Fabrication and Characterization of Transparent, Flexible Metallic Nano-Accordions

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Recent advances in science and technology have led researchers to develop both flexible and transparent conductors using various nanomaterials including metals, carbon based materials, and conducting polymers.[1-3] Amongst those, metals can be an attractive solution due to their excellent structural stability as well as superb electrical and thermal conductivity. Combining metal atomic layer deposition (ALD) with interference lithography (IL), we have demonstrated an approach to fabricate metallic nano-accordion structures for flexible conductors,[4] and introduced a simple process to overcome the limited optical transmission of metallic structures by patterning them.[5] However, the incomplete, low-yield transfer to soft polydimethylsiloxane (PDMS) substrate has restricted the characterization of their mechanical property.

Herein, we introduce a new fabrication and pattern transfer process for large-scale fabrication, and the characterization of the fabricated flexible transparent metallic conductors to demonstrate the advantages from their mechanical, electrical, and optical properties. Figure 1 shows the fabrication process, which starts with coating of thin poly(styrenesulfonate) (PSS) layer and the first photoresist (PR) on top of silicon substrate. The PR layer, then, is patterned to 1D periodic grating shape by IL and ultra-thin layer of tungsten (W) will be deposited by ALD to form a conformal metallic film. To improve optical transparency, the second PR is prepared over metal layer and lithographically patterned to create physical periodic openings parallel to the first accordion fold direction. Through these openings, metal layer is removed using wet etching and leaves only the parts covered by patterned second PR. Subsequently, the residual PR is washed away, and the microstructured metal layer is attached to the pre-cured transparent soft substrate, such as PDMS. Finally, by dissolving PSS layer with water and removing the first PR layer with oxygen plasma, only a group of free-standing nano-accordion structures is left on the soft substrate, so that mechanical, electrical, and optical characterizations can be performed.

The SEM images of actual sample, which contains sacrificial PSS layer, SU-8 polymer grating template, and conformal tungsten film, right after ALD process are shown in Figure 2(a). For controlling transmission of nano-accordions, the proportion of opening area to metal area can be modified, and the preliminary experiment using the sample with 95% of opening (right sample of Figure 2(b)) showed more than 70% of transmission of visible light. Broadband optical transmission, reflection, and scattering test will be conducted by changing the ratio of open and closed areas and the dimensions of metal nanostructures. Also, initial mechanical characterization to demonstrate the nanostructures as flexible conductors was performed using a tensile stage, and the sample with aspect ratio of 0.5 resulted in more than 30% of strain with no systematic collapse, as shown in Figure 2(c). Further investigation using in-situ electron microscopy to seek the strain of more than 100% by controlling the aspect ratio of nanostructure will be conducted. The repeatability of our flexible conductors along with electrical characterization will be discussed.

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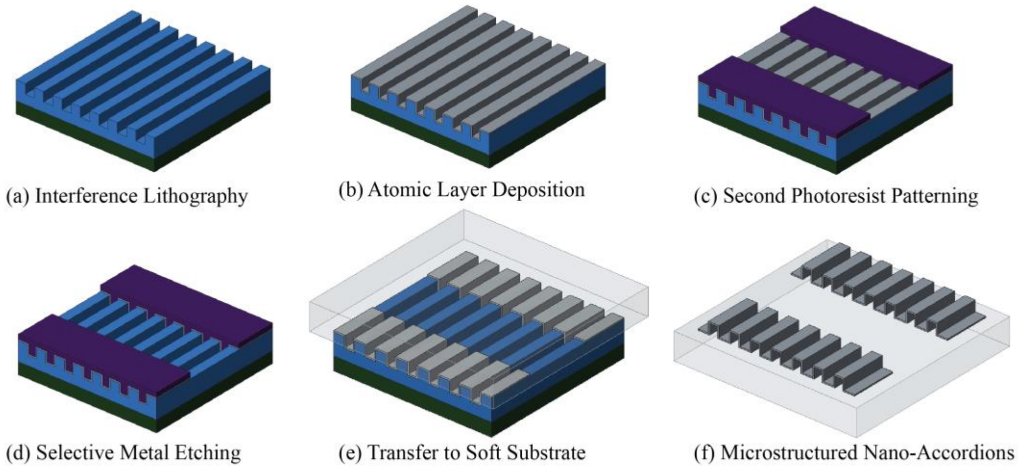

Figure 1. Fabrication process including (a) interference lithography of first PR layer, (b) atomic layer deposition of metal, (c) patterning of second PR layer, (d) selective metal etching, (e) transferring to soft substrate, and (f) final transparent metallic nano-accordions.

