Iberian Nanotechnology Laboratory, Avenida Mestre José Veiga, Braga 4715-330, Portugal; CIETI, Department of Physics, ISEP – Porto School of Engineering, Rua Dr. António Bernardino de Almeida 431, Porto 4249-015, Portugal; i3N, Departamento de Física Universidade de Aveiro, Campus Universitário de Santiago, Aveiro 3810-193, Portugal; orcid.org/0000-0002-1860-7797

Rute A.S. Ferreira – Departamento de Física da Universidade de Aveiro, Campus Universitário de Santiago, Aveiro 3810-193, Portugal; CICECO, Aveiro Institute of Materials, University of Aveiro, Campus Universitário de Santiago, Aveiro 3810-193, Portugal; orcid.org/0000-0003-1085-7836

Pedro M.P. Salomé – INL - International Iberian Nanotechnology Laboratory, Avenida Mestre José Veiga, Braga 4715-330, Portugal; Departamento de Física da Universidade de Aveiro, Campus Universitário de Santiago, Aveiro 3810-193, Portugal; i3N, Departamento de Física Universidade de Aveiro, Campus Universitário de Santiago, Aveiro 3810-193, Portugal

Complete contact information is available at:

<https://pubs.acs.org/doi/10.1021/acsami.6c16045>

Funding

C644876810-00000019, 2022.14053.BD, 2021.02405.CEECIND; CICECO-Aveiro Institute of Materials, UID/50011/2025 (DOI [10.54499/UID/50011/2025](https://doi.org/10.54499/UID/50011/2025)) & LA/P/0006/2020 (DOI [10.54499/LA/P/0006/2020](https://doi.org/10.54499/LA/P/0006/2020))

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported in part by the Innovation Pact “R2UTechnologies-modular systems”, with the reference number C644876810-00000019 and by Component C5–Capitalization and Business Innovation under the Portuguese Resilience and Recovery Plan, through the NextGenerationEU Fund, and

developed within the scope of the CICECO-Aveiro Institute of Materials, UID/50011/2025 (DOI: [10.54499/UID/50011/2025](https://doi.org/10.54499/UID/50011/2025)); LA/P/0006/2020 (DOI: [10.54499/LA/P/0006/2020](https://doi.org/10.54499/LA/P/0006/2020)) financed by national funds through the FCT/MCTES (PIDDAC) and, when eligible, co-funded by EU funds. The work of Xavier L. Pinheiro and Jennifer P. Teixeira was supported by Fundação para a Ciência e Tecnologia (FCT) under grants 2022.14053.BD and 2021.02405.CEECIND, respectively.

