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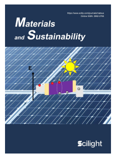

Commentary

Commentary on "Green" Fabrication of High-Performance Transparent Conducting Electrodes by Blade Coating and Photonic Curing on PET for Perovskite Solar Cells

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Abstract: Flexible transparent conducting electrodes (TCEs) are critically important for next-generation optoelectronics, attracting significant interest across diverse research fields. This study presents a clear and timely advance in their manufacturing by demonstrating a scalable, hybrid TCE. The authors combine blade-coated silver nanowires (AgNWs) with flexographically printed metal bus lines (MBLs), cap the structure with an indium zinc oxide (IZO) overcoat, and subsequently fuse the stack using intense pulsed light (IPL) photonic curing. This approach yields a multiscale conductor on polyethylene terephthalate (PET) substrates that simultaneously achieves low sheet resistance, high transparency across the visible and near-infrared spectrum, and low surface roughness. The work is explicitly framed around "green" manufacturing principles, emphasizing a low thermal budget, inherent compatibility with roll-to-roll (R2R) processing, and impressive line speeds of up to 11 $m \cdot min^{-1}$ in stitching mode. Moving beyond fundamental materials metrics, the authors underscore the device-level relevance of their TCE by fabricating p-i-n perovskite solar cells (PSCs). These devices achieved champion power conversion efficiencies (PCEs) of up to 12.2% (averaging ~10.5%), outperforming commercial PET/ITO-based controls by approximately 50%. In this commentary, we first recognize the study's substantive contributions to scalable TCE fabrication. We then propose practical refinements that could further strengthen the scientific rigor and translational potential of the technology. Finally, we conclude with a constructive critique of several unresolved questions; addressing these would undoubtedly represent a significant advance for the field.

Keywords: flexible; transparent conducting electrode; silver nanowires; photonic curing

1. Introduction

The development of high-performance transparent conducting electrodes (TCEs) is crucial for advancing optoelectronic technologies, including light-emitting diodes [1–4], touch screens [5], displays [6], and transparent heaters [7]. The fundamental challenge in TCE design lies in overcoming the inherent trade-off between electrical conductivity and optical transmittance. Based on the semiconductor bandgap theory [8], metallic and graphitic conductors, while possessing high concentrations of free electrons conducive to excellent electrical conductivity, strongly absorb or reflect light, leading to poor transparency. Conversely, wide-bandgap insulators like quartz and acrylic exhibit high transmittance across the visible-NIR spectrum but lack free electrons, resulting in poor electrical conductivity. To navigate this compromise, numerous strategies have been explored as follows. Metal oxides have historically dominated the field, beginning with Bädeker's report on conductive CdO films in 1907, where he investigated the electrical conductivity and thermoelectric properties of several heavy metal oxides, including CdO. It was discovered that CdO exhibited an unusual combination of good electrical conductivity and optical transparency in the visible range [9,10]. This was followed by the development of doped metal oxides—most notably fluorine-doped SnO_2 (FTO) [11], tin-doped In_2O_3 (ITO) [12], and aluminum-doped ZnO (AZO) [13]—which remain industry standards and most widely applied today. However, these materials have significant limitations for modern applications: ITO is fragile and not suitable for flexible device, which is due to its crystalline characteristics. Also, it requires high-temperature processing, and relies on scarce indium; while FTO and AZO, though more abundant, still require high processing temperatures and offer lower conductivities than ITO.

Silver nanowire (AgNW) networks have emerged as a promising alternative, offering a compelling combination of high transparency, excellent conductivity, and mechanical flexibility [14,15]. Their solution-processability further makes them attractive for scalable manufacturing under low temperature. Nevertheless, challenges such as high surface roughness, high junction resistance between nanowires, and susceptibility to be oxidized have impeded their widespread adoption. A current research trend to address these limitations involves designing multi-layered hybrid structures, where different functional materials are deposited layer by layer [16–18]. The authors of the featured article exemplify this approach by engineering a sophisticated three-layer electrode. Their design incorporates flexographically printed metal bus lines (MBLs) to enhance lateral charge transport, a blade-coated AgNW layer for percolation conduction, and a blade-coated indium zinc oxide (IZO) capping layer to reduce roughness and protect the underlying silver. A critical final step involves intense pulsed light (IPL) sintering, which simultaneously dries the AgNW layer, removes insulating stabilizers to improve nanowire contact and reduce resistance, and converts the IZO precursor. This integrated manufacturing strategy successfully yields a flexible TCE with simultaneously high transmittance, low sheet resistance, and robust performance, representing a significant step towards commercially viable, next-generation transparent electrodes.

