

Scalable low-cost laminated carbon electrodes for perovskite solar cells

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While perovskite solar cell (PSC) efficiencies are soaring at a laboratory scale, most of the devices with high power conversion efficiency (PCE) use evaporated gold electrodes.¹ The cost of gold and the evaporation technique will be a barrier for the technology to reach the large-scale production.^{2,3} Carbon electrodes are an alternative for gold, which is significantly cheaper. Also, carbon do not migrate through the device in contrast to metals, hence stable device performances can be achieved. The present work investigates simple to prepare aluminium-supported carbon electrodes derived from commercially available paste precursors that can be applied onto various hole-transporting materials and achieve PCEs equal to that are provided by gold electrodes. The electrodes are based on an aluminium foil, where the carbon paste is doctor bladed on to the aluminium foil and subsequently treated with organic solvents.⁴ The completed electrodes are dried and mechanically pressed onto the device. The device performances are close to that of devices based on gold electrode (Figure 1 and Table 1).

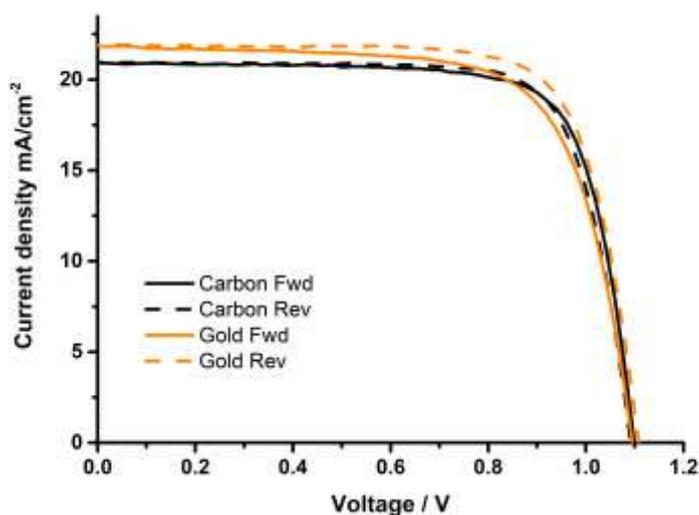


Figure 1. *J-V* curves of the devices with carbon (*black*) and gold (*orange*) electrodes. *J-V* curves are recorded in forward (Fwd) and reverse (Rev) voltage scan directions.

Table 1. *J-V* data of the carbon and gold electrode-based devices derived from the *J-V* curves shown in Figure 1.

Electrode	Rev/Fwd	Voc / V	Jsc / mA cm ⁻²	FF	PCE / %
Carbon	Fwd	1.11	20.9	0.75	17.4
Carbon	Rev	1.09	20.9	0.76	17.4
Gold	Fwd	1.09	21.9	0.71	16.9
Gold	Rev	1.11	21.9	0.75	18.2

A cross section image of a device where Spiro-OMeTAD is used as the hole transporting material (HTM) reveals that the compressive impact of the electrode deposition process has not damaged the HTM layer while the HTM surface is uniformly covered by carbon (Figure 2). The new carbon-based electrode has been introduced into flexible devices produced by a roll-to-roll printing⁵ technology through lamination using an office laminator achieving a PCE of 8%. Moreover, the electrode has shown the compatibility on CuSCN and PTAA HTMs, achieving PCEs of 13% and 12%, respectively.

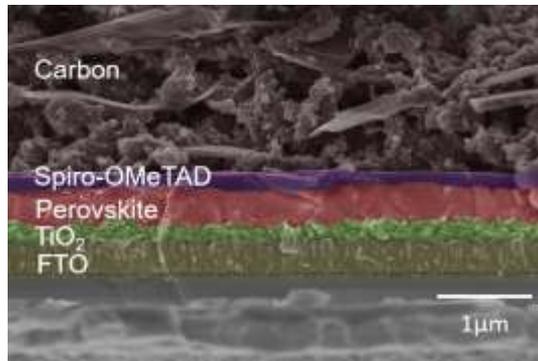


Figure 2. Cross sectional scanning electron microscopic image of a device with a carbon electrode produced using a commercial paste.

The temperature cycling durability tests (IEC 61215, i.e. 200 cycles of -40 °C to 85 °C) and constant temperature test (24 hrs at 65 °C) reveal that the use of carbon electrodes based on commercial pastes on Spiro-OMeTAD damages the devices leading to very low performances (Figure 3). According to the chemical analysis of the carbon paste, we suspect that this incompatibility issue is a result of solvents and adhesive materials that are present in the carbon pastes. Resolving this issue, we introduce tailor-made graphite electrodes devoid of damaging additives, which improve the PSC stability under temperature cycling test and constant temperature test to the level provided by benchmark gold electrodes.

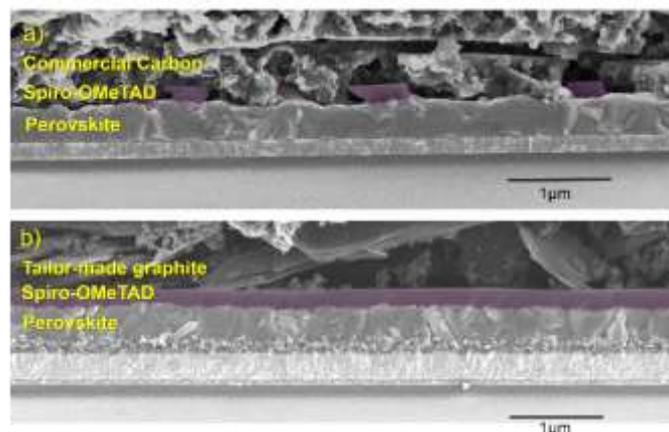


Figure 3. Thermal stability assessment (a) carbon electrode (commercial carbon paste) and (b) graphite (tailor-made graphite paste) after 24 h treatment at 65 °C in N₂-filled glove-box; purple shading highlights the Spiro-OMeTAD layer.

However, this tailor-made graphite electrode is not mechanically strong enough for the large-scale fabrication as the bond strength of carbon to aluminium and the device is not sufficient. Therefore, we have developed our own carbon pastes adding a commercial epoxy as a binder and suitable solvents to reduce the instability issues. We have developed an electrode based on tailor-made carbon paste achieving more than 90% of the PCE of gold electrode-based device. Furthermore, more than 90% of the initial PCE remains after 24 hrs 65 °C heating test. In the next step of this work we aim to achieve a device that retains at least more than 80% of the PCE after the cyclic stability test.

References

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