Fully Elastic Interconnects on Nanopatterned Elastomeric Substrates

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***Abstract*—Elastically stretchable metal interconnects are required for electronic skin. To date, the resistance of such thin-film interconnects has been found to increase much more with mechanical strain than expected from purely geometrical deformation of the conductor. It has been discovered that the resistance change due to fully elastic deformation is minimal when the metal films are deposited on pyramidal nanopatterned surfaces. The nanopattern constrains the film to purely elastic deformation by localizing the microcracks that are formed in the conductor during stretching. Between 0% and 25% mechanical strain, the electrical resistance increases by only 60%, which is in close agreement with purely geometric deformation.**

***Index Terms*—Flexible structures, nanotechnology, silicone rubber, thin-film circuit interconnections.**

I. INTRODUCTION

STRETCHABLE metal interconnects on elastomeric substrates are a new area of research in thin-film electronics. Such interconnects have the ability to sustain large mechanical strain once or many times [1], [2]. Their use in electronic skin [3], retina-shaped photosensor arrays [4], electronic muscles [5], and mechanically matched bioelectrodes [6] calls for reliability and predictability of their electromechanical behavior. Earlier, we had found that gold conductors on an elastomeric substrate may spontaneously form random Y-shaped micrometer-sized cracks [1], [2]. The films retain this microstructure upon stretching to high strains while maintaining electrical conductance. We have tested such conductors up to 60% strain and 1000 stretching cycles. The presence of microcracks allows the metal to elastically deform by deflecting and twisting out of plane, thereby minimizing the strain at the crack tips. The cracks widen during stretching and close during relaxation, thus imparting reversible stretchability [2]. However, these conductors with spontaneously formed microcracks have two drawbacks. One, it has not been possible to control the conditions that produce the microcracks. Two, the lengthening and shrinking of the microcracks raises and reduces the electrical resistance by much more than if the deformation were purely elastic. This is evident from Fig. 1, where the “no-pattern” trace corresponds to the conductor just described [2], and the bottom trace to a conductor calculated to exhibit a purely geometric change in electrical resistance.

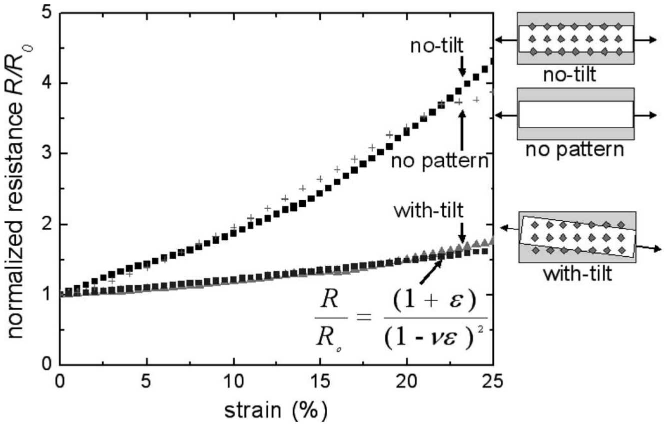

Fig. 1. Normalized electrical resistance R/R_0 curves of elastically stretchable gold conductors as a function of applied strain. Top to bottom: Patterned substrate without tilt, nonpatterned substrate, patterned substrate with tilt, and calculated purely geometric variation. Arrows in the schematic sample structures at the right denote the direction of stretching.

The minimum possible variation in the resistance of a metallic conductor with mechanical strain occurs when it undergoes purely elastic deformation. Consider the uniaxial elastic stretching along its length of a metal conductor from initial dimensions $\ell_o \times w_o \times h_o$ to final dimensions $\ell \times w \times h$. The symbols stand for length, width, and thickness. The strain along the length is defined as $\varepsilon_\ell \equiv (\ell - \ell_o)/\ell_o$, so that $\ell = \ell_o(1+\varepsilon_\ell)$. With a Poisson ratio of ν, $w = w_o(1 - \nu \cdot \varepsilon_\ell)$, and $h = h_o(1 - \nu \cdot \varepsilon_\ell)$. The initial value of resistance R_0 of the conductor is given by

$$R_0 = \rho \left(\frac{\ell_o}{h_o \times w_o} \right) \tag{1}$$

where ρ is its resistivity. The value of the resistance after stretching to length ℓ is given by

$$R = \rho \left(\frac{\ell}{h \times w} \right). \tag{2}$$

Therefore, the resistance R of the stretched conductor in terms of initial resistance, strain, and Poisson ratio is given by

$$R = R_o \frac{(1+\varepsilon_\ell)}{(1-\nu\varepsilon_\ell)^2}. \tag{3}$$

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This geometric variation of the resistance with ε_ℓ represents the smallest variation in resistance that can be achieved when a metal conductor is stretched. This is our target for elastic interconnects. Here, we report that we have discovered that this purely geometric change of the elastic-interconnect resistance can be induced by nanostructuring the substrate's surface.