2. Merits and Comments

A fundamental challenge in TCE design is the inherent trade-off between sheet resistance (R_{sh}) and optical transmittance [19,20]. Typically, achieving a low R_{sh} necessitates a thicker functional layer, which invariably diminishes light transmission. This compromise becomes particularly demanding when high transmittance must be maintained across an ultra-broad spectral range from visible to near-infrared (NIR) wavelengths. A second critical technical hurdle is surface roughness. An irregular surface morphology promotes light scattering, reducing effective transmittance, and complicates the subsequent deposition of uniform, ultra-thin functional layers essential for modern optoelectronic devices. Therefore, achieving an atomically smooth planar surface is paramount for building high-performance multilayer device architectures. The hybrid architecture presented in this work elegantly addresses both challenges through a strategy of scale separation. The design leverages distinct components, each serving a specific function: (i) Printed metal bus lines (MBLs) act as low-resistance "highways" for long-range charge transport; (ii) The AgNW network functions as a dense network of "streets", ensuring effective charge collection across the entire area and bridging the gaps between the MBLs; (iii) The IZO overcoat serves a triple purpose: it provides lateral conduction, planarizes the underlying nanostructured surface, and offers a protective barrier. This division of labor is not only conceptually elegant but also demonstrates practical utility through its implementation under ambient conditions. The efficacy of this approach is convincingly borne out by the authors' exceptional metrics, confirming simultaneous achievement of low R_{sh}, high broadband transmittance, and minimal surface roughness.

Then, the authors demonstrate exceptional process control by judiciously tuning the flash fluence to accommodate the transition from AgNW/IZO on PET to the more complex AgNW/IZO on PET/MBL stack. This careful optimization is critical to avoid substrate damage or ablation of the metal bus lines. A significant manufacturing insight is their demonstration that a previously established 9-pulse sintering recipe can be effectively collapsed into a single pulse. This simplification not only preserves the essential electrical and optical film properties but also facilitates an order-of-magnitude increase in web speeds on the same roll-to-roll hardware, dramatically improving throughput and commercial viability. The performance of these TCEs is convincingly validated through their integration into functional perovskite solar cells (PSCs). Devices fabricated on both the 9-pulse and 1-pulse TCEs achieve champion power conversion efficiencies (PCEs) of 11.4% and 10.7%, respectively, with minimal hysteresis. Most impressively, even when processed in stitching mode at a high web speed of 11 $m \cdot min^{-1}$, the hybrid electrodes enable PSCs with a mean PCE of ~10.5% and a champion device reaching 12.2%. Crucially, this performance represents an approximately 50% average improvement over control devices built on commercial PET/ITO substrates. Beyond efficiency, the authors address the critical metrics of mechanical robustness and scalability—prerequisites for commercial adoption. The hybrid TCEs exhibit exceptional durability, with a negligible change in resistance (<3%) after 2000 bending cycles at a tight 1-inch radius, underscoring their suitability for flexible applications and R2R handling. Furthermore, the successful fabrication of large-area samples (7″ × 8″) with excellent optical and electrical uniformity provides an essential bridge from lab-scale coupons to pilot-compatible formats. Collectively, these results form a remarkably coherent and compelling hybrid architecture.

