Design and Performance of Thin Metal Film Interconnects for Skin-Like Electronic Circuits

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***Abstract*—We prepare stretchable electrical conductors of 25-nm-thick gold films on elastomeric substrates prestretched by 15%. When the substrates relax from the prestretch, the gold stripes form surface waves with ~8.4-μm wavelength and ~1.2-μm amplitude. When the strain is cycled between 0 and 15%, both the wave pattern and the electrical resistance of the gold stripes change in reproducible cycles. Such repeatedly stretchable metallization can serve as interconnects for skin-like, conformal, and electroactive polymer circuits.**

***Index Terms*—Flexible structures, metallization, silicone rubber, strip conductors.**

I. Introduction

SENSITIVE skins for robotics and medical devices [1], conformal displays [2], and electroactive polymers [3] require electrical interconnects that can sustain large and reversible stretching. Here, we show that stripes of gold, deposited on a prestretched elastomeric substrate, retain low electrical resistance over many cycles of stretching. Such repeatedly stretchable thin-film stripes can be used as interconnects between rigid subcircuit islands [2]. Both stretchable interconnects and rigid subcircuit islands will be essential components for the integration of skin-like circuits.

Complex wave patterns of thin metal film on compliant substrates have attracted considerable attention recently [4]–[9]. Compressive stress that may develop in the metal film during its deposition on elastomeric substrates is released by random buckling [4] or waves [5], [6]. Wavy gold films on polydimethylsiloxane (PDMS) membranes can be stretched far more than free-standing gold films, yet remain electrically conducting [6], [7]. Stretchability can be improved when thin film coatings are deposited on prestretched rubber-like substrates [8], [9]. Watanabe *et al.* achieved high electrical resistance compliant electrodes for electroactive polymer actuators from polypyrrole films deposited on elongated polyurethane elastomer [9]. Here, we report that we have succeeded in making the first stretchable metallization with low electrical resistance, for application as elastic electrical interconnects.

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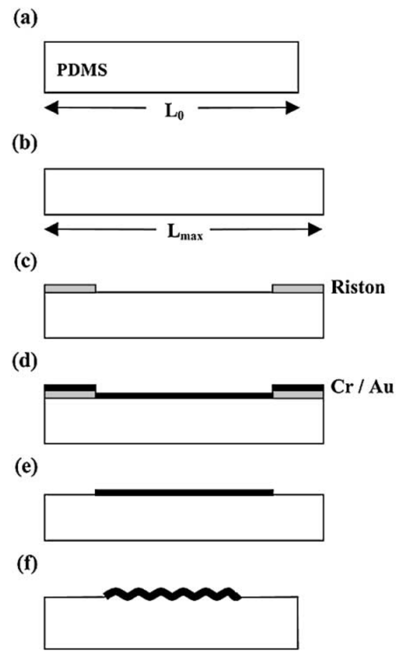

Fig. 1. Fabrication of gold interconnects on an elastomeric PDMS substrate. (a) As-prepared PDMS substrate. (b) Prestretched PDMS. (c) Laminated Riston photoresistt mask. (d) Evaporated metal films. (e) Lift-off. (f) Release from prestretch: the gold stripe buckles.

II. Experiments

Fig. 1 summarizes our fabrication process. The substrate is a 1-mm-thick membrane of PDMS (Dow Corning, Sylgard 184). The substrate length is L_0 when relaxed [Fig. 1(a)], and $L_{\max}$ when stretched [Fig. 1(b)]. A homemade fixture holds the substrate to a prestretch strain $(L_{\max} - L_0)/L_0$, between 10% to 20% [10]. Stripes are patterned on the substrate by liftoff using Dupont Riston photoresist. The UV-exposed and developed Riston film is laminated onto the prestretched PDMS membrane prior to metal evaporation [Fig. 1(c)]. Subsequently, a 5-nm-thick chromium adhesion layer and a 25-nm-thick gold layer are electronbeam evaporated on the PDMS substrate [Fig. 1(d)]. The Riston is stripped in a potassium hydroxide (KOH) solution [Fig. 1(e)]. When the PDMS substrate is released from its holder, the metal stripes and the surface of the silicone substrate buckle together [Fig. 1(f)]. Scanning electron microscopy (SEM) contrast shows that the metal films and the PDMS substrate are bonded (rather than detached) after release from the prestretched strain [10].

