Microscopically crumpled indium-tin-oxide thin films as compliant electrodes with tunable transmittance

Ong, Hui-Yng; Shrestha, Milan; Lau, Gih-Keong

2015

Ong, H.-Y., Shrestha, M., & Lau, G.-K. (2015). Microscopically crumpled indium-tin-oxide thin films as compliant electrodes with tunable transmittance. *Applied Physics Letters*, 107(13), 132902-.

<https://hdl.handle.net/10356/83655>

<https://doi.org/10.1063/1.4932115>

© 2015 AIP Publishing LLC. This paper was published in *Applied Physics Letters* and is made available as an electronic reprint (preprint) with permission of AIP Publishing LLC. The published version is available at: [<http://dx.doi.org/10.1063/1.4932115>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 18:41:52 SGT

Microscopically crumpled indium-tin-oxide thin films as compliant electrodes with tunable transmittance

Hui-Yng Ong, Milan Shrestha, and Gih-Keong Lau

Citation: [Applied Physics Letters](#) **107**, 132902 (2015); doi: 10.1063/1.4932115

View online: <http://dx.doi.org/10.1063/1.4932115>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/apl/107/13?ver=pdfcov>

Published by the [AIP Publishing](#)

Articles you may be interested in

[Highly flexible, hybrid-structured indium tin oxides for transparent electrodes on polymer substrates](#)

[Appl. Phys. Lett.](#) **102**, 241913 (2013); 10.1063/1.4812187

[Influence of gaseous annealing environment on the properties of indium-tin-oxide thin films](#)

[J. Appl. Phys.](#) **97**, 033504 (2005); 10.1063/1.1834984

[Highly electrically conductive indium-tin-oxide thin films epitaxially grown on yttria-stabilized zirconia \(100\) by pulsed-laser deposition](#)

[Appl. Phys. Lett.](#) **76**, 2740 (2000); 10.1063/1.126461

[Electrical, optical, and structural properties of indium-tin-oxide thin films for organic light-emitting devices](#)

[J. Appl. Phys.](#) **86**, 6451 (1999); 10.1063/1.371708

[Electrical, optical, and structural properties of indium-tin-oxide thin films deposited on polyethylene terephthalate substrates by rf sputtering](#)

[J. Vac. Sci. Technol. A](#) **16**, 1636 (1998); 10.1116/1.581133

A promotional banner for Applied Physics Reviews. On the left is a small image of the journal cover for 'Applied Physics Reviews', which features a diagram of a device structure. The main part of the banner has a blue background with a glowing light effect. The text 'NEW Special Topic Sections' is prominently displayed in white. Below this, in an orange bar, it says 'NOW ONLINE' in yellow, followed by 'Lithium Niobate Properties and Applications: Reviews of Emerging Trends' in white. The AIP Applied Physics Reviews logo is in the bottom right corner.

NEW Special Topic Sections

NOW ONLINE
Lithium Niobate Properties and Applications:
Reviews of Emerging Trends

AIP Applied Physics Reviews

Microscopically crumpled indium-tin-oxide thin films as compliant electrodes with tunable transmittance

Hui-Yng Ong,^{1,2} Milan Shrestha,¹ and Gih-Keong Lau^{1,a)}

¹*School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798*

²*School of Engineering, Nanyang Polytechnic, Singapore 569830*

(Received 9 June 2015; accepted 20 September 2015; published online 1 October 2015)

Indium-tin-oxide (ITO) thin films are perceived to be stiff and brittle. This letter reports that crumpled ITO thin films on adhesive poly-acrylate dielectric elastomer can make compliant electrodes, sustaining compression of up to $25\% \times 25\%$ equi-biaxial strain and unfolding. Its optical transmittance reduces with crumpling, but restored with unfolding. A dielectric elastomer actuator (DEA) using the $14.2\% \times 14.2\%$ initially crumpled ITO thin-film electrodes is electrically activated to produce a 37% areal strain. Such electric unfolding turns the translucent DEA to be transparent, with transmittance increased from 39.14% to 52.08%. This transmittance tunability promises to make a low-cost smart privacy window. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4932115>]

