Supplementary information

Monolithic perovskite/silicon tandem photovoltaics with minimized cell-to-module losses by refractive-index engineering

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EXPERIMENTAL PROCEDURES

Si bottom cell fabrication

4-inch *n*-doped float-zone (FZ) Si wafer with a thickness of ~280 µm was used for Si bottom cell fabrication. The double-side texture structure with random distributed pyramids was obtained using an alkaline solution. The size of the pyramids is controlled by adjusting the alkaline concentration and the process temperature. The wafers were dipped in hydrofluoric acid solution followed by cleaning process, before transferred into a plasma enhanced chemical vapour deposition (PECVD) cluster (Indeotec Octopus II) for amorphous silicon (α-Si) deposition. 8 nm intrinsic (i), 6 nm n-doped, and 13 nm p-doped α-Si layer were grown on wafer using the PECVD cluster tool. The process temperatures are 200 °C. 150 nm IZO and 250 nm Ag were sputtered on the backside of the wafer. 15 nm IZO recombination junction was sputtered on the front side. In order to recover sputtering damage, an annealing step at 200 °C for 10 min was carried out.

Perovskite top cell fabrication on Si substrate

The Si bottom wafers were subjected to UV-Ozone treatment for 15 min before transferred into the glovebox. 2PACz as hole transport layer (HTL) was spin-coated on IZO-coated substrates at 5000 rpm for 50 s, followed by drying at 100 °C for 10 min. 1.7 M $Cs_{0.05}FA_{0.8}MA_{0.15}Pb(I_{0.75}Br_{0.25})_3$ perovskite precursor solution was prepared by dissolving a mixture of FAI, MABr, CsI, PbI_2, and $PbBr_2$ in a mixed solvent (DMF/DMSO = 4:1). The perovskite films were spin-coated at 2000 rpm for 50 s then followed with 7000 rpm for 10 s. Chlorobenzene was dropped in the center of the substrates 12 s before the end of the spin-coating process. After the rotation ceased, the substrates were immediately transferred onto a hotplate of 100 °C and were annealed for 15 min. After perovskite deposition, 12 nm C_{60} were subsequently deposited by thermal evaporation. 10 nm SnO_2 was then deposited by atomic layer deposition (ALD) using a Picosun system. 70 nm IZO was sputtered on top of the SnO2 through a shadow mask using a 43 W sputtering power. Ag finger with a thickness of 500 nm was thermally evaporated using a high precision shadow mask. Finally, 100 nm MgF_2 ARC was thermally evaporated as an anti-reflection layer. The thickness of C_{60}, IZO and MgF_2 ARC layers were first calibrated by spectroscopic ellipsometer. The evaporation rate and thickness of each experiment were monitored by quartz crystal microbalance sensors.

Device encapsulation

The tandem devices were sandwiched between two cover glasses using the thermoplastic polyurethane (TPU) as an encapsulant and butyl rubber as an edge sealant. Tinned plated copper strips were used to contact the upper and lower electrodes of the tandem devices using Ag paste, and extend to the outside of the cover glass.

Solar cell characterization

J-V measurements on tandem devices were performed in the air under LED-based solar simulator (Wavelabs Sinus 220). About 200 mV/s scan speed was used and no preconditioning was used in this work. A mask with an aperture area of 1.0 cm^2 for tandem device was used. The light intensity was calibrated using Fraunhofer ISE CalLab certified c-Si solar cells. EQE measurements were measured using a LOANA system (PV-Tools). The chopped monochromatic light beam was focused

entirely on the active area of the solar cells. When measuring Si bottom subcell, a blue LED light (525 nm) was illuminated on the cell and a 0.6 V bias voltages were applied. When measuring perovskite top subcell, a near-infrared LED (950 nm) was illuminated on the cell and a 0.9 V bias voltages were applied.

SHORT CIRCUIT CURRENT DENSITY SUMMARY OF EXPERIMENTAL MODULES

The reverse-scan short circuit current density (J_{sc}) summary of experimental modules is shown in Figure S1. The J/V curves of the modules with the highest J_{sc} in each group are reported in the main text.

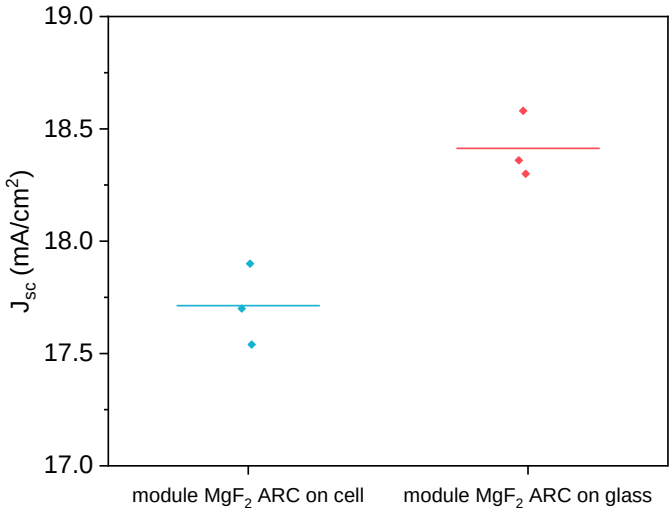

Figure S 1 The reverse-scan J_{sc} summary of experimental modules.