Bio-inspired Nanostructures for Enhanced Light Management

Honglei Wang, Yuchen Liang, Samantha Cheng, Benjamin Li, Andrew Li, George Du and Walter Hu
The University of Texas at Dallas, Richardson, TX75080
Corresponding author: walter.hu@utdallas.edu

Nature has offered us a lot of inspirations for designing and fabricating new functional materials and structures. The biological surfaces, through uninterrupted evolutions, are especially interesting. Recently, it was found that roses have micro- and nano-structures which could enhance light absorption and strengthen color saturation. Imitating such functional surface structures would enable formation of hydrophobic surface for self-cleaning and light harvesting element for photovoltaic and optoelectronic devices. Here we report successful transfer imprint of rose structures to transparent photoresist via polydimethylsiloxane (PDMS) and the incorporation on commercial photodiodes which demonstrate improved sensitivity.

A variety of rose petals were collected and inspected with optical and scanning electron microscopy. A photograph of red rosoideae rosa rose is shown in Fig. 1a. Fig. 1b shows the micro-convex cells (micropapillae) of the rose with nanofolding structures (Fig.1b, inset). A different rose with higher aspect ratio of micropapillae but without nanofolding is shown in Fig.1c as comparison. It was reported that both micropapillae with high aspect ratio and nanofoldings would benefit the light trapping. In order to replicate the rose's micro- and nano-structures, the PDMS mold was prepared and the schematic process is shown in Fig. 2a. The PDMS solution was synthesized from the pre-polymer and cross-linking agent with a 10:1 volume ratio. The solution was transferred onto the rose petals in a petri-dish and then placed in a vacuum chamber to evacuate the air bubbles that may cause defects in replication. After heating for one hour at 60 ^{o}C, the hardened PDMS mold was cleaned in piranha solution (2: 1 mixture of sulfuric acid and hydrogen peroxide) to remove the rose residues. The SEM graph of the resulting PDMS micro-concaves with nanofoldings demonstrated successful negative replicate of the rose structures (Fig. 2b). The contact angle of the PDMS with transferred rose structures has demonstrated super hydrophobicity (150 deg., Fig. 2c), as compared with pristine PDMS (112 deg., Fig. 2d).

In order to create the positive replicate of rose structures, the PDMS was first treated with oxygen plasma to form hydrophilic surface (Fig. 3a-b). The schematic transfer printing process was demonstrated in Fig. 3c. A droplet of SU8 2002 was placed on the substrate, and pressed with the PDMS mold and then cured with UV for 10 mins. After separation of PDMS mold, the imprinted photoresist film was inspected by SEM. The uniform micropapillaes with nanofoldings are positive replication of the rose structures (Fig. 3d). These structures have been successfully imprinted using the same PDMS mold repeatedly. This suggests that the transfer imprint of rose structures with PDMS mold is a simple and cost-effective method. To further evaluate the light management effect of the rose structures and its application on photovoltaic and optoelectronic devices, two identical Si photodiodes were coated with 15 µL of SU8 2002. One was imprinted by PDMS mold with rose structure replications while the other was imprinted by a flat PDMS mold without micro- and nano-structures. These two photodiodes were then tested under dark and light illumination (0.05µW/cm^2 and 2.24µW/cm^2) and the corresponding I-V characteristics were plotted in Fig. 4a. The two photodiodes show comparable dark current while the one with rose structures demonstrated much higher illuminated current compared with the one without rose structures. Their responsivity was calculated at a 10 volts reverse bias and the incorporation of rose structures has improved the sensitivity by 36% at 0.05 µW/cm^2 illumination and 35% at 2.24 µW/cm^2 illumination (Fig. 4b), which suggest strong light trapping effect.

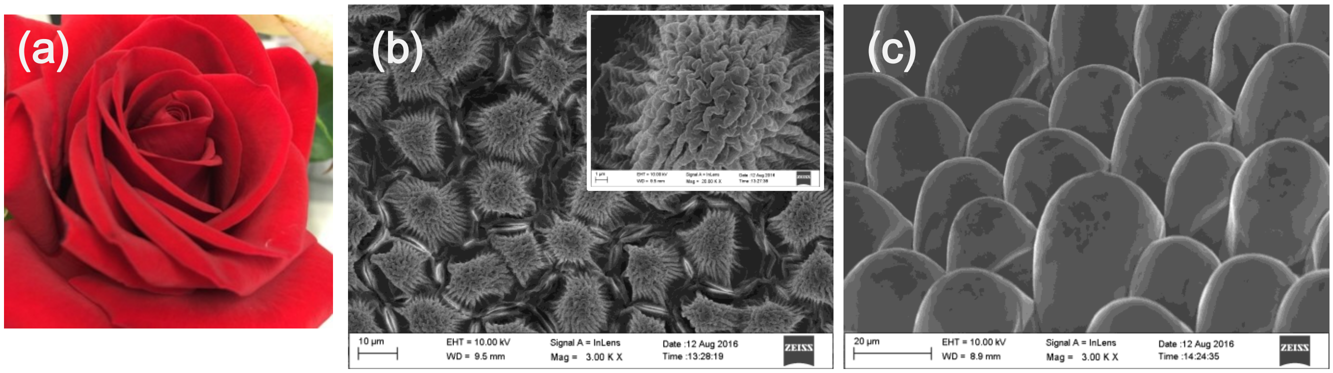

FIG 1: (a) Photograph of red rosoideae rosa rose. SEM graphs of rose petals showing micropapillaes (b) with nanofoldings and (c) without nanofolodings, tilted at 45°. The inset of (b) shows enlarged nanofolding structures.

