Flexible ITO electrodes employing nanostructures for crack growth retardation

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The rise of wearable and flexible electronics has aroused the demand for flexible electrodes [1][2]. However, the widely used electrode, indium tin oxide (ITO), has a small fracture strain, posing a challenge to the prevalence of flexible ITO electrode [3][4]. Here, the fabrication of nanostructured ITO (nano-ITO) electrodes with improved flexibility is reported. The nano-ITO electrode is simply fabricated by two steps of nanoimprint lithography and magnetron sputtering. The nano-ITO electrode exhibits 70 times smaller resistance change compared to flat ITO within a strain up to 2.5% when the flat ITO has lost its conductivity completely and accommodates cyclic bending without significant deterioration of its resistivity. Furthermore, numerical simulation reveals that the nanostructures enable stress redistribution and deterministic cracking patterns, which results in decreasing energy release rate and efficient crack retardation. To demonstrate the potential use of nano-ITO electrodes, a flexible alternative current electroluminescent display (ACELD) using the nano-ITO electrode is fabricated, which works properly without observable damage under a complete bending cycle. The results confirmed the nano-ITO electrodes as a promising candidate for the next generation flexible electrode.

Figure 1(a) shows the top view SEM characterization of the nano-ITO electrode, illustrating the regular nano-hole arrays. The cross-section image in **Figure 1(b)** depicts the conformal profile of the nano-ITO to the patterned COC substrate.

Figure 2(a) presents the resistance change as a function of tensile strain of the ITO electrodes. **Figure 2(b)** demonstrates the sheet resistance change of these three samples subjected to 2000 bending cycles. Compared with the flat ITO, the nano-ITO exhibits enhanced flexibility and excellent mechanical stability even after 2000 bending cycles.

Figure 3(a) and **(b)** are the simulated cracking trajectory during stretching under 3% and 8% strain respectively. For strain up to 3%, the applied strain is mainly accommodated by the generation of the discrete cracks. The further increase of strain finally leads to the failure of the nano-ITO, where the discrete cracks reach the bottom of the nano-hole and meet each other. SEM images of nano-ITO under a small strain and a large strain are shown in **Figure3(c)** and **(d),** which are consistent with the simulated results.

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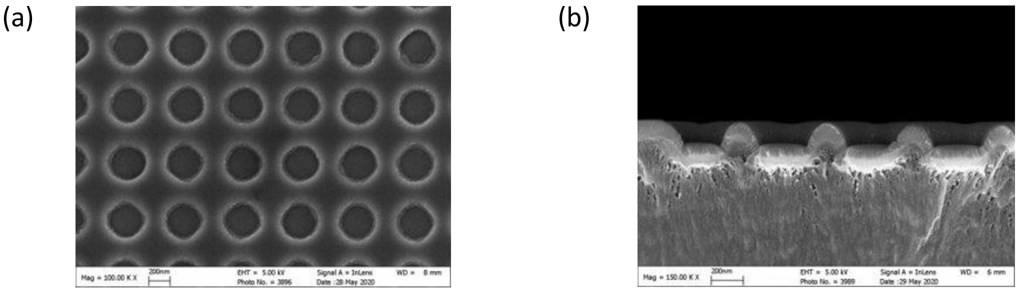

Figure 1. SEM images from top view (a) and cross-section view (b) of the nano-ITO on COC substrate

