Elastic Instability Induced Mechano-Responsive Luminescence for Super-Flexible Strain Sensing

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***Abstract*—This paper reports a novel sensing strategy by employing elastic instability as a key mechanism to achieve super flexible (up to 60%) strain sensing. Inspired by Mechano-Responsive Luminescence (MRL) phenomenon, we have demonstrated this optical strain sensing strategy by employing PDMS based functional luminescence composites multi-thin-layer structure, where fluorescent pattern signal was generated at designed strain values. Line-shaped fluorescent patterns were switched ON and OFF by elastic instabilities (e.g. wrinkling, creasing) on micro-structural soft surfaces during compressive deformation. This has extended the current understanding of large strain sensing where creating electrical connection is challenged by the metal fracture and delamination. The control of switching strain values by micro-structural geometry design has been demonstrated and discussed.**

Keywords* — mechano-responsive luminescence, elastic instability, crease, strain sensing, stretchable

I. Introduction

Bendable and stretchable sensor and actuator technologies based on soft functional materials have become ever popular with emerging applications such as epidermal electronics, artificial skins, and soft robotics [1-4]. Conventional flexible electronics are bendable devices where the substrate has a reduced thicknesses, laminated with metal interconnects to reduce the strain change due to bending. For the emerging stretchable/super-flexible devices [1-4], substrate deformation strain could be much higher than the fracture strains of rigid materials during compressing and stretching. To avoid compromising local features such as metal interconnects and integrated transducers, different strategies have been developed, such as island-bridge and serpentine shaped interconnects [1, 5] and competing growth of elastic instabilities [4, 6].

This paper presents a concept in which large mechanical strain change (up to ~60% or 0.6) is transduced to optical signals switching by elastomeric substrates with micro-engineered materials and structural characteristics. Coupled by fluorescent light, the deforming super-flexible elastomer part of the sensing system is physically separated (Fig. 1) from the fixed rigid detector and signal processing part during operation.

For example, the rigid detection part (Fig. 1) could be integrated to a "close to body" device (e.g. wrist band), while the flexible Mechano-Responsive Luminescence (MRL) part could be mounted to deforming surfaces e.g. a skin patch. Since there is no metal interconnects on the deforming substrate, this development has shown an alternative solution to the challenges faced by stretchable/super-flexible sensor packaging, providing opportunities for future applications in tunable optics and stretchable electronics.

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II. Background

Optical strain sensors have long been developed, mainly in the form of fibre optics [7], although with a relatively low strain span (typically < 0.004 or 0.4%).

This paper presents an elastomer based super-flexible (up to 0.6) optical-strain signal transformation mechanism, utilizing Mechano-Responsive Luminescence (MRL).

A. Mechano-Responsive Luminescence

The term of MRL is getting more researched in recent years, and used to describe a reversible change in photophysical properties such as luminescence color, intensity, pattern or lifetime by mechanical stimulation e.g. expansion, compression and twisting [8, 9].

Examples can be found, such as using the mechanical force to change the arrangement of luminescent molecular which can lead to the optical switching response [8, 9]. Such properties could potentially be facilitated for sensing applications integrated with optical detection systems, such as photo-diodes, fluorescence microscopes (e.g. laser scanning confocal microscope (LSCM), fluorescence lifetime imaging (FLIM)), fluorescence scanners and devices with image sensors (e.g. mobile phones, sports smart wristbands).

B. Elastic Instability Growth on Bi-layer Elastomers

Elastic instabilities such as surface creases play a crucial role in many natural and engineering systems [4, 10]. Recently, super-flexible strain sensing with step-wise electrical signals has been achieved by utilizing elastic instabilities generated on micro-engineered elastomer bi-layers [4, 6].

