Stretchable Interconnects for Elastic Electronic Surfaces

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Contributed Paper

Elastic electronic surfaces will integrate stiff thin film devices onto compliant polymer substrates. These surfaces may be stretched once or many times, by up to tens of percent strain. One way to make such an elastic electronic surface is to distribute rigid subcircuit islands over the polymer surface, and then fabricate active devices on the islands. These islands need to be interconnected with stretchable metallization. We describe stretchable interconnects made of stripes of thin gold film patterned on elastomeric membranes. These membranes can be stretched by up to twice their initial length and maintain electrical conduction. We review the fabrication of these conductors, present their electrical and mechanical properties, and summarize our model for their extreme stretchability. Using such stretchable interconnects, we made the first elastic circuit, an inverter of thin film transistors. The circuit remains functional when stretched and relaxed by 12% strain.

Keywords*—*Elastic electronics, elastomer, electronic surface, flexible structures, interconnects, metallization.

I. Introduction

Electronic surfaces are conformable skin-like structures with large surface area, high mechanical flexibility and even stretchability, and multifunctional capabilities. Such structures will enable electro-active surfaces of arbitrary shape wrapped over airplane wings, buildings, robots, three-dimensional (3-D) displays, and human medical prostheses [1]. These large surfaces will sense physical parameters such as temperature, pressure, or flow, will be electrically powered and controlled, and will assess their condition and environment, and respond to it.

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Depending on their application, electronic surfaces will be mechanically actuated once or many times. A flexible flat panel display may be rolled in and out of its pen-like case many times experiencing tensile stress; a disk-shaped sensor matrix may see its surface doubled to be shaped to a hemisphere, to conform to the surface of a helmet; sensor skin wrapped over a prosthetic hand may be repeatedly stretched and relaxed by $\sim$15%.

These applications need stretchable interconnects that remain intact while cycled through stretching and relaxation. Semiconductor integrated circuits and microelectromechanical systems (MEMS) technology are made of stiff active device films that fracture under a tensile strain of $\sim$1% [2]–[4]. Free-standing metallic thin films also rupture under a tensile strain of $\sim$1%–2% [2].

It is known that stiff inorganic devices can be made and integrated on soft and compliant polymer substrates [5]. A matrix of such stiff cells, for example composed of a transducer and/or electronic circuit [Fig. 1(a)] and integrated on the polymer substrate, can withstand mechanical deformation because the deformation is taken up largely by the exposed polymer substrate between the islands. Fig. 1(b) illustrates schematic strain profiles in the polymer substrate and an island when the surface is stretched. The dashed lines represent the deformation of straight vertical lines in the originally relaxed structure [6]. The cells need to be interconnected with metal conductors that must deform with the polymer substrate. We have discovered that metal films on compliant polymer substrate remain electrically conducting even under large and repeated stretching and relaxation. This discovery opens the way to stretchable metallization and elastic circuits.

In Section II, we review our approach to making stretchable metallization. Its fabrication, topography and experimental results on its electrical and mechanical characteristics are shown in Sections III and IV. Section V presents mechanical modeling of stretchable metallization. The first stretchable active circuit, a simple thin film transistor inverter interconnected with stretchable metallic conductors, is presented

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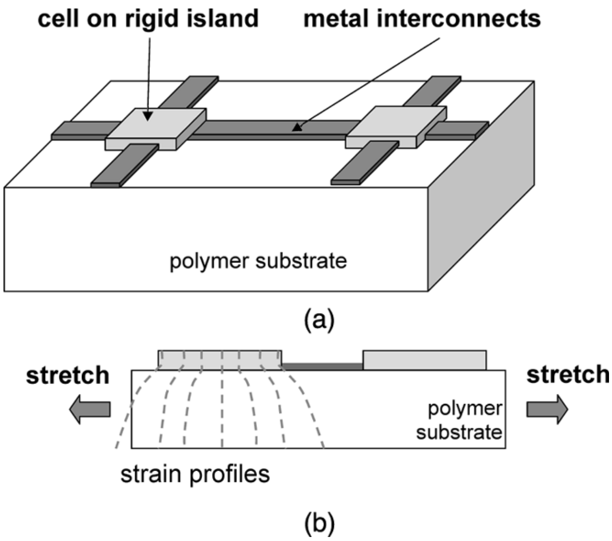

Fig. 1. Architecture of an elastic electronic surface made on a polymer substrate. (a) Active device cells are fabricated on rigid subcircuit islands distributed over the polymer surface. The cells are interconnected with stretchable metallization. (b) Cross-section of the electronic surface. The strain profiles in dashed lines illustrate the mechanical deformation within the polymer substrate and the rigid islands when the surface is stretched. When relaxed, the strain profiles are vertical lines. Note that the islands are designed to undergo very little strain during deformation [6].