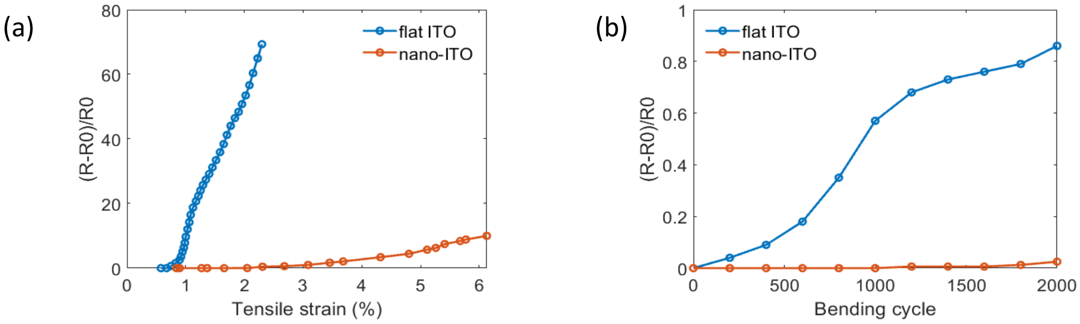

Figure 2. (a) Sheet resistance change of ITO electrodes as a function of the tensile strain under bending. (b) Repetitive bending tests of ITO electrodes.

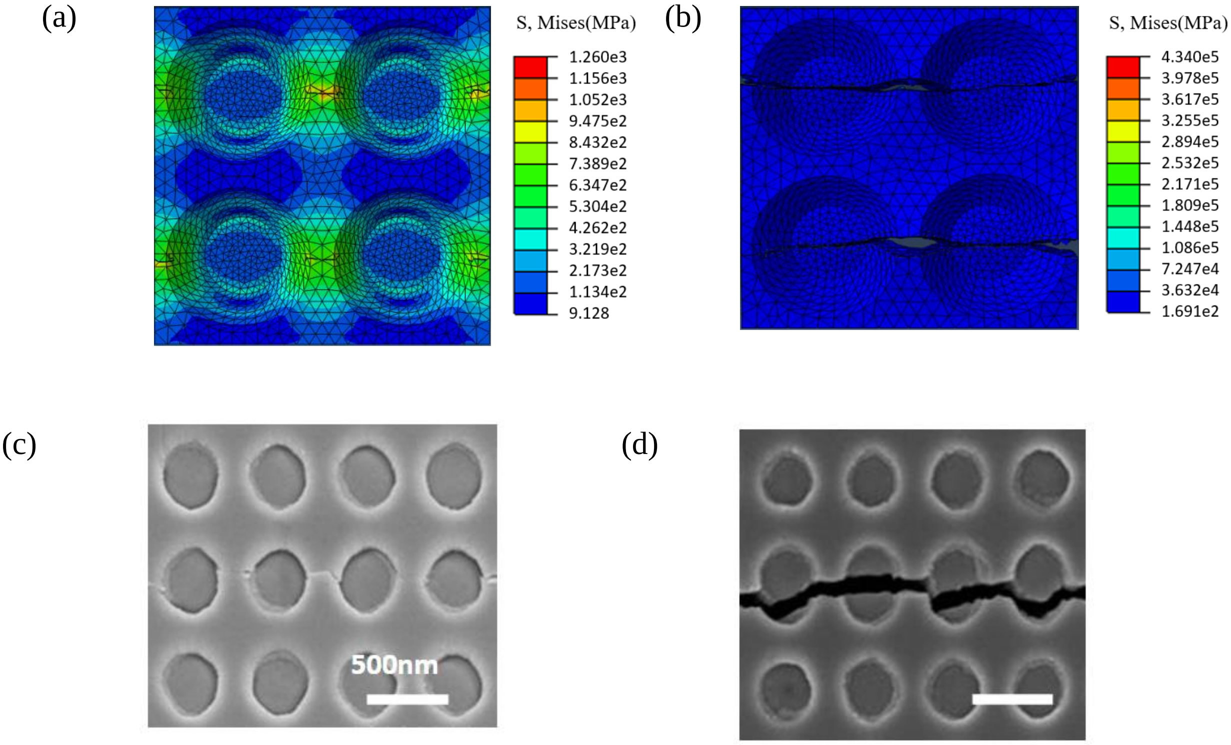

Figure 3. Simulated cracking trajectory during stretching under (a) 3% and (b) 8% strain. (c) SEM image of nano-ITO with discrete cracks on the bridge of nano-holes under a small strain. (d) SEM image of nano-ITO with complete crack development under a large strain.