II. METHODS

We made a two-dimensional (2-D) array of nanosized pyramids of 250-nm height and 1-μm period on the surface of the elastomeric substrate and deposited the thin metal film on top of the patterned elastomer. The surface of the elastomeric substrate was patterned by casting the precursor mixture onto a nanopatterned crystalline silicon-wafer mould. The pitch of the pyramidal array was set to 1 μm to be equal to the typical initial length of microcracks on a nonpatterned substrate [2].

The mould was fabricated in a (100) Si wafer by nanoimprinting and anisotropic wet etching. A 70-nm-thick layer of silicon dioxide grown on the wafer by thermal oxidation was patterned with a 2-D array of square grooves with a rhombic unit cell (83° angle) by imprint lithography and wet etching. Then, the patterned oxide layer was used as the etch mask for an anisotropic wet etching of the silicon wafer in a heated etchant containing 250-g KOH, 800-mL deionized water, and 200-mL isopropyl alcohol. At 70 °C, the etchant was measured to have anisotropic etch rates of $\sim$ 400 nm/min along the $\langle 100 \rangle$ direction and $\sim$ 17 nm/min along the $\langle 111 \rangle$ direction. The etching formed an array of inverted pyramids in the (100) Si substrate. The silicon-oxide mask was removed in HF solution. The fabricated Si-wafer mould was coated with a self-assembled monolayer (SAM) of 1H,1H,2H,2H-perfluoro-octyl trichlorosilane (FOTS) to prevent the elastomer from sticking. Fig. 2(a) shows a sketch of the mould coated with SAM. On top of this mould, 0.5-mm-thick polydimethylsiloxane (PDMS) elastomeric substrates were cast, as shown in Fig. 2(b). The precursor silicon gel (Sylgard 184 from Dow Corning) was mixed with a cross-linking agent in 10 : 1 weight ratio and then cured at 60 °C for about 48 h. The PDMS membrane substrate was then peeled off the Si wafer. It is covered with a rhombic array of nanosized pyramidal hillocks as illustrated by the sketch of Fig. 2(c) and the scanning electron micrograph of Fig. 3. The pyramids have a base of 500 nm × 500 nm, a height of 250 nm, and a pitch of $\sim$ 1 μm.

Thin-film gold stripes were deposited on the nanopatterned PDMS using electron beam evaporation in a Denton/DV-502A evaporator. For adhesion 5 nm of chromium was deposited, followed by 25 nm of gold. Polyimide shadow masks defined the area of the gold stripes. The metal stripes were 1.1- to 1.9-cm long and 380- to 910-μm wide. The stripes were deposited in two different orientations with respect to the array of nanopyramids. In "no-tilt" samples, the length of the stripe runs along a direction of translation of the rhombic unit cell of pyramids. Such a sample is sketched in Fig. 2(d). In "with-tilt" samples, the length of the stripe was kept at an angle with respect to the directions of translation. The two alignments are shown superposed on the scanning electron microscope (SEM) micrograph of Fig. 3.

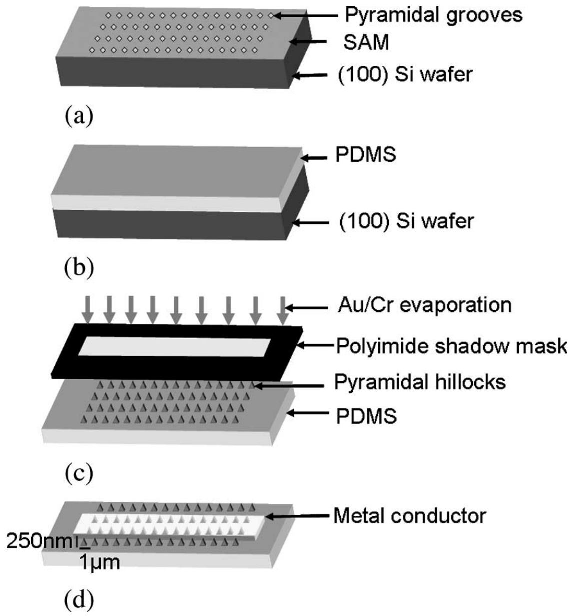

Fig. 2. Schematic sketches of steps in sample preparation. (a) SAM coated (100) Si-wafer mould containing a rhombic array of pyramidal grooves. (b) PDMS membrane substrate cast on the mould. (c) Patterned PDMS substrate is coated with 5 nm of Cr and 25 nm of Au through a shadow mask. (d) Gold conductor on patterned PDMS (no-tilt sample).

