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Metal-Elastomer Surface Deformation Control on Super-Compressible Strain Transducer Arrays

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Abstract— This paper reports the metal-elastomer surface deformation control strategy of a strain transducer array capable of measuring compressive strains up to 60%. Pairs of multi-finger electrodes separated by different inter-digit gap distances are forced into contact by induced surface creasing deformation at different strains. Test structures have been developed to explore and optimize the electrode-elastomer hybrid surface deformation. The deformation is due to large compressive strains in the “x-direction” but stretching caused by the Poisson effect can also take place in the “y-direction”.

Keywords—elastomer, elastic instability, wrinkle, crease, strain sensing, test structure, stretchable electronics

I. INTRODUCTION AND METHODOLOGY

A. Introduction

In the growing field of flexible electronics, devices are subjected to stretching, bending and twisting forces [1-7]. Elastomer substrates can also be compressed, during which surface elastic instabilities will occur, such as wrinkles and creases, which provide potential opportunities in engineering applications [3,7-10].

Initial studies on super-compressible strain gated switches and their applications, have reported a surface creasing induced resistance change in response to mechanical inputs of up to 60% strain [3, 7]. The energy absorbing elastic instabilities (wrinkles and creases) on metal-elastomer surfaces helped to prevent metal electrode damage while providing the sensing mechanism. However, due to the large Poisson’s ratio of the elastomer substrates (close to 50%), the electrodes are also stretched along the y-direction (Fig. 1a), causing unwanted damage.

To understand how to design the metal finger electrode array and interconnects, such that they can survive both large compression as well as stretching caused by Poisson’s effect, requires investigation to determine how Au-PDMS (polydimethyl-siloxane) surfaces deform.

B. Methodology

In situations where Au electrodes cover an area of the PDMS, an “island-bridge” type of flexible device results. The much stiffer Au (Young’s Modulus 50-70 GPa) tends to deform less than the underlying PDMS (0.4 - 4 MPa) when both are subjected to the same substrate compression strain. This has caused creases to be generated on some PDMS surfaces “squeezed” between Au electrodes at a substrate strain < 10%, which is significantly lower than typical creasing strains of around 50% on a plain PDMS surface.

To investigate, Au finger electrode test structures (Fig. 1a) with different thicknesses (16nm - 100nm) were fabricated by patterning electrodes on a silicon carrier wafer, and subsequently transferring them onto PDMS surfaces, supported on pre-stretched VPS (Vinyl-polysiloxane) elastomer substrates (Fig. 1b). Transfer was achieved using a self-assembly thiol based dry-peel-off soft lithography method optimised after [3, 7].

Figure 1c shows the schematics of Au-PDMS surface deformation process under substrate compression. The creasing on PDMS elastomer surface results in Au finger electrode tips coming into contact (resistance step change [3, 7]), with wrinkles on the Au helping to absorb the deformation energy. The 2D geometry deformation (measured while viewing from above) can be measured as a change in either:

- Au finger electrode length L_f and width W_f (fig. 1a)
- or, PDMS surface length between opposite Au finger electrode tips L_g , and the adjacent finger spacing, W_g (fig. 1a)

To investigate the parameter space, a range of finger electrode array devices were fabricated and tested in parallel. Finger length was varied from the longest at 525 μm (F4 in figure 1a) to the shortest at 240 μm (F1), with L_g ranging between 5 and 100 μm , and W_g from 100 to 200 μm .

In an attempt to prevent Poisson's effect related damage, serpentine shaped Au interconnects have been designed to "bridge" connect finger electrodes "islands" across the PDMS spacing W_g in some devices, as shown in Fig 1c inset.

II. EXPERIMENTS AND RESULTS SUMMARY

A. Au-PDMS 2D geometry change under compression

By applying substrate compression through releasing pre-stretched VPS mounting layer [7], differences have been observed in the deformation strain of both the Au finger electrode and PDMS along x (ϵ_{Au-x} , ϵ_{PDMS-x}), and y-direction (ϵ_{Au-y} , ϵ_{PDMS-y}), where:

$$\epsilon_{Au-x} = (L_{f0} - L_f) / L_{f0} \quad (1); \quad \epsilon_{Au-y} = (W_{f0} - W_f) / W_{f0} \quad (2);$$

$$\epsilon_{PDMS-x} = (L_{g0} - L_g) / L_{g0} \quad (3); \quad \epsilon_{PDMS-y} = (W_{g0} - W_g) / W_{g0} \quad (4);$$

The 2D geometry dimension changes have been observed and measured by both Nikon LV100 optical system and Atomic Force Microscope (Fig. 2) at different substrate strains. Fig. 3 shows selected results of PDMS deformation in the gap (L_g) between two finger electrodes ϵ_{PDMS-x} , which are consistently \gg substrate strain (dashed line). The electrode gap strain of 1.0 in these plots indicates the contact of two Au finger tips brought by the formation of surface creases.