REFERENCES

- (1) IEA World Energy Outlook 2025. <https://www.iea.org/reports/world-energy-outlook-2025>, Licence: CC BY 4.0 (report).
- (2) IEA Renewables 2025. <https://www.iea.org/reports/renewables-2025>, Licence: CC BY 4.0.
- (3) IEA Technology: Solar PV and wind – Global Energy Review 2026 – Analysis. <https://www.iea.org/reports/global-energy-review-2026/technology-solar-pv-and-wind> (accessed 2026-06-09)
- (4) Masson, G.; l'Epine, M. d.; Kaizuka, I.; Okazaki, J. Trends in PV Applications 2025 https://iea-pvps.org/trends_reports/trends-2025/ (accessed 2026-03-25).
- (5) European Commission. Directorate General for Energy. In *How to Turn NIMBY into PIMBY?: Key Challenges and Lessons Learned in Overcoming Reluctance and Promoting Public Acceptance of the Energy Transition Locally*; Publications Office of the European Union: Luxembourg, 2025.
- (6) Muñoz, J.; Tormos, R. Mitigating the NIMBY Effect on Renewable Energy: Experimental Evidence from Survey-Based Interventions in Catalonia. *Energy Res. Soc. Sci.* **2025**, *127*, No. 104277.
- (7) Khoja, I. U.-R.; Sattar Saand, A.; Ismail Jamali, M.; Ali Koondhar, M.; Sarwar Kaloi, G.; Albasha, L.; Aoudia, M.; Touti, E. A Comparative Review: Floating Photovoltaic, Agrivoltaics, and Ground-Mounted PV Systems. *IEEE Access* **2025**, *13*, 45853–45873.
- (8) Ding, L.; Zhu, Y.; Zheng, L.; Dai, Q.; Zhang, Z. What Is the Path of Photovoltaic Building (BIPV or BAPV) Promotion? –The Perspective of Evolutionary Games. *Appl. Energy* **2023**, *340*, No. 121033.
- (9) Roy, R.; Pearce, J. M. Is Small or Big Solar Better for the Environment? Comparative Life Cycle Assessment of Solar Photovoltaic Rooftop vs Ground-Mounted Systems. *Int. J. Life Cycle Assess.* **2024**, *29* (3), 516–536.
- (10) Eur-Lex Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast). **2010**, *153*. <https://data.europa.eu/eli/dir/2010/31/oj> (accessed 2026-03-30).
- (11) Eur-Lex COMMISSION RECOMMENDATION on Speeding up Permit-Granting Procedures for Renewable Energy Projects and Facilitating Power Purchase Agreements. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=PI_COM%3AC%282022%293219 (accessed 2023-12-28).
- (12) BUILD UP What is BUILD UP. <https://build-up.ec.europa.eu/en/about/whats-is-build-up> (accessed 2026-03-30).
- (13) European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A221%3AFIN&qid=1653034500503> (accessed 2026-03-30).
- (14) ICARES Consulting. Regulatory Framework for BIPV. file:///C:/Users/xpinheiro50588/Downloads/Attachment_0-2.pdf.
- (15) Martin-Chivelet, N.; Van Noord, M.; Tilli, F.; Yang, R. J.; Weerasinghe, N.; Daun, E.; Baggini, A. BIPV Market Development: International Technological Innovation System Analysis. *Buildings* **2025**, *15* (17), No. 3011.
- (16) Hille, S. L.; Curtius, H. C.; Wüstenhagen, R. Red Is the New Blue – The Role of Color, Building Integration and Country-of-Origin in Homeowners' Preferences for Residential Photovoltaics. *Energy Build.* **2018**, *162*, 21–31.
- (17) Borja Block, A.; Escarre Palou, J.; Courtant, M.; Virtuani, A.; Cattaneo, G.; Roten, M.; Li, H.-Y.; Despeisse, M.; Hessler-Wyser, A.; Desai, U.; Faes, A.; Ballif, C. Colouring Solutions for Building Integrated Photovoltaic Modules: A Review. *Energy Build.* **2024**, *314*, No. 114253.
- (18) Li, Z.; Li, S.; Yan, J.; Peng, J.; Ma, T. Balancing Aesthetics and Efficiency of Coloured Opaque Photovoltaics. *Nat. Rev. Clean Technol.* **2025**, *1* (3), 216–226.
- (19) Lee, H.; Song, H. Current Status and Perspective of Colored Photovoltaic Modules. *WIREs Energy Environ.* **2021**, *10* (6), e403.
