Peel-and-Stick: Fabricating Thin Film Solar Cell on Universal Substrates

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Fabrication of thin-film solar cells (TFSCs) on substrates other than Si and glass has been challenging because these nonconventional substrates are not suitable for the current TFSC fabrication processes due to poor surface flatness and low tolerance to high temperature and chemical processing. Here, we report a new peel-and-stick process that circumvents these fabrication challenges by peeling off the fully fabricated TFSCs from the original Si wafer and attaching TFSCs to virtually any substrates regardless of materials, flatness and rigidity. With the peel-and-stick process, we integrated hydrogenated amorphous silicon (a-Si:H) TFSCs on paper, plastics, cell phone and building windows while maintaining the original 7.5% efficiency. The new peel-and-stick process enables further reduction of the cost and weight for TFSCs and endows TFSCs with flexibility and attachability for broader application areas. We believe that the peel-and-stick process can be applied to thin film electronics as well.

Results

Herein, we report a novel peel-and-stick process to fabricate efficient TFSCs onto virtually any substrates regardless of materials, roughness and rigidity without changing the material deposition conditions and performance of TFSCs. The peel-and-stick process includes two steps: 1) peeling-off fully fabricated TFSCs in water from the nickel (Ni) coated Si wafer used for fabrication, and 2) attaching the peeled-off TFSCs to the surface of any substrate. The peeling process relies on the phenomenon of water-assisted subcritical debonding at interface between Ni and silicon dioxide (SiO₂), which separates the metallic layer together with TFSCs from the original Si wafer. Since the peel-and-stick process does not require any fabrication on the final target substrate, it circumvents all the fabrication challenges associated with these nonconventional substrates discussed above. Importantly, the efficiency of the transferred TFSCs on any target substrate remains the same as the as-fabricated TFSCs on Si wafers. The procedures of the peel-and-stick process are illustrated in Figure 1. First, a Si/SiO₂ wafer is coated with a Ni film (300 nm) by electron-beam (e-beam) evaporation, and subsequently TFSCs are deposited on top of the metallic layer using regular TFSC fabrication procedures (Figure 1a). Second, a thermal release tape (NittoDenko®) is attached to the top of the TFSCs serving as a temporary transfer holder. A transparent protection layer (ProTek®) is spin-casted in between the TFSCs and the thermal release tape to prevent the TFSCs from the tape polymer contamination and direct contact with water. Third, the entire structure is soaked in a water bath at room temperature. Inside the water bath, an edge of the thermal release tape is slightly peeled back to promote water penetration into the Ni and SiO₂ interface. The Ni and SiO₂ interface is separated due to the water-assisted subcritical debonding, leading to the peeling-off the TFSCs from the original Si/SiO₂ wafer.
Finally, the thermal release tape holding the peeled-off TFSCs is heated at 90°C for a few seconds to weaken its adhesion to the TFSCs. The TFSCs are then attached to various surfaces using common adhesive agents, such as double sided tapes or Polydimethylsiloxane (PDMS) (Figure 1c). After removing the thermal release tape, only the TFSCs are left on the target substrate, such as cell phone, paper, metal foils, plastics and textile (Figure 1d).

To demonstrate the peel-and-stick process, we use the a-Si:H TFSCs as our model system. The fabrication conditions for the a-Si:H TFSCs are identical to those that would have been usually used for fabricating TFSCs on Si wafers (See the method section for the TFSC fabrication details). Figure 2a (left image) shows a representative optical image of the as-fabricated a-Si:H TFSCs on the Ni coated Si/SiO2 wafer before the peel-and-stick process, as also described in figure 1a. The big and small round circles correspond to solar cells with an area of 0.28 cm² or 0.05 cm², respectively. After peeling-off the TFSCs in a water bath (Figure 1b), the Si wafer is clean and reusable (Figure 2a, middle image), and the TFSCs are held temporarily by the thermal release tape (Figure 2a, right image). Notably, the TFSCs after the peel-and-stick process show no visible damages. Next, the peeled-off TFSCs are attached to virtually any objects, including cell phone, business card, and building window (Figure 2b), and these objects are previously inaccessible due to the incompatibility issues with the existing TFSC fabrication facilities. The peel-and-stick process provides a simple way for integrating TFSCs into buildings, clothes, and many other nonconventional substrates.

Importantly, the a-Si:H TFSCs show nearly identical efficiency before and after the peel-and-stick process. Figure 3 shows the current-voltage (I–V) characteristics of representative TFSCs before and after the peel-and-stick process to a sheet of stainless steel (left) or a soda-lime glass slide (right), and the I–V characteristics are indistinguishable, implying that no damages are induced in the TFSCs during the peel-and-stick process. Table 1 summarizes the average performance metrics over 20 solar cells with area of 0.05 cm² and 0.28 cm² respectively, showing $\eta = 7.4 \pm 0.5\%$ and $5.2 \pm 0.1\%$ before the peel-and-stick process, and $\eta = 7.6 \pm 0.5\%$ and $\eta = 5.3 \pm 0.1\%$ after the peel-and-stick process. The efficiency difference in different sizes of solar cells is caused by large series resistance in larger solar cells. Nevertheless, more important thing is that both solar cells have nearly identical efficiencies before and after the peel-and-stick process with only 5% variation that is within measurement errors. These results illustrate several key advantages of the present peel-and-stick process: versatility in substrate choices, high fidelity to original TFSC performance, simplicity and scalability of the procedures, and additional cost-saving features with reusable original Si/SiO2 wafers.