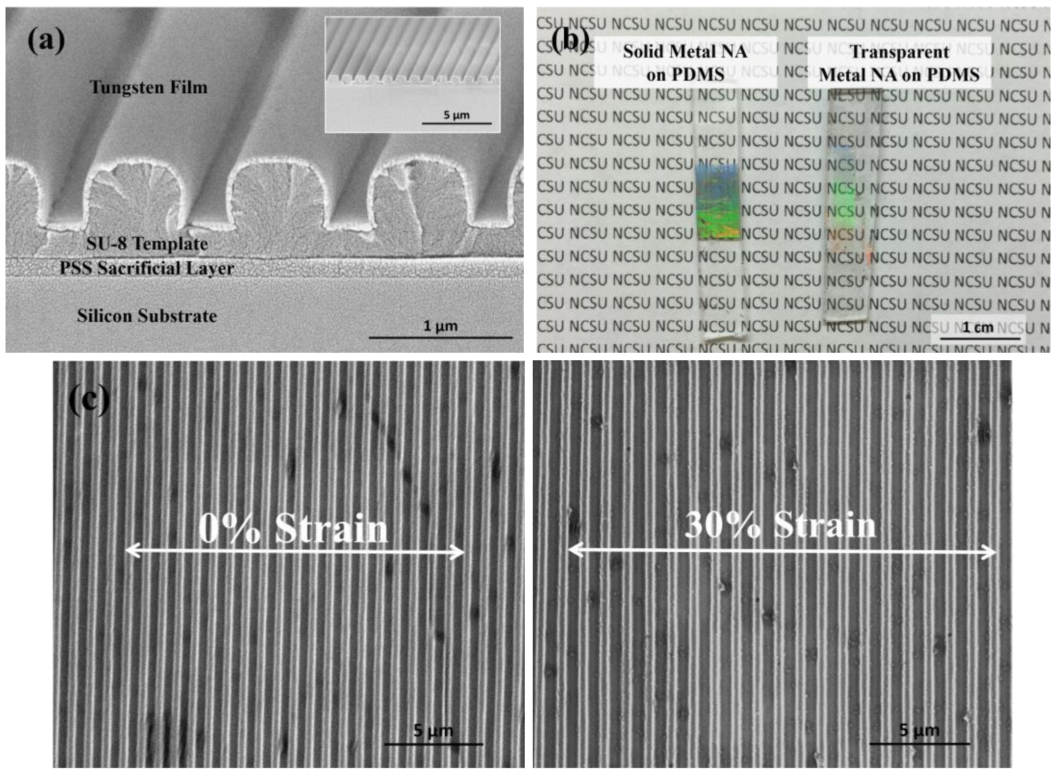

Figure 2. (a) SEM images of tungsten film on polymer template after atomic layer deposition process, (b) photographs of sold and transparent metal nano-accordions on PDMS substrate, and (c) SEM images of initial stretch test on tungsten nano-accordion structures with 30% strain.

References

[1] *J. A. Rogers, et al., Science, 2010, 327, 1603-1607.*
[2] *S. Yao, et al., Advanced Materials, 2015, 27, 1480-1511.*
[3] *D. McCoul, et al., Advanced Electronic Materials, 2016, 2, 1500407.*
[4] *J.-H.Min, et al., Nanoscale 2016, 8, 4984-4990.*
[5] *J.-H.Min, et al., EIPBN, 2016, Pittsburgh.*