Recently, physical means of thin-film wrinkling or unfolding^{1–4} demonstrates variable transparency and promises to make low-cost smart window, as compared to pricey polymer dispersed liquid crystal ($> \$200/\text{m}^2$).^{5–8} van den Ende *et al.*² showed that electric-field activation can induce surface wrinkling of a gold-thin-film coated elastomeric capacitor on glass substrate to conceal an image behind it, albeit at a slight transmittance reduction from 27% to 24% at 550 nm wavelength. Mechanical crumpling of gold thin film on an elastomer membrane from 0% to 70% equi-biaxial compressive strains was reported to reduce the transmittance from 60% to nearly 0%.⁴ Unfolding is the reverse process to wrinkling. A voltage-induced expansion for 100% areal strain of a dielectric elastomer actuator was reported to unfold the crumpled few-layer graphene to increase optical transmittance from 40% to 60%.³ However, these metallic thin films are reflective² despite adequate transmittance at nano-metric film thickness (13 nm).⁴ Transparent conductive oxides (TCO), which was perceived stiff and brittle,⁹ can be made stretchable by wrinkling on the support of elastomer substrate, like wavy Si¹⁰ or ZnO.¹¹ However, it is not clear if the crumpled TCO thin film can be made compliant (highly stretchable and soft) for dielectric elastomer actuator to enable electrically activated transmittance change.

Transparent conductive oxides are often used to make electrode coating on glass for displays, such as liquid crystal displays.^{12,13} Indium-tin oxide (ITO) is one of the most commonly used transparent conductive oxides due to its high electrical conductivity and high optical transparency. ITO is brittle and stiff. Its Young's modulus of 250 GPa (Ref. 13) is high as compared to 1 MPa of acrylic elastomer.¹⁴ Fracture strains of ITO thin films were reported to be low: less than 3% tensile strain when flexed on a plastic substrate.^{15,16} A higher fracture strain of up to 15% uniaxial stretching is achievable by bearing the ITO thin film on a soft silicone substrate.¹⁷ On the other hand, compression also causes

fracture to ITO coating on plastic substrate due to buckle-delamination.¹³ It is believed that good adhesion to elastomer substrate can avoid delamination of the buckled ITO coating. With very high bond strength, poly-acrylate adhesive foam (3M VHB 4905) is suitable for bearing ITO thin film while it makes a dielectric elastomer actuator.

In this letter, we report crumpling and unfolding of ITO thin films on poly-acrylate adhesive foam, enabling stretchability and electrical tunability of its optical transmittance, despite the fact that ITO was deemed to be stiff, brittle, and transparent. The ITO thin film on poly-acrylate adhesive foam can sustain 25% equi-bi-axial compressive strain without showing observable delamination or fracture. Crumpling of the ITO thin film into micro-folds yields a masking effect, turning it from transparent to translucent. Inversely, the crumpled thin films of ITO can be unfolded, just like stretchable and compliant metallic electrodes.^{4,18–22} As such, the dielectric elastomeric capacitor with the crumpled ITO electrodes can be electrically activated to unfold and increase the optical transmittance. Subsequent paragraphs will present a simple strain analysis and fabrication method for crumpled ITO thin film and its characterization for optical and electro-mechanical properties.

Wrinkling or crumpling can make ITO thin film compliant and stretchable, like it does to metal thin films.^{4,18–22} Though ITO thin films are axially stiff, they can readily flex and even buckle into micro-folds on a soft and viscoelastic substrate. According to the beam and plate theory,¹³ the axial strain ε in a bent film is proportional to the film thickness t but inversely proportional to the radius of curvature R , following $\varepsilon = t/(2R)$. This estimates that 50–100 nm thick ITO thin films can bend at 1 μm radius of curvature, without exceeding the 5% tensile fracture strain. In addition, wrinkling helps make ITO thin film axially softer. According to the plate theory,^{21,23,24} the apparent Young's modulus E of a biaxially buckled thin film is only a fraction of the intrinsic modulus E_0 , following the relation: $E/E_0 \propto (t/l)^2$ where t is the film thickness and l is the wavelength. This estimates that a 2–3 μm -pitch wrinkled ITO thin film of 50 nm thick

^{a)} Author to whom correspondence should be addressed. Electronic mail: mgklau@ntu.edu.sg

has its apparent modulus reduced nearly 3–4 order so that its axial stiffness is comparable to that of an 56 μm -thick elastomeric membrane and consequently conforms to the large elastomeric deformation.