Section VI, and its electrical performance in the relaxed and stretched states is analyzed.

II. Stretchable Metallization

Conformable electronic surfaces require electrical conductors that are fully elastic and have a resistivity as low as that of metals. Currently, conductive rubbers—silicones filled with carbon or silver particles—are among the few materials that are both mechanically elastic and electrically conductive. However, they present high electrical resistivity that may change significantly under stretching, leading to poor interconnect performance and reliability [7], [8].

Our approach to stretchable metallization is to use a thin-film conductor compatible with microelectronics, i.e. evaporated metal. The elastomeric substrate is a membrane of polydimethylsiloxane (PDMS). To ensure its stretchability, the thin metal film can be prepared as an ordered wave that can be stretched flat without modifying the conductor structure, hence preserving its electrical conduction. The relaxed and stretched lengths of the conductor are L_0 and L_1, respectively. The applied strain is $\varepsilon = (L_1 - L_0)/L_0$. The theoretical maximum strain, reached when the wavy film is stretched flat ($L_1 = L_{\max}$), depends on the initial wavelength λ and amplitude A. The length of the flattened film $L_{\max}$ is given by (1)

$$L_{\max} = 2N \int_0^{\pi} \sqrt{1 + \left(\frac{2\pi A}{\lambda}\cos\frac{2\pi x}{\lambda}\right)^2} dx \qquad (1)$$

where N is the number of wave periods along the conductor's length.

Metal films are stiff (Young's modulus $E_1 \sim 100\ GPa$) and thin ($h < 1\ \mu\mathrm{m}$); silicone membranes are very compliant ($E_2 \sim 1 - 200\ MPa$) and typically thick ($H > 100\ \mu\mathrm{m}$). When built-in compressive stress develops in the metal film during its deposition on the elastomeric substrate, it can also be released by forming waves [9]–[12]. We modeled the contribution of built-in stress within a thin metal stripe/PDMS structure to the formation of a wave [13], [14] as

$$\frac{2\pi h}{\lambda} = \left(\frac{4(1-\nu_1)^2 E_2}{E_1}\right)^{\frac{1}{3}} \qquad (2)$$

$$\frac{A}{h} = \sqrt{\frac{2}{3}}\sqrt{\frac{\varepsilon_0}{\varepsilon_c} - 1}. \qquad (3)$$

The wavelength λ depends on the metal film thickness h, Young's moduli E_1 and E_2 and Poisson's ratios $\nu_1, \nu_2 = 0.5$ of the metal and the PDMS. The amplitude A depends on the initial built-in strain ε_0 and the critical buckling strain of the film ε_c. ε_0 is produced by the stress that is built-in during film deposition. ε_c is the buckling threshold. When $|\varepsilon_0| < |\varepsilon_c|$, the film remains flat. ε_c depends on mechanical parameters and geometry of the metal film and the polymer substrate.

For a 100-nm thick gold film ($E_1 = 82\ GPa$) on a 1 mm thick PDMS substrate ($E_2 = 1.2\ MPa$), the calculated critical strain for buckling ε_c is 0.016%, and the predicted wavelength is $20\mu\mathrm{m}$. The measured peak-to-valley wave amplitude is $0.5\mu\mathrm{m}$ [11]. The initial built-in strain, i.e., the strain needed to flatten the metal film, is then ~0.5%, a value far too small for practical stretchable interconnects, for which we require strains of up to 15%. However, in experiments conducted to make use of these built-in waves, we discovered that gold stripes on PDMS membranes can be stretched far beyond ε_0, yet remain electrical conducting [11].