B. 3D geometry deformation under compression

The 3D profile of the electrode deformation was primarily measured by AFM (Fig. 2 and 4, Bruker™ 3100). Fig. 4 shows the 3D geometry of the progressive wrinkling of an Au electrode characterised from substrate strain. The wrinkling instability is seen to begin at a substrate strain of 0.009, whereas the theoretical value for Au on PDMS is calculated to be 6.7×10^{-4} . This discrepancy is not a surprise, as 2D geometry observations confirm that Au deformation lags significantly behind that of the substrate.

C. Poisson's Effect and Result Summary

Figure 5 shows the y-direction stretching which affects the Au electrodes, serpentine interconnects and PDMS areas as a result of the Poisson's effect. The y-direction stretching strain of Au and PDMS are measured to be $\epsilon_{Au-y} = 8.7\%$ and $\epsilon_{PDMS-y} = 37.1\%$, under a substrate compression of 33% and a Poisson's ratio of 42% (strain dependant).

III. CONCLUSIONS

Test structures have been developed to characterize the metal-elastomer deformation behaviour of a super-compressible strain transducer array under compression up to 60%. This initial study has been focused on the relationship between electrode geometries and compression strain ratios, with the growth and co-existence of wrinkles and creases on multi-switching electrodes being characterised for the first time. Future work will focus on fully characterising the mechano-responsive electrical switching mechanism of the designed sensors.

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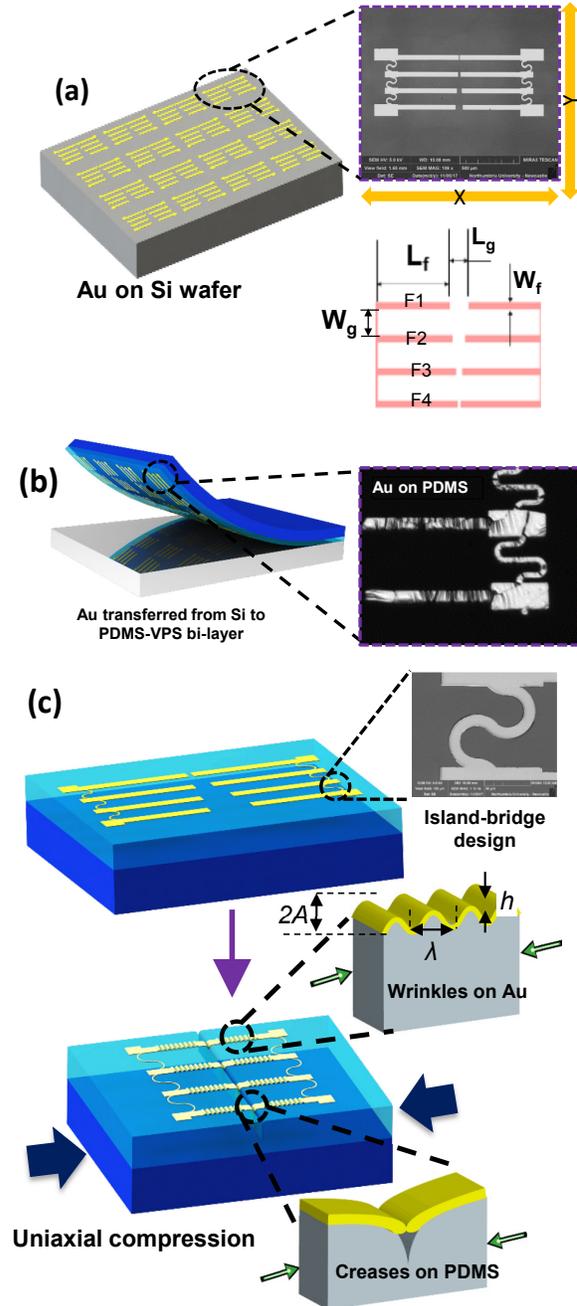


Figure 1. (a) Patterned Au strain transducer test structures on a silicon wafer with a top SEM view and the finger electrode design dimensions (top view); (b) Au transferred to PDMS-VPS bi-layer (inset photo by Nikon microscope) (c) Schematic view of the Au-PDMS 3D deformation process under uniaxial substrate compression.