Such configuration usually consists of multi-layers of elastomer thin films with different Young's Modulus, e.g. a softer Polydimethylsiloxane (PDMS) layer on top of a spre-stretched Vinylpolysiloxane (VPS) layer with higher modulus [4, 6]. By relaxing the pre-stretched VPS layer from a length of L_0 to a reduced lenghth L, the PDMS top layer is compressed controllably [4, 6]. Hence, the elastic instabilities e.g. surface creases would be created subject to the uniaxial compression strain, given by:

$$\varepsilon = (L_0-L)/L_0 \qquad (1)$$

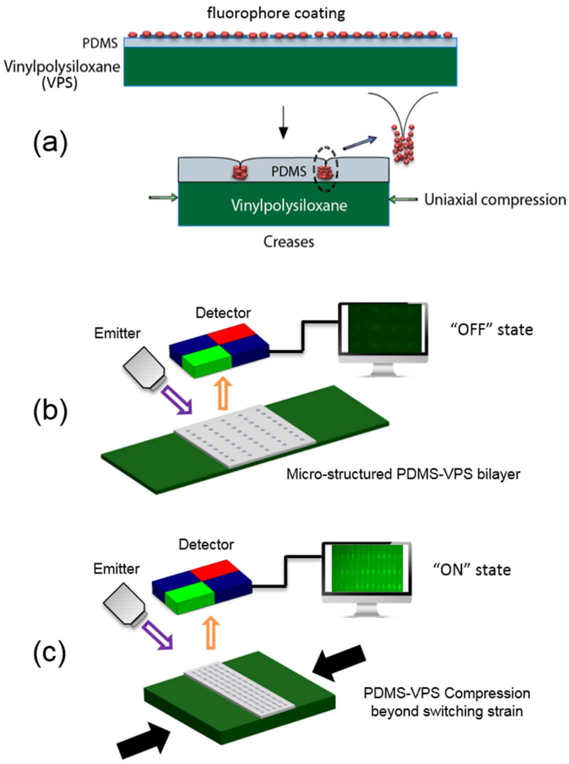

Fig. 1. (a) Cross-section view of the PDMS-VPS bi-layer structure coated with fluorophore (dots). Fluorophore concentration effect can be seen after surface creases generated by uniaxial compression. (b) and (c) The proposed sensing mechanism: optical signal generated by fluorophore-PDMS-VPS is detected by the rigid part of the sensor system giving ON/OFF digital outputs.

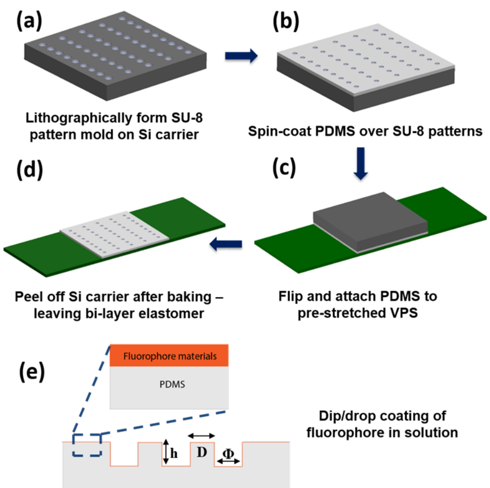

Fig. 2. 3D (a to d) and cross-sectional (e) views of the device fabrication process: (a) lithographically patterned SU-8 on silicon carrier wafer; (b) PDMS spin-coating over SU-8 patterns; (c) flip the silicon carrier and attach PDMS to pre-streched VPS; (d) Peel off silicon/SU-8 after baking, leaving patterned PDMS on VPS; (e) dip/drop coating of fluorophore (fluorescein o-acrylate) on top of plasma treated PDMS surface.

III. Methodology

A. *Surface Creasing Induced MRL for Strain Sensing:*

Fig. 1a shows the set-up of PDMS on pre-stretched VPS bi-layer described in previous section. The fluorophore coating on PDMS surface will be physically concentrated and show high-contrast fluorescence pattern when surface creases generated by uniaxial compression (fig. 1a). And we propose to utilize this surface instability induced MRL effect for strain sensing applications. Fig. 1b and 1c show the proposed optical switch strain sensing mechanism based on MRL:

- **Fabrication:** Micro-structured elastomer bilayer MRL device monitored by fluorescence detector.
- **Surface creasing pattern generation:** Uniaxial compressive generates surface creasing at the surface micro structures (an array of holes in this case)
- **Fluorescent pattern generation:** Surface creasing pattern creates line-shaped fluorescent patterns
- **Signal processing:** The detected signal is then processed, outputting "ON/OFF" status.