Figure 1(a) shows the fabrication process to induce wrinkling or micro-folds on the surface of polyacrylate elastomer (VHB 4905). First, a membrane of polyacrylate elastomer (3M, VHB 4905 of 500 μm initial thickness) was pre-stretched equi-biaxially, say for 3.5×3.5 times. Second, the pre-stretched elastomer membrane is coated with 50 nm-thick ITO thin film by electron-beam evaporation method. Deposition of the evaporated ITO thin film causes heating and thermal expansion of the elastomer substrate. Upon cooling, the thermal expansion mismatch between the ITO film ($7.2 \times 10^{-6}/^\circ\text{C}$ (Refs. 25–27)) and the elastomer substrate ($180 \times 10^{-6}/^\circ\text{C}$ for VHB 4905²⁸) induces mild wrinkles to the ITO coating at an electrode diameter D_I . This thermally induced surface wrinkling is similar to that formed by evaporated metallic thin film on silicone elastomer substrate.²⁹ Third, the ITO-coated elastomer membrane is relaxed from the initially high pre-stretch to a smaller one, say 3×3 times, using a mechanical radial stretcher. Relaxation of the pre-stretched elastomer substrate yields a smaller electrode diameter D_{II} , crumpling the ITO coating at a compressive strain of $c = 1 - D_{II}/D_I$ into micro-folds of a finer pitch l . Meanwhile, the elastomer membrane remained pre-stretched at a stretch ratio $\lambda = D_{II}/D_0$ (with D_0 being the initial non-stretch diameter). Figure 1(b) shows that the 14%-biaxial-strain crumpled ITO coating on elastomer appears translucent and conceals a image behind it; whereas the ITO coating subjected to 5% biaxial-strain stretching becomes clearer to show the image behind.

An electron-beam evaporator (Coaxial Power Systems) was used to evaporate ITO pellets, which have a composition of 90% In_2O_3 and 10% SnO_2 by weight, and to deposit an ITO thin film on unheated elastomeric substrate (VHB). The evaporation conditions were: a vacuum pressure of 2.5×10^{-6} Torr in the chamber; an acceleration voltage of 7.96 kV; an ion current of 10 mA; and the rate of evaporation at about 10 nm/min. The deposited film thickness was controlled by a quartz crystal thickness monitor. Surface temperature of the VHB substrate was not measured during the deposition, but it was inferred to be 60–66 $^\circ\text{C}$ by substrate

reheating that reduces the surface wrinkling. Post annealing above 150 $^\circ\text{C}$ is expected to improve the transmittance and electrical conductivity of the evaporated ITO thin film^{30,31} but was not performed on the pre-stretched VHB membrane, which softens and snaps above 120 $^\circ\text{C}$. In addition, care was taken to avoid unintended membrane popping from causing ITO fracture while a Teflon shadow mask (for electrode patterning) was peeled off the adhesive elastomeric membrane.

The properties of the evaporated ITO thin film depend strongly on the substrate, substrate temperature, and surface wrinkling. The samples of ITO thin film deposited on a glass slide without post annealing appear metallic and lightly brownish as reported in literature^{30,31} and they have a high average sheet resistance of 66.6 $\text{k}\Omega/\square$. The samples of ITO thin films deposited on a VHB membrane appear hazy. The bonded ITO/VHB samples on a glass slide have an average sheet resistance of 244.1 $\text{k}\Omega/\square$; while the free ITO/VHB membrane has a markedly higher average sheet resistance of 2.15 $\text{M}\Omega/\square$ due to more thermally induced wrinkling.

For morphology study, the crumpled ITO thin film on pre-stretched elastomer membrane was transferred and adhesively bonded to a piece of glass slide. The surface micro-structure of the ITO thin film on elastomer was characterized by scanning electron microscopy (SEM) (Hitachi, SU1510) at 10 kV accelerating voltage and 2000 times magnification. Figure 2 shows the effect of bi-axial strains on surface morphologies of the ITO thin film on VHB elastomer. At zero bi-axial compression, the ITO coating on elastomer substrate shows mild wrinkling (see Figure 2(a)) as induced by thermal expansion mismatch. In comparison, the same deposited thin film of ITO on a glass slide (see Figure 2(f)) appears flat with no surface wrinkling. Increasing bi-axial compression, by relaxing the elastomer substrate through a mechanical radial stretcher, further buckles the ITO coating into denser and deeper folds. Micron-diameter and fine-pitch ridges appear distinct in the ITO coating subjected to 14% biaxial crumpling (see Figure 2(c)). At 25% biaxial compression, the micro-folds are so convoluted with deep creases and a 2 μm average pitch between adjacent ridges. Interestingly, there is no crack lines observed in the deeply wrinkled or crumpled ITO coating on elastomer. Neither increasing bi-axial compression of up to 25% strain nor its