- (20) Lumb, M. P.; Yoon, W.; Bailey, C. G.; Scheiman, D.; Tischler, J. G.; Walters, R. J. Modeling and Analysis of High-Performance, Multicolored Anti-Reflection Coatings for Solar Cells. *Opt. Express* **2013**, *21* (S4), A585.
- (21) Lim, S.-K.; Lee, K.-T. Multilayer Dielectric Mirror-Integrated Colored Hybrid Solar Cells. In *2018 International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD)*; IEEE: Hong Kong, China, **2018**; pp 141–142.
- (22) Soman, A.; Antony, A. Colored Solar Cells with Spectrally Selective Photonic Crystal Reflectors for Application in Building Integrated Photovoltaics. *Sol. Energy* **2019**, *181*, 1–8.
- (23) Lee, S.; Yoo, G. Y.; Kim, B.; Kim, M. K.; Kim, C.; Park, S. Y.; Yoon, H. C.; Kim, W.; Min, B. K.; Do, Y. R. RGB-Colored Cu(In,Ga)(S,Se)₂ Thin-Film Solar Cells with Minimal Efficiency Loss Using Narrow-Bandwidth Stopband Nano-Multilayered Filters. *ACS Appl. Mater. Interfaces* **2019**, *11* (10), 9994–10003.
- (24) Rudzikas, M.; Donėlienė, J.; Bužavaitė-Vertelienė, E.; Balevičius, Z.; Leuvrey, C.; Šetkus, A. Design and Investigation of 1D Photonic Crystal Based Structures for BIPV Cell Colorization by Sol-Gel Dipping Technology. *Sol. Energy* **2023**, *250*, 285–294.
- (25) Kim, R.; Cho, D.-H.; Lee, W.-J.; Hwang, T.-H.; Kang, M.; Shin, D.; Kim, K.; Chung, Y.-D. Color-Tunable and Conductive ITO-Based Multilayer Electrodes for Cu(In,Ga)Se₂ Thin-Film Solar Cells. *Dyes Pigments* **2026**, *251*, No. 113697.
- (26) Yoo, G. Y.; Jeong, J.; Lee, S.; Lee, Y.; Yoon, H. C.; Chu, V. B.; Park, G. S.; Hwang, Y. J.; Kim, W.; Min, B. K.; Do, Y. R. Multiple-Color-Generating Cu(In,Ga)(S,Se)₂ Thin-Film Solar Cells via Dichroic Film Incorporation for Power-Generating Window Applications. *ACS Appl. Mater. Interfaces* **2017**, *9* (17), 14817–14826.
- (27) Blasi, B.; Kroyer, T.; Kuhn, T.; Hohn, O. The MorphoColor Concept for Colored Photovoltaic Modules. *IEEE J. Photovoltaics* **2021**, *11* (5), 1305–1311.
- (28) Kromatix. *Kromatix PV Modules*. <https://demo.kromatix.com/pv-modules/> (accessed 2026-03-31).
- (29) SOLAXESS SA WHITE & COLOR SOLAR TECHNOLOGY. <https://www.solaxess.ch/en/> (accessed 2026-03-31).
- (30) Fraunhofer Institute for Solar Energy Systems Photovoltaics Report. <https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf&ved=2ahUKEwi737Wg8KyLAXGRvEDHUsHfQFnoECAGQAQ&usq=AOvVaw3OrHXD84JKUrhXxjkYeEo> (accessed 2025-02-03).
- (31) Lindahl, J.; Zimmermann, U.; Szaniawski, P.; Tordahl, T.; Hultqvist, A.; Salome, P.; Platzer-Bjorkman, C.; Edoff, M. Inline Cu(In,Ga)Se₂ Co-Evaporation for High-Efficiency Solar Cells and Modules. *IEEE J. Photovoltaics* **2013**, *3* (3), 1100–1105.
- (32) Carron, R.; Avancini, E.; Feurer, T.; Bissig, B.; Losio, P. A.; Figi, R.; Schreiner, C.; Bürki, M.; Bourgeois, E.; Remes, Z.; Nesladek, M.; Buecheler, S.; Tiwari, A. N. Refractive Indices of Layers and Optical Simulations of Cu(In,Ga)Se₂ Solar Cells. *Sci. Technol. Adv. Mater.* **2018**, *19* (1), 396–410.
- (33) Chirilă, A.; Buecheler, S.; Pianezzi, F.; Bloesch, P.; Gretener, C.; Uhl, A. R.; Fella, C.; Kranz, L.; Perrenoud, J.; Seyrling, S.; Verma, R.; Nishiwaki, S.; Romanyuk, Y. E.; Bilger, G.; Tiwari, A. N. Highly Efficient Cu(In,Ga)Se₂ Solar Cells Grown on Flexible Polymer Films. *Nat. Mater.* **2011**, *10* (11), 857–861.
- (34) Peters, I. M.; Rodriguez Gallegos, C. D.; Sofia, S. E.; Buonassisi, T. The Value of Efficiency in Photovoltaics. *Joule* **2019**, *3* (11), 2732–2747.

