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Electrically tunable window based on microwrinkled ZnO/Ag thin film

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ABSTRACT

Micro-winkling can turn a transparent thin-film of zinc oxide (ZnO) to be 'opaque' that can be reversed by unfolding to restore back to the clear state. This principle was previously used to make a mechanically tunable window device. However, ZnO thin film cannot make a compliant electrode to enable electrical unfolding due to its insulator nature. This paper reports the use of multilayer thin films of 10nm silver (Ag) and 30nm thick ZnO to form a compliant electrode with electrically tunable transmittance. A dielectric elastomer actuator (DEA) with a pair of such compliant Ag/ZnO thin films on both sides of a polyacrylate elastomeric membrane (3M VHB 4910) makes an electrically tunable window device. The DEA without radial compression of the elastomer has wrinkle-free electrode. Hence, it is clear with a 47% in-line transmittance (for 550nm wavelength light). In the wrinkled form, under 10% radial compression, it becomes opaque (with less than 1% transmittance). A voltage induced areal expansion of 10% radial strain enables the electrical unfolding of the initial wrinkles. In addition, this device continues to work after 4000 cycles of unfolding and micro-wrinkling of Ag/ZnO. The performance of electrically tunable window device is comparable to the existing smart window technologies.

Keywords: Smart window, transparency tuning, dielectric elastomer actuator, wrinkles

1. INTRODUCTION

Smart windows are installed to buildings for regulating the natural lighting of indoor. They are capable of electrically switching between transparent and opaque states, eliminating the need for motorized blinds and curtains. Current technology of smart windows is based on the polymer-dispersed liquid crystal (PDLC) [1] and electrochromic glasses [2, 3]. Their adoption is however limited due to their high cost (\$200 per square foot [4, 5]) and some other concerns. For example, the problems of aging, a slow response (5 minutes for a 0.01 square meter panel), and incomplete 'opaqueness' (5% transmittance [3]) of electrochromic glasses making them less useful as privacy glasses. Similarly, PDLC smart window is subjected to the problems of being lightly hazy and the need for AC power during its clear state [6].

As a low-cost alternative, an elastomeric tunable optical diffuser also makes a smart window. Typically, it varies its surface roughness to tune the light diffusion. It is clear when its surface is flat; whereas, it becomes 'opaque' when its surface is roughened. A typical device of the tunable optical diffuser has a transparent thin film coated on a pre-stretched elastomer membrane. A mechanical release of the elastomeric pre-stretch causes an in-plane compression and thus micro-wrinkling of the transparent thin film. Mechanical stretch can unfold and flatten these micro-wrinkles. Electrical unfolding of these micro-winkles is possible by the configuration of a dielectric elastomer actuator (DEA) [7, 8] using a pair of such wrinkled transparent compliant electrodes.

Though gold and silver are highly reflective, their nanometric flat thin films appear mildly transparent (with 60% in-line transmittance). Nanometric thin films of gold were previously used to make the compliant electrode with tunable transparency [9, 10]. They become 'opaque' when they are highly wrinkled under a very high compression of up to 70% radial strain [9]. However, this requirement for large areal reduction (i.e. to achieve the high compression) makes it impractical for window installation. Alternatively, silver nanowires were used to electrically indent the surface of a transparent elastomeric substrate, roughening the surface [11]. Yet, the coating of silver nanowires on the flat substrate is hazy (with a moderate transmittance of 68%) inherently due to the light scattering by the nanowires [11].

Transparent conductive oxides (TCOs) can make compliant electrodes with tunable transparency when deposited as a nanometric thin film on elastomer substrate. Yet, most transparent conductive oxides are brittle and their deposition

requires substrate heating to achieve high transparency. Substrate heating causes thermally induced wrinkle and even melting to the elastomeric substrate. This limits the choices of transparent conductive oxides to be room-temperature deposit-able, compromising the transparency. For example, the electron-beam evaporated thin film of indium tin oxides (ITO) onto an elastomer substrate near room-temperature appears brownish (with a limited transmittance of 52%) and slightly wrinkled due to thermally induced residual stress [12]. These factors effectively limit the best clear state of the window device based on the wrinkled ITO nanometric thin films. Our recent work [13] found that electron-beam evaporated zinc oxide (ZnO) is flat and highly transparent as deposited on an elastomer substrate. It effectively maximizes the transparency tuning range of a window device, by mechanical means of compression and stretching. However, ZnO thin film cannot make compliant electrode to enable electrical unfolding due to its insulating nature.

In literature [14, 15] [16], a conductive multilayer coating of Zn/Ag/ZnO deposited on a glass substrate shows a high transparency over 90% (at 580 nm wavelength of light) and a low surface resistance of $3\Omega/\square$. These multi-layer coatings are sub-micron thick and rigidly bonded to the glass substrate. Hence, they are too rigid to buckle into wrinkles on a soft substrate. It is not clear how thin the multi-layer coating should be to form the wrinkled compliant electrode with tunable transparency.