FIG. 1. Crumpling of ITO thin film on the substrate of elastomeric membrane: (a) the process steps to (i) pre-stretch elastomeric membrane, (ii) deposit ITO thin film by e-beam evaporation method, and (iii) mechanically crumple the ITO thin film by relaxing the radial pre-stretch in the elastomeric substrate; (b) A dielectric elastomer membrane coated with ITO thin film by means of e-beam evaporation. The ITO thin film subjected to 5% biaxial stretching appears clear, but the same film subjected to 14.2% biaxial compression appears translucent to hide the image on the LCD screen behind it.

FIG. 2. Effect of equi-bi-axial strains on the surface morphology of ITO thin films on VHB membrane: micrographs (a)–(d) showing the formation of ITO thin-film micro-folding with increasing biaxial compression, with no observation of thin-film fracture; micrograph (e) showing criss-crossing crack lines in the ITO coating subjected to 3% strain biaxial stretching. For comparison, micrograph (f) shows the flat morphology of e-beam evaporated ITO on a glass slide.

reverse back to zero biaxial strain causes an observable crack in the wrinkled ITO coating. The “crack-free” crumpling of the ITO thin film is attributed to nanometric film thickness and the very high bond with the VHB substrate. In addition, viscoelastic nature of VHB substrate could have helped absorb energy and relax interfacial stress at the buckled surface. However, when subjected to 3%-strain biaxial stretching (see Figure 2(e)), the ITO coating cracks with criss-crossing fine lines. This biaxial fracture patterns on elastomer are different from the parallel crack lines on polyester as induced by uniaxial loading at 3.42%.¹⁵

The optical transparency of the ITO-coated dielectric elastomer was measured by UV/VIS spectrometer (PerkinElmer, Lambda 950) in the wavelength range of 300–800 nm at normal incidence. The opening on the photo detector is fixed at 5 mm diameter during this measurement. Though ITO thin film is transparent, its wrinkling on VHB substrate reduces the optical transmittance. Figure 3 shows that bi-axial strains have profound impact on its transmittance spectra of the ITO-thin-film coated VHB membrane. At zero-strain thin-film crumpling, the ITO-coated VHB membrane shows an optical transmittance of 55.1% at

FIG. 3. Effect of equi-bi-axial strains on the optical transmittance of ITO/VHB: (a) transmittance spectra through the ITO/VHB at various equi-bi-axial strains; (b) transmittance at 550 nm wavelength through the ITO/VHB as a function of equi-bi-axial strains; (c) and (d) images of the RGB colorbar filtered by the biaxially strained ITO/VHB at 0% and 25% crumpling, respectively; (e) change of ITO/VHB surface resistance over cycles of compressive strains.

550 nm wavelength. This moderate transmittance is due to low crystallinity and no post annealing of the ITO thin film on VHB substrate. Crumpling by 25% biaxial strain reduces the ITO/VHB's transmittance down to 31.0%, resulting in partial masking of the RGB colorbar behind it (see Figure 3(d)). The reduced transmittance is attributed to diffuse refraction² through the convoluted micro-folds of the crumpled ITO thin film. On the other hand, the same relaxation (i.e., reduced pre-stretch) of the bare VHB membrane does not show impact on the visible-light transmittance (see Figure 3(b)) even though the VHB membrane thickens more than the initial pre-stretched thickness.

Figure 3(e) shows the sheet resistance change of an ITO thin film (75 × 26 mm) on a pre-stretched VHB membrane over cycles of compression and relaxation, as driven by a tensile tester (Instron) through a radial stretcher. In each cycle of folding/unfolding, the ITO thin film was equi-biaxially compressed to a peak compressive strain and subsequently relaxed to a 2% compressive strain to avoid unintended fracture. The cycles of folding/unfolding was repeated 5 times for each peak compressive strain, which ranges from 14%, 18%, up to 25%. Meanwhile, resistance of the ITO thin film was measured using a multimeter (Agilent, 34410A). During folding, except that for the first cycle, the resistance of ITO thin film decreases with increasing compressive strain due to negative gage factor.³² During unfolding, the resistance increases with decreasing compressive strain, due to sub-micron crack formation at the tensioned parts of the crumpled thin film. Interestingly, the rate of resistance increment decreases over cycles for a given peak compression, suggesting no fresh formation of submicron cracks. However, a higher peak of compression causes further resistance rise. As a result of these 15 cycles of folding and unfolding with increasing peak compression, sheet resistance of the crumpled ITO thin film increased from 2.17 MΩ/□ up to

6.33 MΩ/□. Despite having mega-ohm resistance, this crumpled ITO thin film is conductive enough for use as compliant electrodes for dielectric elastomer actuators.