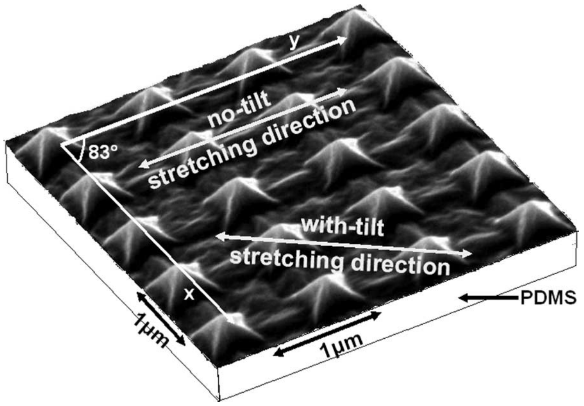

Fig. 3. SEM micrograph of PDMS with pyramidal hillocks with overlay inscriptions that depict the orientations of the metal conductor with respect to the pyramidal array in "no-tilt" and "with-tilt" samples. The pyramids are 250-nm high and are spaced at a pitch of $\sim$ 1 μm. The "with-tilt" angle is $\sim$ 30°.

An inspection with an optical microscope and an SEM (Philips XL30 FEG) revealed a continuous deposit of gold over the PDMS surface, as shown in Fig. 4. The films did not have any initial built-in structure of microcracks as is found on nonpatterned PDMS substrates [2]. The electrical resistivity calculated from resistance R_0 and nominal dimensions for various samples ranged from 1.5×10^{-5} to 8×10^{-5} $\Omega \cdot$ cm. The resistivity for 30-nm-thick gold films on glass is about 7×10^{-6} $\Omega \cdot$ cm [7]. We speculate that the resistivity on PDMS is increased by surface scattering in the films, which conform to the substrate roughness that is visible in atomic-force micrographs [8], and possibly by contamination from the silicone.

Individual conductors were stretched uniaxially along the length of the metal stripe using a custom-made microtensile

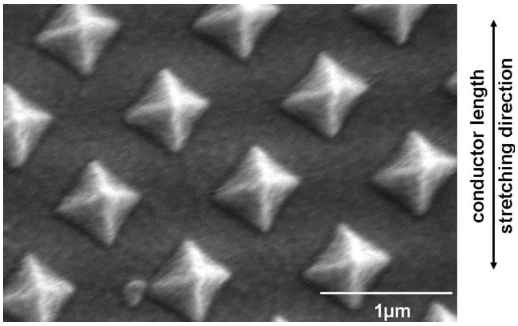

Fig. 4. SEM micrograph of as deposited gold conductor on nanopatterned PDMS substrate in a sample "with-tilt." The surface of the gold film is microscopically smooth and contains no visible cracks.

stretcher consisting of a strain tester, clamps for the sample, leads for *in situ* resistance measurements, and a microscope equipped with a charge-coupled-device (CCD) camera [9]. In this way, "no-tilt" samples were stretched parallel to a translation vector of the pyramidal lattice and "with-tilt" samples at an angle to it. The samples were stretched in increments of 0.5% every 90 s. Electrical resistance and mechanical force values were recorded every 15 s. Electrical contacts were of gold wires set in conducting epoxy paste. The normalized electrical resistance (R/R_o) was plotted in function of the applied strain.

III. RESULTS AND DISCUSSION

The results obtained from the uniaxial stretching were astonishing (Fig. 1). The electrical resistance of "with-tilt" conductors followed very nearly the geometric function calculated from (3) with $\nu = 0.42$ during both stretching and relaxation. On the other hand, the change in the resistance of the "no-tilt" conductors was nearly identical to that of the "no pattern" conductors made on nonstructured substrates [2].

In the present experiments, no cracks are observed by SEM in samples immediately after deposition. The cracks only form during the initial stretching. But in "with-tilt" conductors on patterned surfaces, the cracks remain localized and do not propagate. These "with-tilt" conductors stretch purely elastically, which is reflected in the small change in resistance with the application of mechanical strain. In the "no-tilt" samples, the cracks also form during the beginning of stretching but then continue to grow over the length of many unit cells while the sample is stretched. The electrical resistance of these "no-tilt" conductors varies with strain just like that of the earlier samples made on nonpatterned surfaces.

IV. CONCLUSION

Thin gold film conductors on top of nanopatterned (2-D pyramid array) elastomeric PDMS substrates retain their conductance during stretching and relaxation. Films made on flat nonpatterned substrates contain microcracks that accommodate the stretching by lengthening and shrinking reversibly. Their electrical resistance increases and decreases by much more than predicted from purely elastic deformation. When the gold thin film conductors are made and oriented properly on elastomeric substrates with periodic surface topography on the submicrometer scale, their resistance changes upon straining following a purely geometrical model. It is likely that randomly structured substrates will induce this characteristic along any direction of conductor orientation and stretching. Such conductors, with the minimally possible change of resistance along any direction of stretching, will meet a key requirement for interconnects in electronic skin.

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