While the paper presents an unusually complete dataset bridging materials development and device integration, and TCEs are highly demanding in various applications, future work necessitate more attentions in the following aspects to fully realize the potential of the reported TCEs and strengthen their broader impact. First, on the optical side, haze—an essential metric for displays, touch sensors, and photovoltaics—need to be further improved to meet the high standard for certain ultra-transparent substrate's application scenarios. Overcoating, such as the IZO layer discussed in the article, can serve as a universal strategy to mitigate scattering from underlying gradients, such as the AgNW network. This approach deserves greater attention for realizing the angle-resolved transmission required in application-specific benchmarking. Second, from an electrical perspective, the "highways and streets" analogy is conceptually compelling. The presented hybrid architecture offers a unique opportunity for predictive analysis: analytical or finite-element modeling of in-plane current collection, supported by a parametric study varying bus-line pitch, AgNW density, IZO conductivity, and interfacial resistance, would elevate the narrative from proof-of-concept demonstration to a transferable, physics-based design framework that the community could readily adopt. Third, the paper's claim of 'green' manufacturing is an important contribution. Such a characteristic is especially valuable in the pursuit of a carbon-zero society. To substantiate this merit, it would be useful to quantify the thermal budget in energy-per-area terms ($Wh \cdot m^{-2}$) and to estimate peak substrate temperatures during IPL curing, either through IR thermography or 1D heat-diffusion modeling. These steps would enable direct comparison with competing TCE processes and help establish the true environmental advantage. Then, materials sustainability and chemical safety are also integral aspects of 'green' manufacturing. The optimization of In-rich IZO composition raises important future work about the optimal trade-off between conductivity and mechanical resilience, as well as the long-term reliance on scarce indium. These issues warrant further optimization. Exploring whether pulse shaping or alternative precursors (e.g., ligands, complexants) could increase Zn incorporation, and testing indium-lean alternatives such as AZO or GZO under identical IPL conditions, would convincingly position the approach as composition-agnostic. In parallel, the environmental, health, and safety concerns surrounding solvents such as 2-methoxyethanol and PVP, along with possible mitigation strategies like solvent capture or greener substitutes, also is a critical direction in the future work. Finally, scalability and reliability, one of the most important merits need to realize in the rigorous conditions during the industrialization. Future work should also report the mechanical characterization—such as bending, tensile strain testing and mixed-mode deformation—would clarify performance in emerging use cases like stretchable electronics and conformal heaters. Likewise, higher-resolution uniformity mapping (e.g., 1 cm^2 pitch) is essential to uncover edge effects or coating artifacts, while detailed seam analysis of stitched regions should confirm that no local optical, electrical, or structural weaknesses are introduced during roll-to-roll processing. At the device level, validating the electrodes on larger-area perovskite solar cells or submodules, combined with even short-term accelerated stability testing (e.g., 85 °C/85% RH or dry heat). Although the IZO overcoat provides protection, silver oxidation remains a potential failure mode [21], particularly under mechanical flexing where micro-cracks in encapsulation may form, especially considering that the corrosive nature of perovskite materials, such as iodide migration, represents another risk to Ag-based electrodes. As such, it could demonstrate both robustness and manufacturability in the future TCEs development.

3. Conclusions

This manuscript presents a cohesive and credible pathway toward manufacturing flexible, high-performance TCEs through ambient, solution-based deposition and millisecond photonic curing. The ingenious hybrid architecture—integrating printed Ag bus lines for long-range conduction, an AgNW network for effective current collection, and a thin IZO layer for planarization—successfully navigates the critical three-way trade-off between low sheet resistance (~9–11 $\Omega\ cm^{-2}$), high transmittance (~80–81% absolute, ~90% relative to PET, with strong NIR performance), and low surface roughness (~4–6 nm). Furthermore, the electrodes demonstrate the mechanical resilience required for roll-to-roll (R2R) conveyance. A key process engineering insight is the identification of a safe fluence window to avoid substrate damage, enabling the collapse of a multi-pulse (9-pulse) curing recipe into a single 10 ms pulse. This advancement facilitates impressive web speeds of up to 11 $m \cdot min^{-1}$ in stitching mode. The device-level validation is equally compelling: the fabrication of perovskite solar cells achieving 10–12% power conversion efficiency (PCE) on flexible substrates, outperforming commercial PET/ITO controls by ~50%, highlights the application relevance of the materials gains. To further elevate the impact and translational potential of developing high performance TCEs, several areas merit deeper attention. As also mentioned by the authors, while photonic curing is energy-saving and compatible with high-speed manufacturing, the applied blade coating technique needs to be updated with faster deposition methods, such as gravure or flexographic printing. Additionally, the simultaneous resolution of efficiency, scalability, stability, and cost barriers is the decisive step needed for this promising hybrid electrode platform to emerge as a standard for next-generation flexible optoelectronics, which however, still remains a significant challenge.

Author Contributions

B.C.: Conceptualization, Writing—original draft preparation; M.C.: Conceptualization, Writing—reviewing and editing. All authors have read and agreed to the published version

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Conflicts of Interest

The authors declare no conflict of interest.

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