In this work, we present that a two-layer coating of 10nm thick Ag and 30nm thick ZnO can make a micro-wrinkled compliant electrode under 10% radial compression. A dielectric elastomer actuator using a pair of such wrinkled Ag/ZnO compliant electrodes are opaque (with less than 1% light transmittance). These Ag/ZnO micro-wrinkles show better concealing effect as compared to the Ag submicron wrinkles formed under the same radial compression. Voltage activation of the DEA unfolds and flattens the compliant electrode and thus turns to a clear state (with 47% transmittance). In addition, we subjected this tunable window device to pulsed activation for more than 4000 cycles to test for their reliability for long-life operation.

2. DEVICE DESIGN AND FABRICATION

This tunable window device is as a dielectric elastomer actuator with micro-wrinkled compliant electrodes that have variable transparency. The device substrate is a pre-stretched dielectric elastomer membrane (3M VHB 4905) while the compliant electrodes are multi-layer thin films of Ag/ZnO which were deposited on the initially flat elastomeric substrate. Wrinkle formation of the multi-layer Ag/ZnO thin films happens under a mechanical compression induced by a partial release of the substrate's pre-stretch. The wrinkled transparent thin film appears opaque due to light diffusion [13]. Application of an electric field by voltage V across the pre-stretched dielectric elastomer membrane of thickness t induces a Maxwell stress to expand the electrode area [7, 8]. The Maxwell stress is given by $p_e = \epsilon_r \epsilon_0 (V/t)^2$ where ϵ_r is the dielectric constant and ϵ_0 is the air's permittivity. The voltage induced area expansion, in turn, unfolds the initial micro-wrinkles and restores the transparency.

Figure 1: The working principles and fabrication steps for this tunable window device.

Figure 1 shows fabrication steps to make the tunable window device. First, a VHB membrane is radially pre-stretched 3 times relative to its original dimension using a custom-made stretcher. A Teflon film mask is used to define the area for thin-film coating. Second, e-beam evaporation technique (Coaxial Power Systems) was used to deposit a 30nm ZnO thin film on each side of the elastomer substrate. The evaporation material is 99.9% undoped ZnO pellets. The process parameters for ZnO sputtering are: 4.2×10^{-5} torr pressure, 1.6-mA current, and 4.89-kV bias voltage. A silver layer of 8-10nm is DC magnetron sputtered on the ZnO layer to form a conductive electrode. The process parameters of silver sputtering are: 4.0×10^{-4} torr pressure and DC power of 100 watts. The deposited film thickness is monitored using a quartz crystal microbalance. Though not actively controlled, the substrate temperature is kept near the room temperature, given the gradual evaporation of nanometre thin film and the absence of thermally induced wrinkling. Third, the pre-stretch of the elastomer is partially released to form micro-wrinkles on the elastomer surface. The radial compressive strain is defined as $c = 1 - D_{II}/D_I$ where D_I is initial the diameter of the coated area and D_{II} is the reduced diameter. Strips of aluminium foil strips make the electrical lead out from the device to the voltage supply. A high voltage power supply (TREK 610E) is used to activate the dielectric elastomer actuator.

Figure 2: A spectrometer setup to measure in-line transmittance of transparency tuning device

The setup (see Figure 2) for in-line transmittance spectrum measurement consists of a spectrometer (AvaSpec-USB2 Fibre Optic) and a halogen light source (AvaLight-Hal-S-Mini). The spectrometer measures the intensity of the collimated light passing through window device from the light source. Surface morphology of the device's wrinkled compliant electrode is measured by a scanning electron microscopy (SEM); it leads to the determination of the micro-wrinkles' wavelength and amplitude. A function generator is used to control a high voltage supply for the square pulse activation. A black and white logo is placed at 10mm under the tunable window device. Video of the logo appearance during the device activation provides a measure for the perceived transparency in terms of the Michelson contrast. Image J software is used to extract the grayscale intensity of the logo from the captured video frames. The device response time is obtained from the time change of the contrast ratio due to the pulsed voltage activation.

3. RESULTS AND DISCUSSIONS

The sample under test is a DEA which has a pair of 10nm-Ag/30nm-Zn thin-film electrodes sputtered on both sides of a pre-stretched dielectric elastomer membrane (VHB 4905). Figures 3 shows the morphology of the sputtered multilayer thin films and its effect on DEA' optical appearance. The multi-layered thin films as sputtered is nearly flat as the elastomeric substrate, with a roughness not more than $0.16\mu\text{m}$. They have a bluish due to the plasmonic resonance effect [17] of nanometric silver thin film that partially absorbs other visible light except for the blue light. When subjected to a radial compression, the multi-layer thin films wrinkle with a $3.35\mu\text{m}$ wavelength and a maximum roughness of $1.443\mu\text{m}$ (see Figure 3(c). This wrinkled multilayer of Ag/ZnO appears opaque, completely concealing the logo beneath it (see Figure 3(d)).