Stretchability can also be improved when thin metal coatings are deposited on prestretched elastomer membranes [15]. The PDMS typically is prestretched uniaxially by 10 to 25%. Upon release, the metal film is compressed to an ordered sinusoidal surface pattern, with A and λ following (1). Fig. 2 presents the 3-D profile of a gold surface wave on PDMS membrane after release from 15% prestretch.

III. Thin Gold Conductors on PDMS Substrate

A. Fabrication

The substrate is a 1-mm-thick PDMS membrane (Sylgard 184 from Dow Corning) prepared by mixing the silicone gel with cross linker in a 10:1 weight ratio, and casting then curing for at least 12 hours at 60°C in a plastic Petri dish. PDMS so prepared is compatible with microelectronic clean room equipment. We use the full surface of the PDMS and no surface treatment is performed before metal deposition.

Thin metal films, typically 25–500nm thick layers of gold on top of a 5nm thick adhesion interlayer of chromium, are deposited in one run by successive electron beam evaporation on the PDMS held at room temperature. The PDMS substrate is mounted on a stage rotating at constant speed during the process. The base pressure in the chamber is 0.5 mPa prior to the evaporation and 1 mPa during evaporation; the metal

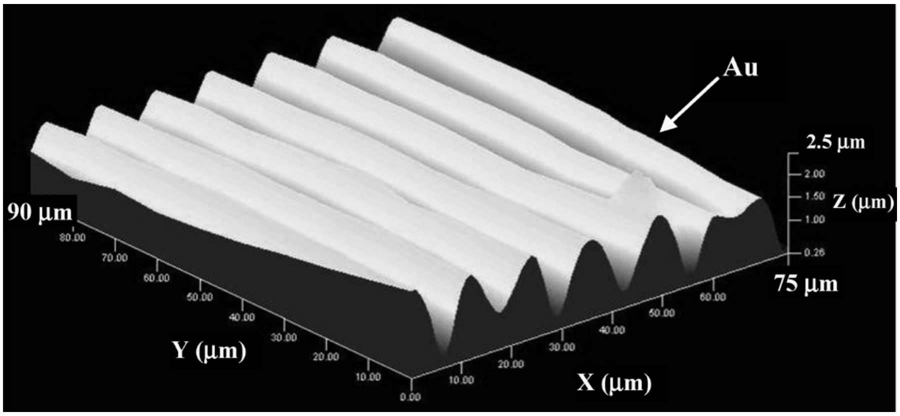

Fig. 2. Three-dimensional profile of a gold surface wave after release from 15% pre-stretch. The Au film deposited on a 1 mm thick PDMS membrane is 25-nm thick. The measured wavelength and amplitude are 8.4 μm and 1.2 μm, respectively [15].

deposition rate is $\sim$ 2Å/s. The measured temperature of the sample holder does not exceed 50°C.

The stretchability of initially flat stripes of gold film allowed us to develop two techniques to fabricate stretchable conductors.

i) The gold film is directly deposited on a relaxed PDMS membrane.
ii) The gold film is deposited on a PDMS membrane that was prestretched by 10 to 25%. When the substrates relax from the prestretch, the gold stripes form surface waves.

1) Relaxed Substrates: A shadow mask is made of a 50 μm thick polyimide foil with 2.54cm long openings which are from 0.25 to 2.5-mm wide. The shadow mask is made to adhere to the PDMS membrane prior to metal evaporation. This is an easy and dry technique to pattern thin films on PDMS.

2) Pre-Stretched Substrates: The PDMS membrane first is uniaxially prestretched by 10%–25% and held in a homemade fixture. Metal film conductors are patterned with shadow masks made of 31 μm thick dry photo-resist (Riston from Dupont) that is laminated onto the extended PDMS substrate. Following metal evaporation, the Riston is lifted-off in KOH solution, and the PDMS membrane is released from its holder. The gold stripes form waves (Fig. 2) with amplitude and wavelength values predicted by (1).

B. Surface Topography

The sample surface is characterized using optical microscopy and scanning electron microscopy (SEM). To avoid charging, a 1.5nm thick layer of iridium is sputtered onto each sample prior to SEM imaging.