- (35) Best Research-Cell Efficiency Chart. <https://www.nrel.gov/pv/cell-efficiency.html> (accessed 2023-12-11).
- (36) Keller, J.; Kiselman, K.; Donzel-Gargand, O.; Martin, N. M.; Babucci, M.; Lundberg, O.; Wallin, E.; Stolt, L.; Edoff, M. High-Concentration Silver Alloying and Steep Back-Contact Gallium Grading Enabling Copper Indium Gallium Selenide Solar Cell with 236% Efficiency. *Nat. Energy* **2024**, *9* (4), 467–478.
- (37) REPowerEU: A Plan to Rapidly Reduce Dependence on Russian Fossil Fuels and Fast Forward the Green Transition. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_3131 (accessed 2025-02-03).
- (38) COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474> (accessed 2025-02-05).
- (39) Mansfield, L. M.; Kanevce, A.; Harvey, S. P.; Bowers, K.; Beall, C.; Glynn, S.; Repins, I. L. Efficiency Increased to 15.2% for Ultra-thin Cu(In,Ga)Se₂ Solar Cells. *Prog. Photovolt. Res. Appl.* **2018**, *26* (11), 949–954.
- (40) Wang, T.; Song, L.; Bayat, S.; Melchiorre, M.; Valle, N.; Philippe, A.-M.; Defay, E.; Glinsek, S.; Siebentritt, S. Sub-Micron Cu(In,Ga)Se₂ Solar Cells with an Efficiency of 18.2% Enabled by a Hole Transport Layer. *EES Sol.* **2025**, 1102.
- (41) Horsley, S. A. R.; Wu, J.-H.; Artoni, M.; Rocca, G. C. L. Revisiting the Bragg Reflector to Illustrate Modern Developments in Optics. *Am. J. Phys.* **2014**, *82* (3), 206–213.
- (42) Chong, C. K.; McDermott, D. B.; Razeghi, M. M.; Luhmann, N. C.; Pretterebner, J.; Wagner, D.; Thumm, M.; Caplan, M.; Kulke, B. Bragg Reflectors. *IEEE Trans. Plasma Sci.* **1992**, *20* (3), 393–402.
- (43) Zhang, Q.; Jin, Q.; Mertens, A.; Rainer, C.; Huber, R.; Fessler, J.; Hernandez-Sosa, G.; Lemmer, U. Fabrication of Bragg Mirrors by Multilayer Inkjet Printing. *Adv. Mater.* **2022**, *34* (33), No. 2201348.
- (44) Floyd, P. D.; Merz, J. L. Optical Properties of Disordered GaAs/(Al,Ga)As Distributed Bragg Reflectors. *J. Appl. Phys.* **1994**, *75* (12), 7666–7668.
- (45) Murtaza, S. S.; Campbell, J. C. Effects of Variations in Layer Thicknesses on the Reflectivity Spectra of Semiconductor Bragg Mirrors. *J. Appl. Phys.* **1995**, *77* (8), 3641–3644.
- (46) Callard, S.; Gagnaire, A.; Joseph, J. New Method for in Situ Control of Bragg Reflector Fabrication. *Appl. Phys. Lett.* **1996**, *68* (17), 2335–2336.
- (47) Dong, W. J.; Lo, N.-T.; Jung, G. H.; Ham, J.; Lee, J.-L. Efficiency Enhancement and Angle-Dependent Color Change in See-through Organic Photovoltaics Using Distributed Bragg Reflectors. *Appl. Phys. Lett.* **2016**, *108* (10), 103902.
- (48) Li, Z.; Ma, T.; Chen, Y.; Li, S.; Dai, Y.; Zhang, D.; Yang, H.; Yan, J. Structural Coloring of Solar Photovoltaics with Quasi-Ordered Photonic Pigments. *Nexus* **2025**, *2* (4), No. 100101.
- (49) Chen, Y.; Li, Z.; Li, S.; Liu, J.; Dai, X.; Ma Lu, S.; Ma, T. Colored and Patterned Silicon Photovoltaic Modules through Highly Transparent Pearlescent Pigments. *Sol. Energy Mater. Sol. Cells* **2024**, *275*, No. 113033.
- (50) Eggers, H.; Gharibzadeh, S.; Koch, S.; Schackmar, F.; Ritzer, D. B.; Abzieher, T.; Richards, B. S.; Erban, C.; Paetzold, U. W. Perovskite Solar Cells with Vivid, Angle-Invariant, and Customizable Inkjet-Printed Colorization for Building-Integrated Photovoltaics. *Sol. RRL* **2022**, *6* (4), No. 2100897.
- (51) Li, S.; Chen, Y.; Li, T.; Li, Z.; Ma, T. Multilayer Thin Film Design for Neutral-Colored Opaque Photovoltaics. *Appl. Energy* **2025**, *378*, No. 124710.
- (52) Adachi, L.; Hanashi, G.; Kubota, S.; Xu, Z.; Sai, H.; Kondo, M.; Wada, H. Highly Efficient Color-Control Technique for Building-Integrated Photovoltaics Using Optical Dielectric Thin Film. *Jpn. J. Appl. Phys.* **2023**, *62* (SK), SK1010.
- (53) Lee, J.-H.; Kim, K.-R.; Kim, C.-S. Subpixel Rendering for Diamond-Shaped PenTile Displays Using Patch-Based Adaptive Filters. *J. Vis. Commun. Image Represent.* **2021**, *78*, No. 103144.
- (54) Jeong, H. I.; Jeong, Y. J. General Design Method for Three-Dimensional Displays with Horizontally Asymmetric Pixel Structures. *Displays* **2021**, *68*, No. 102006.