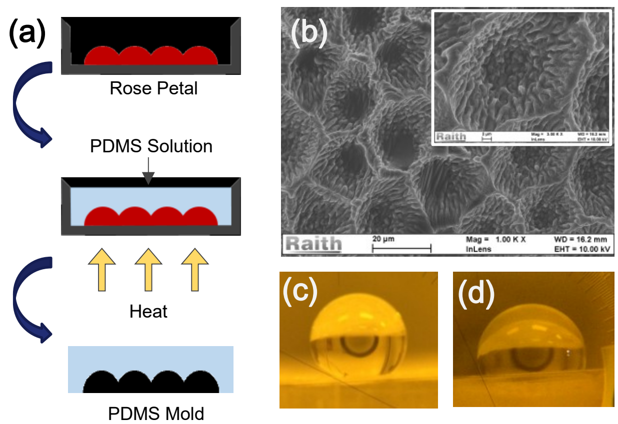

FIG 2: (a) The schematic of process to create PDMS mold with negative replication of rose structures. (b) SEM image of negative replicated PDMS showing micro-concaves with nanofoldings. Inset shows enlarged nanofolding structures. Photograph of water droplets on PDMS surface (c) with negative replicated rose structures, showing contact angle of 150° and (d) without rose structures, showing contact angle of 112°.

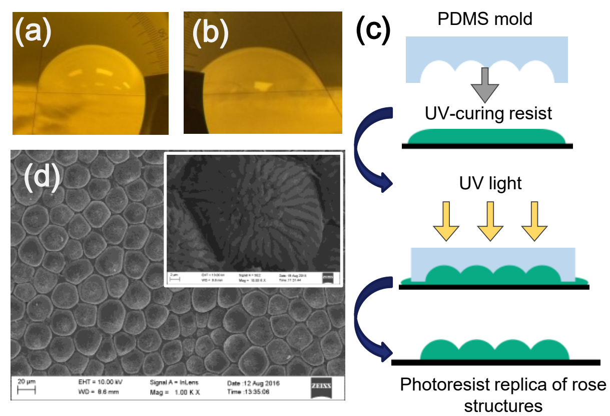

FIG 3: Photograph of water droplets on PDMS surface (a) with rose structures (contact angle of 86°) and (b) without rose structures (contact angle of 62°) after treatment with oxygen plasma. (c) The schematic transfer printing process with PDMS mold. (d) SEM image of imprinted photoresist film, showing uniform micropapillaes with nanofoldings which are positive replication of the rose structures. Inset shows enlarged nanofolding structures.

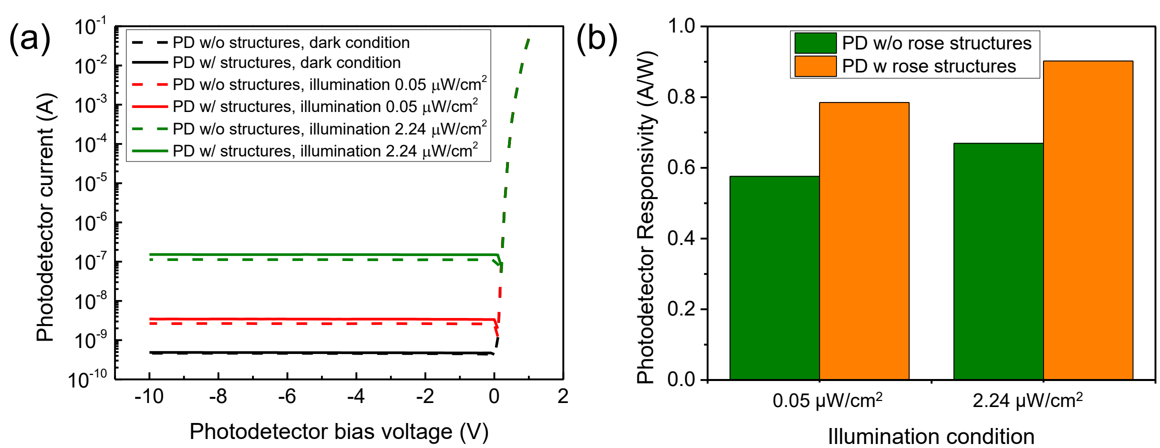

FIG 4: (a) I-V characteristics of Si photodiodes tested under both dark and light illumination conditions (0.05μW/cm2 and 2.24μW/cm2) in logarithm scale. The solid line represents the photodiode with replicated rose structures on photoresist while the dashed line represents the one without imprinted structures. (b) Calculated photodetector responsivity, showing 36% improvement at 0.05 $\mu W/cm^2$ illumination and 35% improvement at 2.24 $\mu W/cm^2$ illumination by incorporating rose structures.