25.1%-efficient monolithic perovskite/silicon tandem solar cell based on a *p*-type mono-crystalline textured silicon wafer and high temperature passivating contacts

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A monolithic two-terminal perovskite/c-Si tandem solar cell based on an industrial, high temperature tolerant p-type c-Si bottom cell with a steady-state power conversion efficiency of 25.1% is demonstrated.

Crystalline silicon (c-Si) solar cells dominate the photovoltaics (PV) market due to their high efficiencies, low manufacturing costs and long-term stability, overall enabling a competitive levelized cost of electricity (LCOE). Today the main driver for further cost reduction is improving efficiencies, which requires innovative strategies as the conversion efficiency of single junction c-Si solar cells is inherently limited to 29.4%[1]. The most promising solution to surpass this limit relies on stacking semiconductors with different bandgaps on top of each other in a multi-junction cell architecture that reduces thermalization losses. However, up to now, no high-efficiency multi-junction technology has shown the potential to achieve a competitive LCOE. Perovskite solar cells may change this scenario as their high spectral response at low wavelengths, low-cost potential and high initial performance of up to 23.7% at the single-junction level[2] make them the ideal partner to c-Si cells in multi-junctions. By adding a perovskite top cell through only a few additional process steps, c-Si technologies have the potential to be upgraded to >30%. So far all of the reported perovskite/silicon tandem devices with an efficiency >25% feature an *n*-type c-Si heterojunction (SHJ) as bottom cell. Despite their record efficiencies, the choice of SHJ bottom cells has some drawbacks. First, SHJ cells degrade when experiencing processing temperatures >250°C, which limits the choice of carrier-selective contacts that can be used below the perovskite absorber. Second, high-quality wafers are required to achieve high efficiencies as the processing temperature of SHJs is too low to trigger any wafer improvement process (impurity gettering or deactivation of thermal donors). In fact, the vast majority of manufactured c-Si cells (>90%) relies on high temperature fabrication processes, enabling at the same time junction/contact formation as well as bulk-material improvement and hence the use of lower-quality/less-expensive *p*-type wafers. In spite of this *p*-type market domination, there is only little reporting about monolithic perovskite/silicon tandem featuring *p*-type wafers. Typically, the use of aluminum back surface field (Al-BSF) for the bottom cell[3] leads to high recombination at the wafer/metal interface results in a suboptimal tandem open-circuit voltage (V_{oc}). Tandem devices based on such bottom cells reported so far achieved 1.42 V on 1 cm^2. While switching to a passivated emitter and rear cell (PERC) bottom cell mitigates recombination losses, the approach has been demonstrated only on *n*-type substrates (achieving V_{oc}'s of ~1.7 V and efficiencies of ~23%)[4,5]. Another design based on a more advanced passivating contact scheme that combines high efficiency, temperature stability, compatibility with lower quality wafers and industrial processes, has been known under the acronyms TOPCON, poly-Si or POLO junction. Optimized solar cell designs achieve high single-junction efficiencies (up to 26.1%[2] with *p*-type wafers, in back-contacted design with photolithography) thanks to low recombination, which results from the combination of a thin oxide (SiO_x), a heavily doped Si-based layer

and an annealing step at >800°C. Here, we demonstrate the first tandem solar cell featuring a *p*-type bottom cell based on such contacts, achieving a steady-state efficiency of 25.1%. The bottom cell is processed using a simple fabrication sequence based on full area deposition and a single thermal annealing as reported in Ref.[6]. In brief, a *p*-type float-zone (100) c-Si wafer, which is flat on its rear and textured on its front, is capped on both sides by a ~1.2 nm chemically grown SiO_x. Doped silicon-rich silicon carbide (SiC_x) layers are deposited by plasma enhanced chemical vapor deposition (PECVD) over the full area. SiC_x is doped with boron on the rear side ($SiC_x(p)$) to form the hole contact. The front is doped with phosphorous to provide electron selectivity ($SiC_x(n)$)[7]. A single annealing step at 850°C then triggers the partial crystallization of the doped SiC_x and the diffusion of dopants from the doped layers into neighboring wafer regions, lowering both contact resistivity and parasitic absorption. Following an hydrogenation step and metallization, bottom cells achieve a single-junction efficiency of 22.6% for a 4 cm^2 aperture area[6]. For the case of tandems, the $SiC_x(n)$ layer is capped by a *p*-type nanocrystalline silicon (nc-Si(*p*):H) layer deposited by PECVD to form the recombination junction. The low lateral conductivity of such layers has been shown to mitigate the interconnection of localized shunts in the perovskite top cell[8]. The perovskite top cell is then deposited in the *p-i-n* configuration using spiro-TTB and LiF/C_{60} as hole- and electron-selective contacts, respectively[9]. The perovskite absorber is processed using the hybrid deposition method[10], which ensures a conformal deposition of the absorber on the micron-sized Si pyramids for optimum light management. The method combines the co-evaporation of CsBr and PbI_2, before spin-coating an organo-halide solution and crystallizing the photoactive phase through an annealing step at 150 °C. Tandem cells with an active area of 1.42 cm^2 are then finalized by depositing a SnO_2/IZO/Ag front electrode by atomic layer deposition, sputtering and evaporation, respectively, as well as an MgF_2 antireflection coating by evaporation. The tandem structure depicted in Fig. 1a-b yields a steady state efficiency of 25.1% during maximum power point tracking for 600 s (Fig. 1c), which is an absolute gain of 2.5% compared to the c-Si single-junction. Forward and reverse scans yield efficiencies of 24.9% and 25.4%, respectively (Fig. 1c). The current density is 19.5 mA/cm^2 (19.7 mA/cm^2 excluding shadowing induced by the metallization as shown by the external quantum efficiency, EQE, in Fig 1d). This demonstrates that monolithic perovskite/silicon tandem solar cells with a state-of-the-art efficiency >25% can be fabricated on *p*-type wafers using a c-Si bottom cell fabrication process that is compatible with c-Si-industry-standard high-temperature diffusion processes. Future improvements of the perovskite top cell should lead to higher fill factor (80%), and improved current in the blue region (20.5 mA/cm^2), as well as to a 100 mV gain in the top cell design (1.85 V), bringing the 30% target within reach.

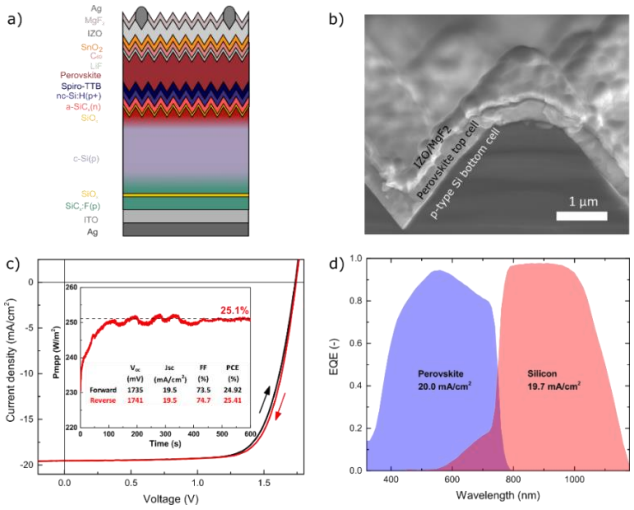

Figure 1. (a) Schematic view of the perovskite/p-type c-Si bottom cell. (b) Secondary electron scanning electron microcopy image of the cross-section of the front side of the perovskite/silicon tandem solar cell. (c) J-V properties and maximum power point tracking of the tandem (aperture area of 1.42 cm^2), (d) corresponding EQE spectra.

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