- (55) Aketagawa, K.; Tanaka, M.; Horiuchi, T. Relationship Between Display Pixel Structure and Gloss Perception. *J. Imaging* **2026**, *12* (2).
- (56) Fang, L.; Au, O. C.; Tang, K.; Wen, X. Increasing Image Resolution on Portable Displays by Subpixel Rendering – a Systematic Overview. *APSIPA Trans. Signal Inf. Process.* **2012**, *1*, e1.
- (57) Mallett, A. Subpixel Zoo: A Catalog of Subpixel Geometry <https://geometrian.com/resources/subpixelzoo/index.html> (accessed 2026-03-20).
- (58) Karunakaran, B.; Chung, S. J.; Velumani, S.; Suh, E.-K. Effect of Rapid Thermal Annealing on the Properties of PECVD SiNx Thin Films. *Mater. Chem. Phys.* **2007**, *106* (1), 130–133.
- (59) Xu, X.; Zhang, L.; Huang, L.; He, Q.; Fan, T.; Yang, Z.; Jiang, Y.; Li, Z. A Comparison of Structures and Properties of SiN_x and SiO_x Films Prepared by PECVD. *J. Non-Cryst. Solids* **2012**, *358* (1), 99–106.
- (60) Zhang, S.; Xue, W.; Yu, Z. Moisture Barrier Evaluation of SiO_x/SiN_x Stacks on Polyimide Substrates Using Electrical Calcium Test. *Thin Solid Films* **2015**, *580*, 101–105.
- (61) Pirot-Berson, L.; Couderc, R.; Bodeux, R.; Jay, F.; Lefillastre, P.; Dupuis, J. Study and Mitigation of Moisture-Induced Degradation in SHJ Modules by Modifying Cell Structure. *Sol. Energy Mater. Sol. Cells* **2025**, *285*, No. 113557.
- (62) Iliescu, C.; Avram, M.; Chen, B.; Popescu, A.; Dumitrescu, V.; Poenar, D. P.; Sterian, A.; Vrtacnik, D.; Amon, S.; Sterian, P. Residual Stress in Thin Films PECVD Depositions: A Review. *J. Optoelectron. Adv. Mater.* **2011**, *13*, 387.
- (63) Huff, M. Review Paper: Residual Stresses in Deposited Thin-Film Material Layers for Micro- and Nano-Systems Manufacturing. *Micromachines* **2022**, *13* (12), 2084.
- (64) Bras, P.; Frisk, C.; Tempez, A.; Niemi, E.; Platzer-Björkman, C. Ga-Grading and Solar Cell Capacitance Simulation of an Industrial Cu(In,Ga)Se₂ Solar Cell Produced by an in-Line Vacuum, All-Sputtering Process. *Thin Solid Films* **2017**, *636*, 367–374.
- (65) Larouche, S.; Martinu, L. OpenFilters: Open-Source Software for the Design, Optimization, and Synthesis of Optical Filters. *Appl. Opt.* **2008**, *47* (13), No. C219.
- (66) Samanta, P. Basic Principles of Colour Measurement and Colour Matching of Textiles and Apparels. In *Colorimetry*; Kumar Samanta, A., Ed.; IntechOpen: United Kingdom, **2022**.
- (67) Mokrzycki, W. S.; Tatol, M. Colour Difference ΔE - a Survey. *Mach. Graph. Vis. Int. J.* **2011**, *20* (4), 383–411.
- (68) Jana, S.; Sreekanth, K. V.; Abdelraouf, O. A. M.; Lin, R.; Liu, H.; Teng, J.; Singh, R. Aperiodic Bragg Reflectors for Tunable High-Purity Structural Color Based on Phase Change Material. *Nano Lett.* **2024**, *24* (13), 3922–3929.
- (69) Wang, D.; Ji, C.; Li, M.; Xing, Z.; Gao, H.; Li, X.; Zhou, H.; Hu, Y.; Lin, Z.; Zhang, C. Large-scale High Purity and Brightness Structural Color Generation in Layered Thin Film Structures via Coupled Cavity Resonance. *Nanophotonics* **2024**, *13* (24), 4491–4503.
- (70) Kwak, H.; Jung, I.; Kim, D.; Ju, S.; Choi, S.; Kang, C.; Kim, H.; Baac, H. W.; Ok, J. G.; Lee, K.-T. Resonant-Mode Engineering for Additive Reflective Structural Colors with High Brightness and High Color Purity. *Sci. Rep.* **2024**, *14* (1), 13694.
- (71) Ashraf, M.; Chapiro, A.; Mantiuk, R. K. Resolution Limit of the Eye — How Many Pixels Can We See? *Nat. Commun.* **2025**, *16* (1), 9086.
- (72) Schneider, T.; Dethloff, C.; Hölscher, T.; Kempa, H.; Scheer, R. Comparison of Mo and ITO Back Contacts in CIGSe Solar Cells: Vanishing of the Main Capacitance Step. *Prog. Photovolt. Res. Appl.* **2022**, *30* (2), 191–202.
- (73) Scheer, R.; Schock, H. *Chalcogenide Photovoltaics: Physics, Technologies, and Thin Film Devices*; Wiley: Germany, **2011**; 1st Ed.
- (74) Yahya, M.; Fadavieslam, M. R. Effect of Oxygen Plasma on ITO Surface and OLED Physical Properties. *Microelectron. Reliab.* **2023**, *144*, No. 114981.
- (75) Park, Y. S.; Kim, E.; Hong, B.; Lee, J. Characteristics of ITO Films with Oxygen Plasma Treatment for Thin Film Solar Cell Applications. *Mater. Res. Bull.* **2013**, *48* (12), S115–S120.