B. *Fabrication of Patterned Elastomer Bi-layer*

Fig. 2 shows the fabrication process of patterned elastomer bi-layer by using SU-8/Si dry peel-off soft lithography technology. Different thicknesses of SU-8 photoresist was spin-coated and lithographically patterned on silicon carrier wafer (fig. 2a). PDMS (Sylgard 184^{TM} kit) mixture with 30:1 base to curing agent ratio was then spin-coated over SU-8 patterns (fig. 2b). The PDMS coated silicon carrier was then flipped and attach to pre-streched VPS to form a VPS-PDMS bond (fig. 2c). After baking at 70°C for 8 hours, the silicon/SU-8 carrier mold was peeled off, leaving patterned PDMS on VPS (fig. 2d). After a 30 sec oxygen plasma treatment, the PDMS surface was then coated with fluorescein o-acrylate (Sigma Aldrich®) (fig. 2e).

The patterned PDMS surfaces consist of arrays of circular holes with different diameters Φ, pitches $r = D/\Phi$ and depths h (fig. 2e), by designing SU-8 mold dimensions and thicknesses.

IV. Results and Discussion

A. *Surface Creasing Pattern Generation*

The arrays of circular holes on PDMS surface control surface creasing patterns during uniaxial compression, by concentrating the local energy. Thus, surface creases are expected to form along the column of holes perpendicular to the compression axis.

Fig. 3 shows the surface instability growth on hole patterned PDMS surface, during the uniaxial compression of the pre-stretched VPS. When substrate strain $\varepsilon=0$ (fig. 3a), there is only hole array geometry on the PDMS surface. When the uniaxial compression (fig. 3b, horizontal direction) initiates (e.g., a small $\varepsilon=0.13$), the surface instabilities start to grow at or near the hole patterns. After the compression strain goes beyond a critical point (in this case $\varepsilon=0.515$ *or 51.5%*), large creases perpendicular to the compression axial start to form along the column of holes (fig. 3c).

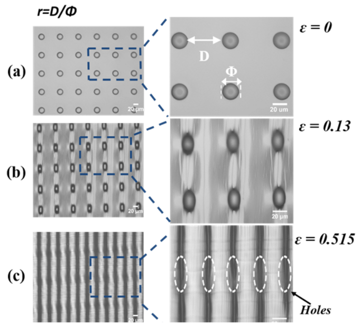

Fig. 3. Microscopic view of hole-patterned PDMS surface during uniaxial compression (horizontal direction), with D=20µm, r=3 and h=13µm at different strains: (a) ε=0; (b) ε=0.13; (c) ε=0.515.

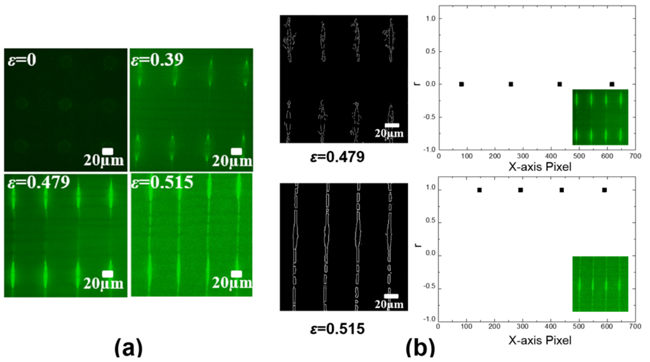

Fig. 4. (a) Fluorescent patterns on patterned PDMS surface under uniaxial compression at different strain values. (b) Fluoresecence image signal processing to determine whether line pattern is formed: (left) Canny edge detection; (right) Hough conversion.

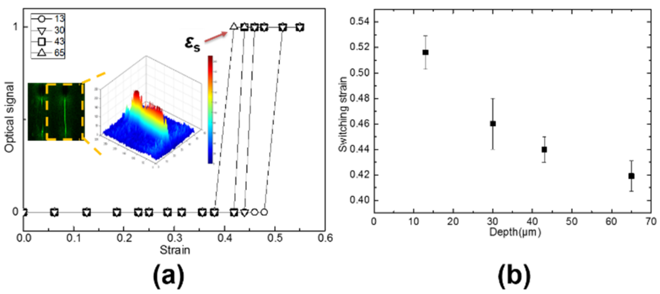

Fig. 5. Relationship between (a) strain ε and output signal switches from 0 to 1, (b) switching strain ε and hole depth h, representing the formation of fluorescence line pattern.