1) Conductors on Relaxed Substrates: Under the optical microscope all gold stripes are shiny and continuous. The stripe edges are rough from shadow mask patterning. Two sample topographies are observed. The metallic conductor surface is either wavy [Fig. 3(a)] or flat [Fig. 3(b)].

When the metal is deposited in stripes of width <1 mm, ordered parallel waves may form in the Au layer as shown in Fig. 3(a) [11]. The wavelength increases with the Au film thickness as predicted by (2). The wave amplitude A is $<$ 1 μm. SEM imaging shows that those wavy films are continuous and appear to have a granular microstructure. The grain size increases from 15 to 35 nm for 25 to 200-nm thick films.

On the other hand, flat films, as shown Fig. 3(b), exhibit no waves. However, clearly visible under the SEM is a network of randomly arranged micro-cracks that covers the surface of the gold stripe. The cracks are micrometer size, Y-shaped, not connected to each other, and apparently form at grain boundaries [13]. They possibly arise from local tensile stress in the gold film during deposition. The shape and distribution of the cracks do not depend on the Au thickness.

We do not yet understand what causes the differences between the two topographies and microstructures. The PDMS surface is not treated prior to metal deposition. The average roughness of a 0.5 $\mu\text{m} \times 0.5$ μm PDMS surface measured by Atomic Force Microscopy was 8.5 nm [16]. The surface roughness may result in spatially varying adhesion of the metal film. No obvious correlation is evident between the Au film thickness, buckling, and microstructure. The difference in topography suggests that the metal films may experience either compressive or tensile stress or both, during and after evaporation.

2) Conductors on Prestretched Substrates: From now on, we define the X and Y-directions as the directions of conductor length and width, respectively. ε_x and ε_y correspond to the strain along the X and Y-directions.

Upon release from pre-stretch, the PDMS substrate contracts in the X-direction $(\varepsilon_x < 0)$ and expands in the Y-direction due to the Poisson effect $(\varepsilon_y = -\varepsilon_x.\nu_2 > 0)$. The metal film comes under compressive stress in the X-direction, and forms a wave with vector in the X-direction. Simultaneously the metal film is under tensile stress in the Y-direction, and cracks along the length of the stripe form in the metal film [Fig. 3(c)], regardless of the gold stripe's thickness.

IV. Stretchable Interconnects

A. Characterization

To evaluate the electrical resistance, electrical contacts are made to the Au conductors using a non cured epoxy-based