A dielectric elastomer actuator (DEA) consists of a pre-stretched dielectric elastomer membrane sandwiched by a pair of ITO thin films. A DEA with flat ITO thin-film electrodes hardly actuate due to high stiffness of flat electrodes.^{33,34} However, crumpled thin film of ITO is expected with reduced axial stiffness. To study its stiffening effect, various extent of crumpling is introduced to the pair of ITO thin-film electrodes on the same pre-stretched dielectric elastomer membrane at 3 × 3 times. To yield 10% crumpling of the ITO thin film, the elastomer substrate needs to be relaxed from 3.3 × 3.3 times (D_I/D_0) to 3 × 3 times; to yield 25% thin-film crumpling, the stretch relaxation of the elastomer substrate is from 4 × 4 times to 3 × 3 times. Performance comparison among these DEA samples could reveal the restraint effect of various crumpled thin films of ITO.

For electromechanical activation, ITO thin-film electrodes of a DEA are connected to the high voltage power supply (Trek, 610E) via thin aluminium foils, which were staggered on each opposite side. A voltage ramp at a 1 kV voltage step is supplied to activate the DEA until its breakdown. When subjected to Maxwell stress during activation, the dielectric elastomer actuator decreases in membrane thickness and expands in electrode area. This field-activated areal strain s_A for DEA is defined as $s_A = (D_{act}/D_{II})^2 - 1$, where D_{act} is the electrode diameter during the activated state while D_{II} is the electrode diameter at the inactive pre-stretched state. Figure 4 shows electromechanical activation of dielectric elastomer actuators using crumpled ITO thin-film electrodes. The 14.2% crumpled ITO electrodes for the inactive DEA (see Figure 4(a)) appear translucent and effectively conceal the black grids on a paper behind it. Activation of the DEA with 6 kV produces a 37% areal expansion at 6 kV, unfolding

FIG. 4. Electromechanical activation of the dielectric elastomer actuators with crumpled ITO thin-film electrodes: (a) the in-active dielectric elastomer appears translucent at initial crumpling strain $c = 1 - D_{II}/D_I$; (b) the activated dielectric elastomer cause electrode area expansion and increased optical transmission by unfolding the crumpled ITO electrodes; (c) the voltage-induced electrode expansion of DEA and its dependence on the initial electrode crumpling strain; (d) the voltage-induced transmittance spectra change for a DEA with initially 14%-crumpled ITO electrodes; inset showing the voltage-induced transmittance change at 550 nm wavelength. (Multimedia view) [URL: <http://dx.doi.org/10.1063/1.4932115.1>]

the crumpled ITO thin-film electrodes and revealing the grid lines on the paper behind it. This activation at 6 kV results in a 52.08% transmittance at 550 nm wavelength, higher than the in-active transmittance of 39.14%. In addition, the DEA can be repeated switched on and off, for example, between 5.5 kV and 0 kV (see Figures 4(a) and 4(b) (Multimedia view)). This cyclic actuation suggests that the crumpled ITO-thin-film electrodes remain integral.

It is found that the initial crumpling of 14.2% is conducive to generating large dielectric elastomeric actuation. However, sub-optimal crumpling of the ITO thin-film electrodes is restraining. For example, the DEA with 10% biaxially crumpled thin-film electrodes of ITO produces at most 12% areal strain at 5 kV. This limited actuation is attributed to the stiffening effect of the inadequately crumpled electrodes. Over-crumpling of the ITO thin-film electrodes neither helps. Over crumpling at 25% biaxial strain leads to an increased effective thickness with deepened creases in micro-folds (see Figure 2(d)). Hence, a DEA with 25% biaxially crumpled ITO thin-film electrodes produces less areal expansion than that produced by the DEA with 14.2% crumpled electrodes at the same driving voltage. The DEA with 25% crumpled electrodes produces at best 30% areal expansion at 7 kV, beyond which electrical breakdown and self-clearing happen but compromise the actuation performance.