In contrary, a thin film of 10nm thick silver alone does not form micro-wrinkles when subjected to the same radial compression on the elastomer substrate. Instead, it forms local sub-micron creases or folds and remains largely flat on the elastomeric surface due to its nanometric thickness and low axial stiffness [18]. Thus, its transparency tuning range is limited: 35% transmittance at the flat uncompressed state; and 8% transmittance at the 10% compressed state. It can barely conceal a logo beneath it even when it is compressed for 10% radial strain. A thicker silver thin film could produce micro-wrinkles under the compression but it turns to be opaque for good. Hence, an undercoat of 30nm thick ZnO thin film is added beneath the silver thin film, adding to the thickness and stiffness is necessary for micro-wrinkle formation.

Figure 3: Scanning electron micrograph of one of the two ZnO/Ag thin-film compliant electrodes that sandwich a VHB membrane and the visibility of a logo placed 10 mm beneath the sandwich: (a)–(b) the clear state at 0% radial compressive strain; and (c), (d) the translucent state at 10% radial compressive strain.

Figure 4: Optical micrograph of one of the two Ag thin-film compliant electrodes that sandwich a VHB membrane and the visibility of a logo placed 10 mm beneath the sandwich: (a)–(b) the clear state at 0% radial compressive strain; and (c), (d) the translucent state at 10% radial compressive strain.

The dielectric elastomer actuator with the wrinkled Ag/ZnO compliant electrodes can be electrically activated to tune its transparency. As shown in Figure 5, it was initially opaque (with 1% in-line transmittance as shown in Figure 5). Hence, it can conceal a logo beneath it (at a 0.05 Michelson contrast ratio as shown in Figure 6). Its activation by 6.5kV (i.e. 54MV/m) produces an electrode expansion of 10% radial strain to completely unfold and flatten the electrodes. Thus, this voltage-induced unfolding help restores the transparency (with 47% in-line transmittance) and show up the logo beneath it (at 0.72 Michelson contrast ratio). Upon the voltage removal, the DEA returns to be opaque.

Figure 5: Inline transmittance through the transparency tuning device throughout the visible range of light.

Figure 6: Change in Michelson contrast of the image placed beneath Ag/ZnO/VHB/ZnO/Ag and radial compressive strain when applied voltage is gradually increased.

Figure 7 shows that a pulsed voltage activation (6kV, 50% duty cycle, and 0.5Hz) can fast switch the DEA between opaque and clear states. This on state induces a 7% radial expansion to the electrodes. During the off-state, the dynamic recovery is however incomplete due to the VHB's viscoelastic effect. Visibility of a logo during the devices' pulsed activation leads to the determination of device time constant. During the on state, the device takes less than 0.5 seconds to reach 90% of the clear state (at 0.72 Michelson contrast). During its off state for the few initial cycles, it returns to be at 0.3 Michelson contrast. However, the restored opaqueness during the off states decreases after 4000 cycles. Its full return to the initial opaqueness happens provided the voltage removal, and it takes more than 10 seconds. It is believed that the pulsed resistive heating of the elastomeric substrate may be the cause to the incomplete recovery. Despite long cycles of activation, the tested device continues to work with no major performance degradation. This proves it to be reliable for long-life operation.

This tunable window device consumes only a moderate power (e.g. 0.05 W/cm^2 at 6 kV) during on state despite the need for high voltage. Its power consumption is due to the leakage current across the dielectric elastomer membrane while subjected to high electric field, for example, $30 \mu\text{A}$ at 6 kV for this device (see Figure 7(a)). Though not posing a danger at a lower power, the high driving voltage requires an expensive high-voltage driver. Future work will reduce the driving voltage requirement by means of thinning down the dielectric elastomer membrane. Proper insulation such as by dielectric gel coating [19] will help reduce the leakage current. A higher sensitivity of contrast change with respect to micro-wrinkling may also help bring down the high-voltage requirement.

Figure 7: Time response of the device when instantaneously 6 kV is turned off and on at 0.5 Hz ; (a) Voltage and leakage current waveform supplied to the device in cyclic electrical activation tests; (b) Change in Michelson contrast presented for the first four cycles; (c) Change in Michelson contrast presented for the last three of the 4000 cycles indicating the prolonged time to reach the fully opaque state.

4. CONCLUSION

We showed that a multilayer of $10\text{-nm Ag}/30\text{-nm ZnO}$ makes a wrinkled compliant electrode with variable transparency. Micro-wrinkling of this transparent multilayer thin film is effective for light diffusion, showing a strong concealing effect at 0.05 Michelson contrast ratio. Its integration to a dielectric elastomer actuator enables the voltage-induced unfolding to restore the perceived transparency as much as 0.76 Michelson contrast ratio. This tunable window device shows a fast response, taking less than a second to switch between opaque and clear states. It continues to work after thousands of cycles of unfolding and wrinkling. It can potentially be useful as reliable privacy glasses.

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