Before release from an elongation of 15%, the Au stripes are 500 μm wide and 4.6 mm long. Their electromechanical properties are evaluated in a homemade tensile tester [11]. We measure the electrical resistance with a Keithley 4140 source-meter, the

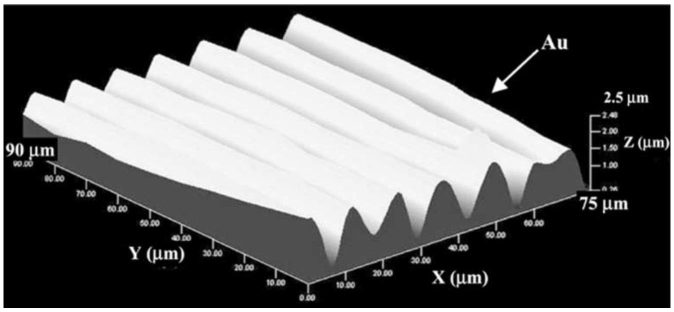

Fig. 2. Three-dimensional profile of a Au surface wave after release from 15% prestretch.

elongation with the stepper motor position, the surface topography with a DuncanTech DT1100-PLUS charge-coupled device (CCD) camera microscope, and the force with a load cell.

III. Results and Discussion

A. Initial Topography and Electrical Resistance

Fig. 2 shows the three-dimensional profile of a gold film after the substrate is released. The film was continuous, and formed a wave in the prestretch direction *X*. The wavelength was $\lambda \approx 8.4$ μm and the amplitude A ≈ 1.2 μm. The built-in strain ε_0 calculated from the length of the sine wave trace λ_{trace} as $\varepsilon_0 = (\lambda_{\mathrm{trace}} - \lambda)/\lambda$ [12] was ~10.5%. ε_0 was smaller than the design prestretch, $(L_{\max} - L_0)/L_0$ of 15%. We ascribe the difference between design and actual strain to film–substrate interactions that we had observed earlier [4], [10], [11], but do not yet understand.

The electrical resistance of a 25-nm-thick gold stripe evaporated on glass is 7.5 Ω. We have observed the resistances of a dozen samples to vary between this on-glass value and several megaohms [10]. The electrical resistance of the Au conductor decreases by ~30% from prestretched to relaxed state.

B. Electrical Resistance Under Mechanical Deformation

The initial test is stretching to electrical failure. We raised the applied strain in steps of 0.5% every 30 s. The electrical resistance was recorded every 2 s and photographs were taken. Fig. 3 presents the electrical resistance of one sample as a function of the applied strain, and photographs at 1, 15, and 28% tensile strain.

Upon substrate release, the PDMS membrane contracts in the *X* direction by 15% and expands in the *Y* direction by ~30% according to the Poisson effect. This brings the metal film into compressive stress in the *X* direction, and it buckles to a wave in the *X* direction. The tensile stress in the *Y* direction produces cracks in the metal film, normal to the *Y* direction. These cracks are evident at 1 and 15% strain in the photographs of Fig. 3. Judging from the spacing between the cracks, we expect that gold stripes of a width less than ~50 μm will not form such cracks. A systematic study of the fracture behavior will be reported in a separate paper.

When the substrate was stretched in the *X* direction beyond about 15%, the metal film was under a tensile stress in the *X* direction, and under a compressive stress in the *Y* direction. Consequently, in the metal film, cracks formed normal to the *X* direction, and waves formed normal to the *Y* direction as shown on photograph taken at 28% in Fig. 3.