- (76) Zin, N. Recombination-Free Reactive Ion Etch for High Efficiency Silicon Solar Cells. *Sol. Energy Mater. Sol. Cells* **2017**, *172*, 55–58.
- (77) Zin, N. S.; Blakers, A.; Weber, K.; Zhang, C. Investigation of Lifetime Degradation of RIE-Processed Silicon Samples for Solar Cells. In *2009 34th IEEE Photovoltaic Specialists Conference (PVSC)*; IEEE: USA, **2009**; pp 000039–000043.
- (78) Rahman, M.; Deng, L. G.; Wilkinson, C. D. W.; van den Berg, J. A. Studies of Damage in Low-Power Reactive-Ion Etching of III–V Semiconductors. *J. Appl. Phys.* **2001**, *89* (4), 2096–2108.
- (79) Hong, J. W.; Park, J. S.; Kim, C. H.; Lim, W. S.; Kim, J. Y.; Kim, D. S.; Yeom, G. Y.; Kim, D. W. A Review of Plasma-Induced Damage and Interface Recovery in GaN-Based Materials Etching Processes. *Mater. Sci. Semicond. Process.* **2026**, *209*, No. 110568.
- (80) Hegedus, S. S.; Shafarman, W. N. Thin-film Solar Cells: Device Measurements and Analysis. *Prog. Photovolt. Res. Appl.* **2004**, *12* (2–3), 155–176.
- (81) Scheer, R. Towards an Electronic Model for $\text{CuIn}_{1-x}\text{Ga}_x\text{Se}_2$ Solar Cells. *Thin Solid Films* **2011**, *519* (21), 7472–7475.
- (82) Schaefer, S.; Lüdemann, R. Low Damage Reactive Ion Etching for Photovoltaic Applications. *J. Vac. Sci. Technol., A* **1999**, *17* (3), 749–754.
- (83) Misra, D.; Heasell, E. L. Electrical Damage to Silicon Devices Due to Reactive Ion Etching. *Semicond. Sci. Technol.* **1990**, *5* (3), 229.
- (84) Zin, N. S.; Blakers, A.; Weber, K. RIE-Induced Carrier Lifetime Degradation. *Prog. Photovolt. Res. Appl.* **2010**, *18* (3), 214–220.
- (85) Oliveira, A. J. N.; Teixeira, J. P.; Ramos, D.; Fernandes, P. A.; Salomé, P. M. P. Exploiting the Optical Limits of Thin-Film Solar Cells: A Review on Light Management Strategies in Cu(In,Ga)Se_2 . *Adv. Photonics Res.* **2022**, *3* (6), No. 2100190.