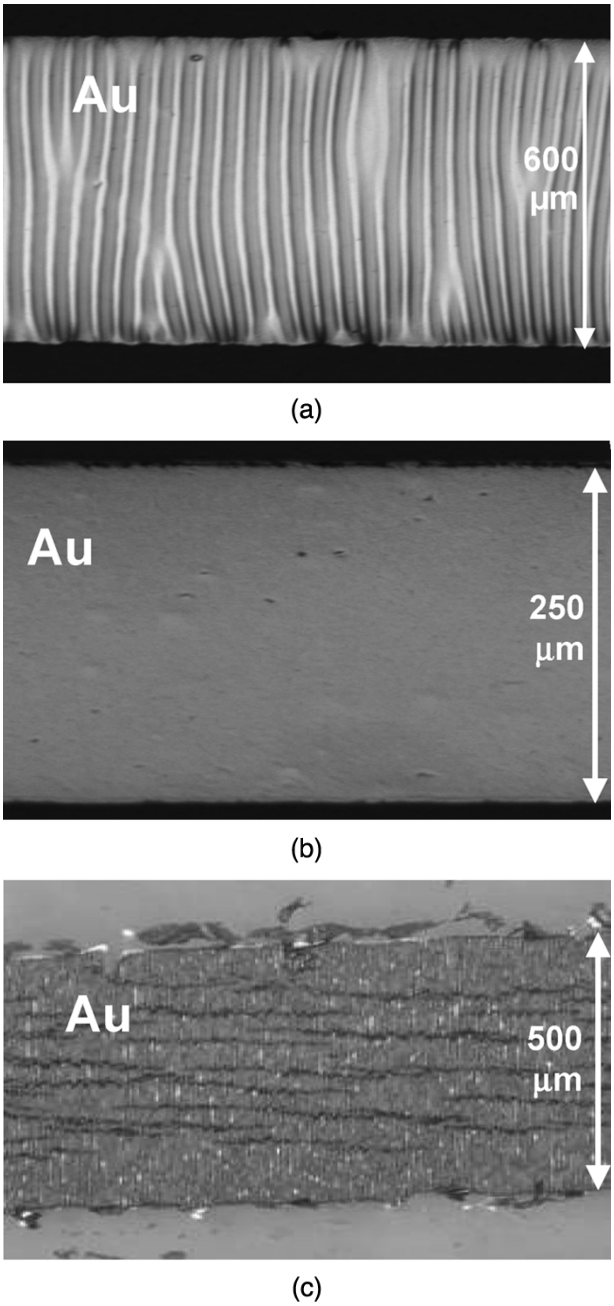

Fig. 3. Optical micrographs showing the topography of three Au stripes on 1 mm thick PDMS membranes. (a) *Built-in waves* are observed in a 100-nm thick, 600-$\mu\mathrm{m}$ wide, 2.54-cm long gold conductor patterned on relaxed PDMS. The wavelength is $\sim 25\ \mu\mathrm{m}$. (b) 100-nm-thick, 200 $\mu\mathrm{m}$ wide, 1.6-cm-long *flat* gold conductor prepared on relaxed PDMS. (c) 25-nm-thick Au film on a PDMS membrane released from *15% prestretch*. Longitudinal waves and tension cracks are formed upon release. The wavelength is $\sim 8\ \mu\mathrm{m}$ [20].

paste. A 100 $\mu\mathrm{m}$ diameter gold wire is embedded in the conductive paste and is sandwiched between the substrate and another PDMS piece to ensure electrical conduction as well as structural compliance. The electrical resistance R is recorded with a Keithley 4140 source-meter.

The samples are stretched in a custom made micro-tensile tester [11]. The sample topography and eventual devel-

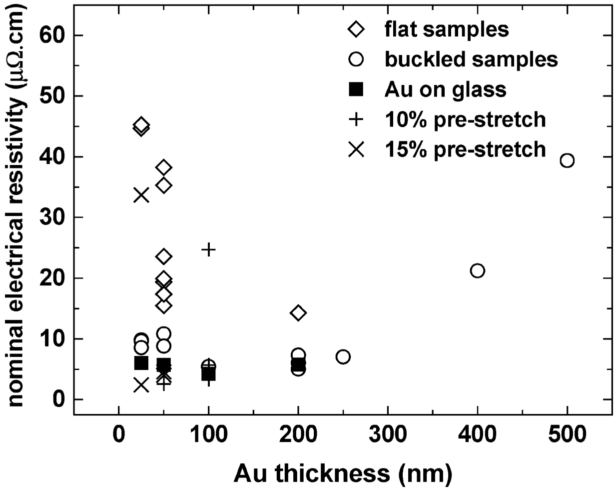

Fig. 4. Nominal electrical resistivity of gold stripes as a function of layer thickness. ◇ films grown on relaxed PDMS and initially flat. ○ films grown on relaxed PDMS and initially buckled. ■ films grown on glass slide. + and x films were prepared on 10% and 15% prestretched PDMS membranes, respectively.

opment of cracks during the mechanical deformation are recorded with an Infinity optical microscope provided with a digital CCD camera and mounted on an XYZ platform, and the sample elongation between holding clamps is measured from the stepper motor's position. The external strain is defined as $\varepsilon_x = (l_1 - l_0)/l_0$, with l_0 the sample's initial length and l_1 the sample's stretched length. Note that l_0 and l_1 are longer than the gold stripe L_0 and L_1, and $\varepsilon_x = (l_1 - l_0)/l_0 = (L_1 - L_0)/L_0$ assuming the absence of viscous flow in the PDMS membrane.

We begin by measuring the electrical resistance of the gold conductors under mechanical strain, up to electrical failure. Our definition of failure strain is the strain applied at electrical failure. Typically, the test is run slowly, at strain rate of 0.1%–1% per minute. Most often electrical conduction is restored by relaxing the sample after stretching to electrical failure. We continue by evaluating the electrical resistance under mechanical cycling.