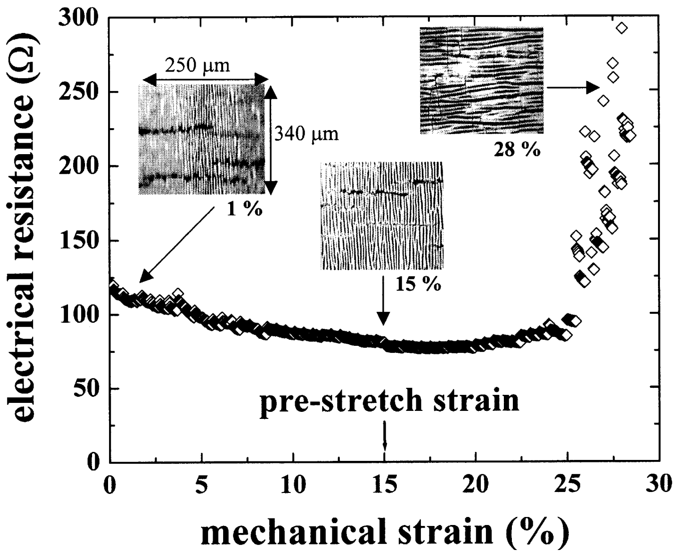

Fig. 3. Variation of the electrical resistance R of a 500-μm-wide, 25-nm-thick, gold stripe with applied tensile strain ε. Direction of stretching in the photographs is horizontal.

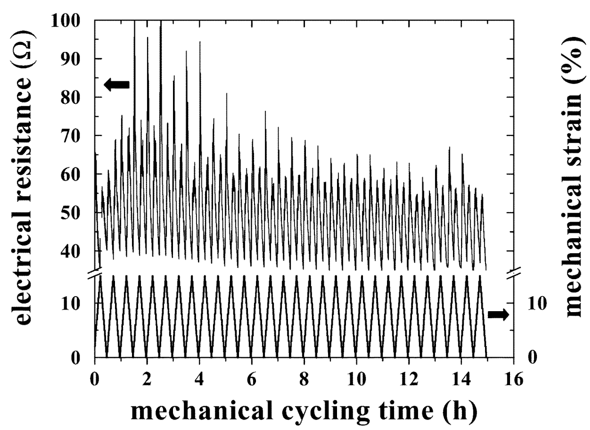

Fig. 4. Electrical resistance during mechanical cycling between 0% and 15% strain.

In the prestretch direction *X*, the Au stripe remained electrically conducting much beyond the typical fracture strain of free-standing thin films of 1% to 2% [13], similar to stripes on nonprestretched PDMS substrates [4], [12]. Fig. 3 exhibits two regimes. The resistance first decreases with increasing strain ε up to 17%, i.e., beyond the value of the prestretch of 15%. At higher strain the resistance keeps increasing until it rises suddenly to open circuit at ~28% strain. The highest strain we have reached before electrical failure was 100%. We have no evidence for plastic deformation of the PDMS substrate.

Fig. 4 shows the electrical resistance under cyclic strains between 0 and 15%, stepping 1% every minute. The electrical resistance first stabilized and then settled between ~38 and ~70 Ω. In our longest tests, samples remained stable through 100 cycles. Elastic interconnects may be cycled a few times (in shaping a conformal display or inserting a tracheal tube) to millions of times (in a polymer actuator). These prestretched gold stripes can function as interconnects for thin film transistor circuits on elastomer substrates, as they meet input/out impedance requirements in the megaohm range, and can be deformed repeatedly.

A comparison of the resistance and strain traces of Fig. 4 shows that the electrical cycle is half as long as the mechanical cycle. The electrical resistance reaches its minimum at each of the minima and maxima of the mechanical strain; the resistance has maxima halfway through the mechanical extension or relaxation. We observed similar behavior in flat Au stripes [11]. Modeling suggests that several of the deviations of the electrical resistance from first-order approximations observed in our experiments may result from mechanical phenomena that occur on a length scale comparable to the metal film thickness, i.e., on the nanometer scale [14], [15].

IV. Conclusion

The preshaping of a gold stripe to a wave on an elastomeric substrate makes the stripe reversibly stretchable with little change in electrical resistance. This technique is capable of providing interconnects for stretchable integrated circuits.

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