In conclusion, we make ITO thin films stretchable and compliant by means of surface buckling on an adhesive elastomeric substrate. The bi-axially crumpled ITO thin films on adhesive elastomer can undergo cycles of compression and unfolding and survive a large compressive radial strain of up to 25% without observable fracture. Its transmittance decreases with compression, but restored upon unfolding. Dielectric elastomer actuators using the crumpled ITO thin-film electrodes demonstrate electrical unfolding and tunable transparency for repeated cycles. This electrical tunability of transparency promises to make a low-cost privacy glass if further optimized.

The authors would like to thank Soo Siong Pek of Micro-machine Laboratory, Nanyang Technological University for his help to perform e-beam evaporation. The first author would like to thank Joon Huang, Chiew Keat Lim, and Hengky Chang of Nanyang Polytechnic for their guidance on the use of characterization equipment.

- ¹S. G. Lee, D. Y. Lee, H. S. Lim, D. H. Lee, S. Lee, and K. Cho, "Switchable transparency and wetting of elastomeric smart windows," *Adv. Mater.* **22**(44), 5013–5017 (2010).
- ²D. van den Ende, J. D. Kamminga, A. Boersma, T. Andritsch, and P. G. Steeneken, "Voltage-controlled surface wrinkling of elastomeric coatings," *Adv. Mater.* **25**(25), 3438–3442 (2013).
- ³J. Zang, S. Ryu, N. Pugno, Q. Wang, Q. Tu, M. J. Buehler, and X. Zhao, "Multifunctionality and control of the crumpling and unfolding of large-area graphene," *Nat. Mater.* **12**(4), 321–325 (2013).
- ⁴C. Cao, H. F. Chan, J. Zang, K. W. Leong, and X. Zhao, "Harnessing localized ridges for high-aspect-ratio hierarchical patterns with dynamic tunability and multifunctionality," *Adv. Mater.* **26**(11), 1763–1770 (2014).
- ⁵P. S. Drzaic, "Polymer dispersed nematic liquid crystal for large area displays and light valves," *J. Appl. Phys.* **60**(6), 2142–2148 (1986).
- ⁶J. W. Doane, N. A. Vaz, B. G. Wu, and S. Zumer, "Field controlled light scattering from nematic microdroplets," *Appl. Phys. Lett.* **48**(4), 269–271 (1986).
- ⁷J. W. Doane, "Polymer-dispersed liquid crystals: Boojums at work," *MRS Bull.* **16**(01), 22–28 (1991).