B. Initial Electrical Resistance

Fig. 4 presents the nominal electrical resistivity of the Au stripes as a function of their fabrication technique, thickness, and initial topography. The nominal resistivity is calculated as $\rho = R_{\mathrm{exp}} L/Wh$, where R_{exp} is the measured resistance, and L, W, and h are the macroscopic length, width, and thickness of the gold stripe, respectively. Samples prepared on glass slides were used as reference for conductance. Their electrical resistivity is $\sim 5\ \mu\Omega.cm$, which is about twice that of bulk gold (2.3 $\mu\Omega.cm$ [17]).

The electrical resistivity of all samples with built-in or prestretched waves usually lies in the range of that of samples on glass. The electrical resistivity of the flat, micro-cracked stripes is 3 to 100 times that of Au films on glass. In the latter samples, the electrical path in the Au layer must be tortuous and complex, as the film is a dense network of gold that surrounds randomly arranged voids. Thus the electrical conduction of the network depends on the effective length and width of the gold conductor.

The electrical resistance of a conductor prepared on a relaxed PDMS membrane was monitored for an extended period in its as-prepared, relaxed state. The resistance of the wavy film was found to fall over a four-day period from an initial 320Ω down to 35Ω. Its resistance calculated from the resistivity of bulk gold and the stripe geometry was 33Ω [18]. The initial resistance of initially flat and micro-cracked stripes was recorded for 20 hours and remained nearly unchanged. From Fig. 4, and the preceding observations it is evident that the electrical resistivity of gold stripes on PDMS substrates highly depends on their thickness and microstructure.

C. *Electrical Resistance Under Mechanical Deformation*

Regardless of the gold films' topography, they can be stretched far more than free-standing gold film yet they remain electrically conducting. However, we find that Au stripes thicker than 100 nm prepared by e-beam evaporation on 1-mm-thick PDMS fail below 2% strain, similarly to free-standing metal films [19]. Therefore, we present data on gold conductors thinner than 100 nm.

1) Buckled Conductors on Relaxed Substrate: Most of the initially buckled samples show similar electro-mechanical behavior [11], [18]. Over the region of 0–1% strain the resistance stays close to the initial value. In this regime the buckled stripes are flattened. At higher strain the electrical resistance increases linearly with the applied strain ε_x, reaches a critical strain above which the resistance jumps dramatically; at a somewhat larger strain the sample fails electrically. The value of the critical strain depends on the Au film thickness and ranges from 10% to 20%.

The elastic deformation of the PDMS substrate upon stretching causes the conductor width to decrease due to the large Poisson's ratio of PDMS, which induces longitudinal buckling in the thin gold film at right angles to the original waves in similar orientation as the cracks of to Fig. 3(c). Cracks often form at the intersection of these lengthwise and these transverse waves. Furthermore, above the strain at which the film stretches flat, cracks develop from one side to the other. The electrical conductance is not lost, however, indicating that these transverse cracks do not run through the entire depth and width of the film [11], [18]. Usually, no macroscopic topography change is observed in the film from below to above the critical strain at which the resistance begins to increase significantly.

2) Flat Conductors on Relaxed Substrate: Fig. 5 presents a test run in which an initially micro-cracked, 25nm thick, 200 $\mu\mathrm{m}$ and 1.6-cm-long sample was stretched until electrical failure. The initial resistance is high ($R_{ini} = 690\Omega$) compared to the value on glass of 74 Ω, and increases steadily by 270% to $R_{\max} = 2550\Omega$ at $\varepsilon_x = 60\%$ strain. Despite the high applied strain, the sample did not fail electrically, and negligible macroscopic change in the film was observed.

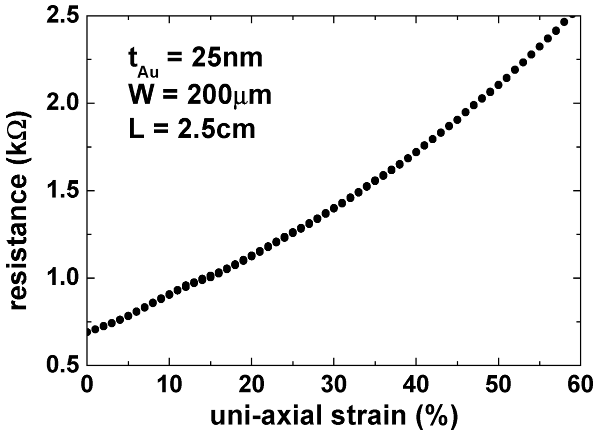

Fig. 5. Electrical resistance as a function of the applied tensile strain of an initially flat 25-nm-thick, 200-$\mu\mathrm{m}$-wide, 2.54-cm-long Au stripe prepared on a relaxed PDMS substrate.