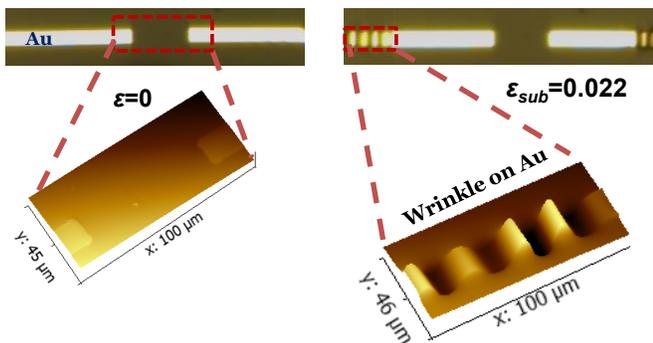


Figure 2. AFM image showing Au 3D deformation initialization under uniaxial substrate compression (0% and 2.2% strains).

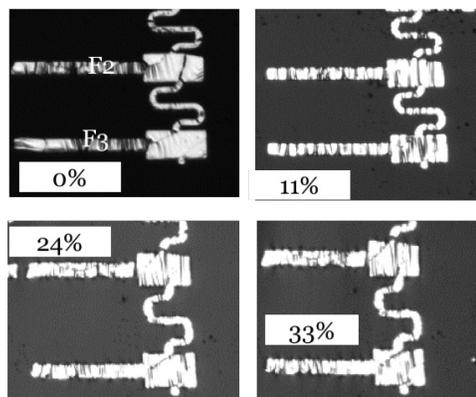


Figure 5. Y-direction stretching (Poisson's Effect) of PDMS and Au under various x-direction compression strains

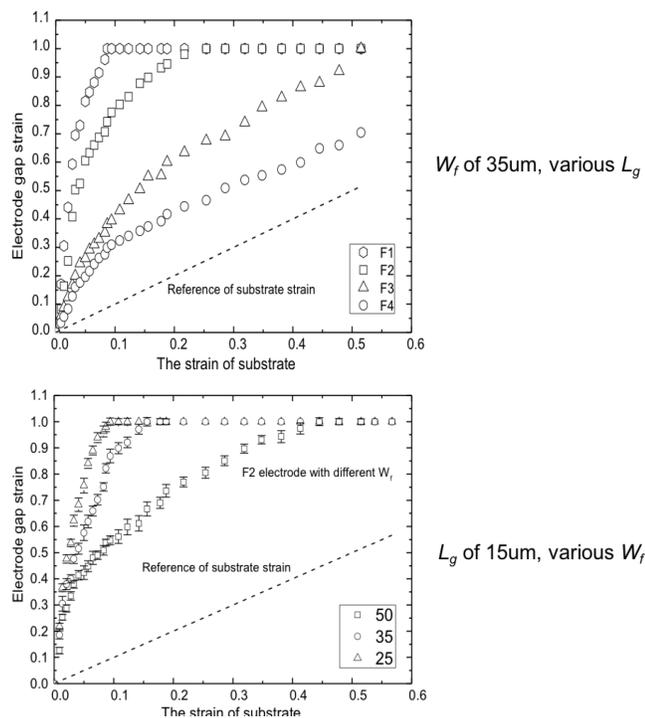


Figure 3. Electrode gap PDMS strain ϵ_{PDMS-x} vs. applied substrate strain (from 0 to 60%) with different Au electrode geometry designs

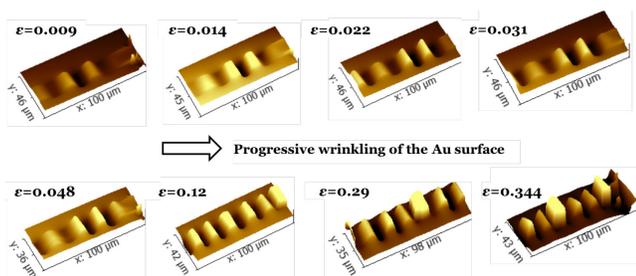


Figure 4. AFM profile of wrinkle development on Au electrode at various substrate strains