The applications of TFSCs may require intentional bending or non-planar shaping. The peel-and-stick process also enables TFSCs to be integrated with flexible or curved surfaces (e.g., wavy building roof, helmets, and portable electronics). To demonstrate this, a-Si:H TFSCs are transferred on a flexible sheet of stainless foil (~0.2 mm thick) and manually bended as shown in figure 4a (inset). As a result, I-V characteristics of the TFSCs remain the same after bending the flexible sheet with a range of bending radius from ∞ down to 7 mm (Figure 4a). In addition, the solar cell performances are unchanged over 3000 cycles of bending with bending radius...
about 10 mm (Figure 4b), demonstrating the mechanical flexibility and robustness of the transferred TFSCs. It should be noted that the mechanical properties of the final solar cells are not determined by the peel-and-stick process, but rather by the intrinsic material properties and dimensions of the TFSCs (e.g., a-Si:H as an active material, indium tin oxide (ITO) as an electrode).

### Discussion

In conclusion, we report a novel and versatile peel-and-stick process to directly build TFSCs on diverse previously inaccessible substrates, such as paper, plastic, cell phones, and buildings. The peel-and-stick process, while preserving the TFSC performance, circumvents the fabrication challenges associated with the nonconventional substrates by separating the fabrication process with the final target substrate. These previously inaccessible substrates for TFSCs enable further reduction of the cost and weight, and endow TFSCs with flexibility and attachability to greatly broaden their application areas. Though we only demonstrate the transfer of a-Si:H TFSCs herein, we believe that the peel-and-stick process can be applied to other kinds of TFSCs and thin film electronics as well.

### Methods

#### Fabrication of the a-Si:H TFSCs

A Si wafer (500 μm thick) with thermally grown SiO₂ (300 nm) was cleaned by the standard wafer cleaning procedures. The metallic layer (Ni, 300 nm) and subsequent Ag bottom electrodes (1 μm) were deposited on the Si/SiO₂ wafer at room temperature by using e-beam evaporation with deposition rate of around 1-3 Å/sec. The a-Si:H TFSCs with n-i-p structure were deposited by plasma enhanced chemical vapor deposition (PECVD) in a multi-chamber cluster tool (MVSystems, Inc.) at a substrate temperature of approximately 200 °C with...
13.56 MHz RF power. The n-layer (20 nm) was grown using SiH4 and PH3/H2 with $E_{\text{inj}} = 1.75$ eV and $\sigma_{\text{dark}} \sim 2 \times 10^{-12}$ S/cm. The p-layer (300 nm) was grown using SiH4 without hydrogen dilution with $E_{\text{inj}} = 1.78$ eV and $\sigma_{\text{dark}} \sim 2 \times 10^{-10}$ S/cm. The p-layer (8 nm) was grown using SiH4, BF3, and H2 with $E_{\text{inj}} = 2.1$ eV and $\sigma_{\text{dark}} \sim 5 \times 10^{-12}$ S/cm. Finally, ITO (90\% In$_2$O$_3$, 10\% SnO$_2$) dots were RF sputtered at 200°C using an Ar/O2 mixture to define individual solar cells with the RF power of $\sim 0.25$ W/cm$^2$ and deposition rate of $\sim 1$Å/sec.

**Peel-and-stick process.** The as-fabricated a-Si:H TFSCs were cleaned by solvents and dried on a hot plate at 120°C for 3 minutes. A transparent protection layer (ProTek®) was spin-casted at 3000 rpm and annealed at 110°C for 3 minutes sequentially. The ProTek® residues at the Si wafer sidewalls were removed by a razor blade. After applying thermal release tape on top of the ProTek®, the whole structure was immersed into a water bath at room temperature. An edge of the thermal release tape was slightly peeled-off to initiate the water penetration, causing the separation of the Ni layer together with the TFSCs from the Si/SiO$_2$ wafer. The lifted TFSCs were dried by N2 gun and heated at 90°C for around 30 seconds to weaken the adhesion of the thermal release tape. In the mean time, the target substrate was pasted or coated with commercial adhesive agents such as double sided tape or PDMS. Finally, the TFSCs were attached on the target substrate and the thermal release tape was removed. The ProTek® protection layer was then removed by remover for the I–V curve measurements.

**Characterization of the TFSCs.** The solar cell properties were characterized under AM 1.5G illumination (Class AAA solar simulator, Model 94063A, Oriel). Before each measurement, the solar simulator intensity was calibrated with a reference Si solar cell and a readout meter for solar simulator irradiance (Model 91150V, Keithley). To prevent the damage of the electrodes of the solar cells with tungsten probes that are connected to a semiconductor analyzer (Model 4200-SCS, Keithley), the solar cell properties were characterized under dark conditions. The solar cells were attached on the target substrate and the thermal release tape was removed. The ProTek® protection layer was then removed by remover for the I–V curve measurements.

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