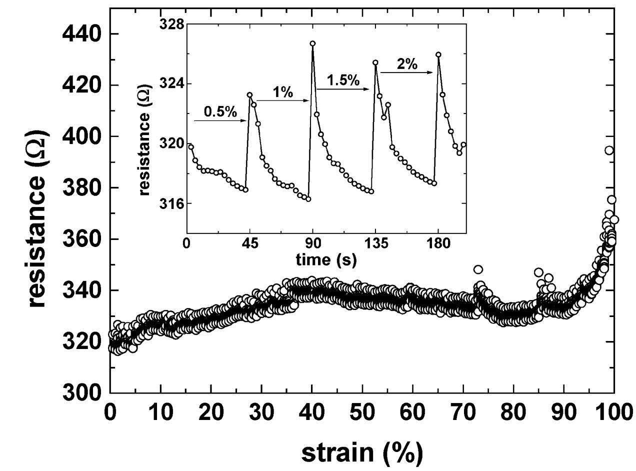

Fig. 6. Electrical resistance of a 20nm thick, 3mm wide, 1.6cm long Au stripe made on 25% prestretched PDMS membrane [20]. The inset illustrates the resistance relaxation between two 0.5% strain steps from 0% to 2% total strain.

3) Buckled Conductors on Prestretched Substrate: Fig. 6 presents the electrical resistance of a stripe prestretched by 25% as a function of the applied strain from 0% to 100%. Upon release, the stripe is compressed by 25% along the X-direction and simultaneously stretched by ~12% along the Y-direction. Consequently, cracks form parallel to the sample length and from partially separated parallel stripes of wavy Au films [Fig. 3(c)] [15], [20].

The initial resistance at 0% strain of this sample is 316 Ω. At $\varepsilon_x = 25\%$, its resistance has risen by only 4.4% to 330 Ω. Up to $\varepsilon_x = 100\%$, the resistance increases by a further 25%. Thus, at 100%, strain the metal remained electrically conductive. The mass of data points in Fig. 6 is produced by the relaxation of R at each strain increment. In this experiment, the strain was raised in steps of 0.5% every 45s (inset to Fig. 6). At each step R responds with a jump, to the value denoted by the top open circle, and then relaxes to the lower values, which produce the many overlapping data points.

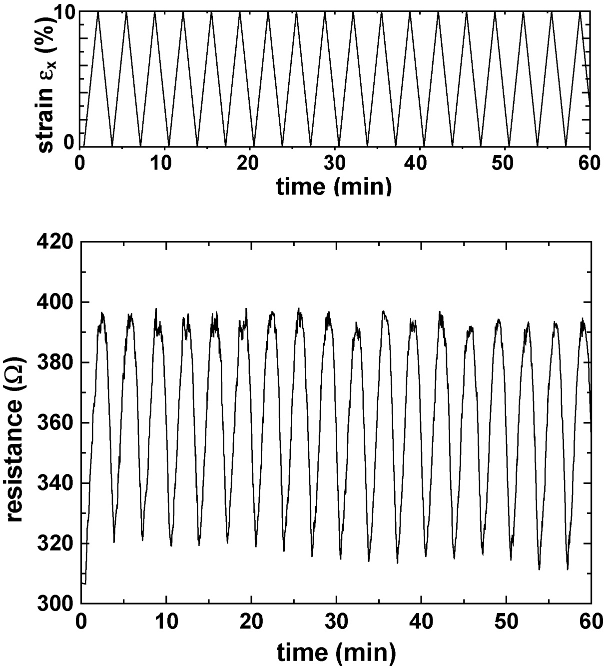

Fig. 7. Electrical resistance during mechanical cycling between 0% and 10% strain of an initially flat 25nm thick, $200\mu\mathrm{m}$ wide, 1.6cm long Au conductor made on relaxed PDMS. One strain cycle takes 200s.