B. Fluorescent Pattern Generation

To observe the fluorescence signals, a Leica® DMR fluorescence microscope has been used initially. Fig. 4a shows the fluorescent patterns generated by the surface creases during uni-axial (horizontal direction) substrate compression at different strain values. The line patterns along the holes start to form after a compression strain of 0.515 (51.5%).

C. Signal Processing

The ON/OFF (or 0/1 output) switching strain has been defined to be the value at fluorescent line pattern forming. To automatically determine whether fluorescent line patterns have been formed (logic “1”), we: (1) used the Canny edge detection (2) Mapping of edge points to the Hough space in an accumulator (r, theta), followed by infinite line conversion to finite lines (min. length set to 200 pixels). Hence a detected line longer than 200 px. will return a logic “1” as in Fig. 4b.

D. Hole Depth vs. Switching Strain

Fig. 5 shows the relationship between hole depth h and switching strain ε_s. For different hole geometries, the output signal changes from 0 to 1 when substrate strain increases beyond the switching strain ε_s (Fig. 5a). Fig. 5b indicates a trend of increased switching strain ε_s.

Fig. 5b shows that the switching strain ε_s value increases from 0.410 to 0.515, with reduced hole depth from 65 µm to 13 µm respectively. This suggests the switching strain value could be controlled by micro-structure geometry design, giving the opportunity to develop future MRL strain sensors with multiple switching strain values.

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REFERENCES

[1] D.-H. Kim, et al., “Epidermal Electronics”, Science, Vol. 333, pp. 838-843, 2011.

[2] W. Wu , X. Wen , and Z. L. Wang , “Taxel-Addressable Matrix of Vertical-Nanowire Piezotronic Transistors for Active and Adaptive Tactile Imaging”, Science, Vol. 340 , pp. 952-957, 2013.

[3] Y. Su, et al., “In-Plane Deformation Mechanics for Highly Stretchable Electronics”, Advanced Materials, Vol. 29, pp. 1604989, 2017.

[4] B.B. Xu , D. Chen , and R. C. Hayward, “Mechanically Gated Electrical Switches by Creasing of Patterned Metal/Elastomer Bilayer Films”, Advanced Materials, Vol. 26, pp. 4381-4385, 2014.

[5] Y. Zhang, et al., “Buckling in serpentine microstructures and applications in elastomer-supported ultra-stretchable electronics with high areal coverage”, Soft Matter., Vol. 33, pp. 8062-8070, 2013.

[6] C. Wang, B. Xu, J. G. Terry, S. Smith, A. J. Walton and Y. Li, “Test Structures for Stepwise Deformation Sensing on Super-flexible Strain Sensors”, IEEE ICMTS, Grenoble, France, pp. 150-155, 2017.

[7] R. Maaskant, T. Alavie, R. M. Measures, G. Tadros, S. H. Rizkalla, A. Guaha-Thakurta, “Fiber-optic Bragg grating sensors for bridge monitoring”, Cement and Concrete Composites, Vol. 19, pp. 21-33, 1997.

[8] Y. Sagara, S. Yamane, M. Mitani , C. Weder, and T. Kato, “Mechanoresponsive Luminescent Molecular Assemblies: An Emerging Class of Materials”, Adv. Mater., Vol. 28, pp. 1073–1095, 2016.

[9] S. M. Jeong, S. K. Song, H. Kim, K. I. Joo, and H. Takezoe, “Mechanoluminescence Color Conversion by Spontaneous Fluorescent-Dye-Diffusion in Elastomeric Zinc Sulfide Composite”, Adv. Funct. Mater. Vol. 26, pp. 4848-4858, 2016.

[10] A. Auguste, L. Jin, Z. Suo and R. C. Hayward, “Post-wrinkle bifurcations in elastic bilayers with modest contrast in modulus”, Extreme Mechanics Letters, Vol. 11, pp. 30-36, 2017.