- ⁸J. W. Doane, "PDLC shutters: Where has this technology gone?," *Liq. Cryst.* **33**(11–12), 1313–1314 (2006).
- ⁹S. Shian, R. M. Diebold, A. McNamara, and D. R. Clarke, "Highly compliant transparent electrodes," *Appl. Phys. Lett.* **101**(6), 061101 (2012).
- ¹⁰W. M. Choi, J. Song, D. Y. Khang, H. Jiang, Y. Y. Huang, and J. A. Rogers, "Biaxially stretchable "wavy" silicon nanomembranes," *Nano Lett.* **7**(6), 1655–1663 (2007).
- ¹¹K. Park, D. K. Lee, B. S. Kim, H. Jeon, N. E. Lee, D. Whang, and J. H. Ahn, "Stretchable, transparent zinc oxide thin film transistors," *Adv. Funct. Mater.* **20**(20), 3577–3582 (2010).
- ¹²J. Lewis, "Material challenge for flexible organic devices," *Mater. Today* **9**(4), 38–45 (2006).
- ¹³Z. Chen, B. Cotterell, W. Wang, E. Guenther, and S. J. Chua, "A mechanical assessment of flexible optoelectronic devices," *Thin Solid Films* **394**(1), 201–205 (2001).
- ¹⁴G. Kofod, P. Sommer-Larsen, R. Kornbluh, and R. Pelrine, "Actuation response of polyacrylate dielectric elastomers," *J. Intell. Mater. Syst. Struct.* **14**(12), 787–793 (2003).
- ¹⁵D. R. Cairns, R. P. Witte II, D. K. Sparacin, S. M. Sachsman, D. C. Paine, G. P. Crawford, and R. R. Newton, "Strain-dependent electrical resistance of tin-doped indium oxide on polymer substrates," *Appl. Phys. Lett.* **76**(11), 1425–1427 (2000).
- ¹⁶Y. Leterrier, L. Medico, F. Demarco, J. A. Manson, U. Betz, M. F. Escola, and F. Atamny, "Mechanical integrity of transparent conductive oxide films for flexible polymer-based displays," *Thin Solid Films* **460**(1), 156–166 (2004).
- ¹⁷P. Gutruf, C. M. Shah, S. Walia, H. Nili, A. S. Zoofakar, C. Karnutsch, K. Kalantar-zadeh, and M. Bhaskaran, "Transparent functional oxide stretchable electronics: Micro-tectonics enabled high strain electrodes," *NPG Asia Mater.* **5**(9), e62 (2013).
- ¹⁸X. Wang, H. Hu, Y. Shen, X. Zhou, and Z. Zheng, "Stretchable conductors with ultrahigh tensile strain and stable metallic conductance enabled by prestrained polyelectrolyte nanoplateforms," *Adv. Mater.* **23**(27), 3090–3094 (2011).
- ¹⁹S. H. Low and G. K. Lau, "The effect of folds in thin metal film electrodes used in dielectric elastomer actuators," *Proc. SPIE* **8687**, 86872P (2013).
- ²⁰S. Rosset and H. R. Shea, "Flexible and stretchable electrodes for dielectric elastomer actuators," *Appl. Phys. A* **110**(2), 281–307 (2013).
- ²¹S. H. Low and G. K. Lau, "Biaxially crumpled silver thin-film electrodes for dielectric elastomer actuators," *Smart Mater. Struct.* **23**, 125021 (2014).
- ²²M. Drack, I. Graz, T. Sekitani, T. Someya, M. Kaltenbrunner, and S. Bauer, "An imperceptible plastic electronic wrap," *Adv. Mater.* **27**(1), 34–40 (2015).
- ²³S. Timoshenko and S. Woinowsky-Krieger, *Theory of Plates and Shells* (McGraw-Hill, New York, 1959), Vol. 2, p. 120.
- ²⁴S. P. Timoshenko and J. M. Gere, *Theory of Elastic Stability* (McGraw-Hill, New York, 1961).
- ²⁵K. D. Kundra and S. Z. Ali, "Thermal expansion of In₂O₃," *J. Appl. Crystallogr.* **3**(6), 543–545 (1970).
- ²⁶Y. Shigesato, S. Takaki, and T. Haranou, "Crystallinity and electrical properties of tin-doped indium oxide films deposited by DC magnetron sputtering," *Appl. Surf. Sci.* **48**, 269–275 (1991).
- ²⁷W. F. Wu and B. S. Chiou, "Mechanical properties of rf magnetron sputtered indium tin oxide films," *Thin Solid Films* **293**(1), 244–250 (1997).
- ²⁸See <http://multimedia.3m.com/mws/media/981742O/vhb-tds.pdf> for 3M, VHB Tape: Technical Data. 3M, Apr. 2014. Web. 7 Nov. 2014.
- ²⁹N. Bowden, S. Brittain, A. G. Evans, J. W. Hutchinson, and G. M. Whitesides, "Spontaneous formation of ordered structures in thin films of metals supported on an elastomeric polymer," *Nature* **393**(6681), 146–149 (1998).
- ³⁰I. Hamberg, A. Hjortsberg, and C. G. Granqvist, "High quality transparent heat reflectors of reactively evaporated indium tin oxide," *Appl. Phys. Lett.* **40**(5), 362–364 (1982).
- ³¹J. George and C. S. Menon, "Electrical and optical properties of electron beam evaporated ITO thin films," *Surf. Coat. Technol.* **132**(1), 45–48 (2000).
- ³²S. E. Dyer, O. J. Gregory, P. S. Amons, and A. B. Slot, "Preparation and piezoresistive properties of reactively sputtered indium tin oxide thin films," *Thin Solid Films* **288**(1), 279–286 (1996).
- ³³G. K. Lau, J. F. L. Goosen, F. Van Keulen, P. J. French, and P. M. Sarro, "Actuated elastomers with rigid vertical electrodes," *J. Micromech. Microeng.* **16**(6), S35 (2006).
- ³⁴S. H. Low, L. L. Shiao, and G. K. Lau, "Large actuation and high dielectric strength in metallized dielectric elastomer actuators," *Appl. Phys. Lett.* **100**(18), 182901 (2012).