Hence, the prestretching of the PDMS substrate, to preshape the gold film to a controlled wave makes a highly stretchable conductor whose electrical resistance changes little over a wide range of strain.

D. Mechanical Cycling

Fig. 7 shows the electrical resistance of an initially flat, 25-nm-thick, 0.2-mm-wide and 1.6-cm-long Au stripe on PDMS under cyclic strain between 0% and 10%, stepped by 0.2% every 2s. R swings by $+/-20\%$ as it follows the mechanical deformation. We have also cycled built-in and prestretched wavy Au conductors. To date, we have tested samples through 1,000 cycles and found them to remain electrically stable.

V. Mechanical Modeling

Originally we had designed the stretchable conductor as wavy gold line made by evaporation on prestretched PDMS. The stretchability of such a wave to flatness is not surprising even though we do not yet understand the details of electrical conduction during the flattening of the wavy stripe in the X direction which is accompanied by its compression in the Y direction. In contrast, the discovery of electrical continuity in flattened then over-stretched flat films was a surprise, because flat free-standing metal films can be stretched by only 1%–2% before they rupture [4]. By mechanics modeling, we are beginning to understand why the metal film bonded to PDMS can be stretched far more than its freestanding counterpart [21].

The rupture of a free-standing metal film under stretch results from the film necking at its weakest cross-section. Once a neck forms, the strain in the metal film localizes at the neck; the rest of the metal film stretches little. As a result, the overall rupture strain is usually small (~1–2%) [4]. A key condition for stretchability is that the metal film is bonded well to the elastomeric substrate. When this is the case, strain does not localize in one spot to cause the film to neck down. Instead, the strain in a substrate-supported film remains distributed over the entire length of the substrate and film; the substrate and film deform together. As soon as the film debonds from the substrate in one spot, the film necks down and breaks. Finite element simulations show that certain combinations of elastic moduli and thickness ratios of film and substrate indeed can be stretched by as much as 100% while the metal film remains continuous. We cannot yet model the reversibility of this stretching. Likewise, the explanation of subsidiary phenomena that we observe in experiments, such as the film structures described in Section III and the resistance decay of Section IV, await more detailed experimental and modeling studies [22].

VI. First Elastic Circuit

The use of rigid device islands on a compliant polymer substrate already has been demonstrated in circuits that undergo one-time mechanical deformation [5], [6]. For this purpose the interconnects were made by deforming a sacrificial mask for metal evaporated *after* deformation. The principal advance reported in the present paper is the ability to make reversibly stretchable interconnects that can be made *before* deformation, and comply with it. To demonstrate this advance, we fabricated an elastic circuit that relies on reversibly stretchable interconnects. The circuit is an inverter made of two amorphous silicon thin film transistors (a-Si TFTs), which had been fabricated on 50-μm thick Kapton E polyimide foil, which has the color of honey. The circuit schematic, and a photograph of the circuit and of one TFT are shown in Fig. 8. The clear PDMS substrate covers the entire frame of the larger photograph of Fig. 8(b), and is partially underlaid by paper ruled with a millimeter scale. Gold pads and stretchable interconnects were patterned directly on the PDMS. Two a-Si TFTs with matching contacts were mounted face-down (as shown in the small photograph) on the Au/PDMS pads. Gold wires were attached to the off-membrane input–output contact pads using silver paste.

The gold interconnects were 25nm thick, $\sim 200\mu\mathrm{m}$ wide, patterned by lift-off using Riston photo-resist. Contact pads were made 1.35mm $\times$ 1.35mm for the TFT terminals, and 2mm $\times$ 2mm for the off-membrane connections.

The ON resistance of the a-Si TFTs is of the order of 2 $M\Omega$. As the resistance of these interconnects lies in the range of 0.1 $k\Omega$ to 1 $k\Omega$, they have a negligible effect on the overall circuit resistances.

We evaluated the electrical and mechanical performance of the inverter in its relaxed and stretched (by up to 12%) states. The circuit was mounted in a uniaxial tensile tester. It

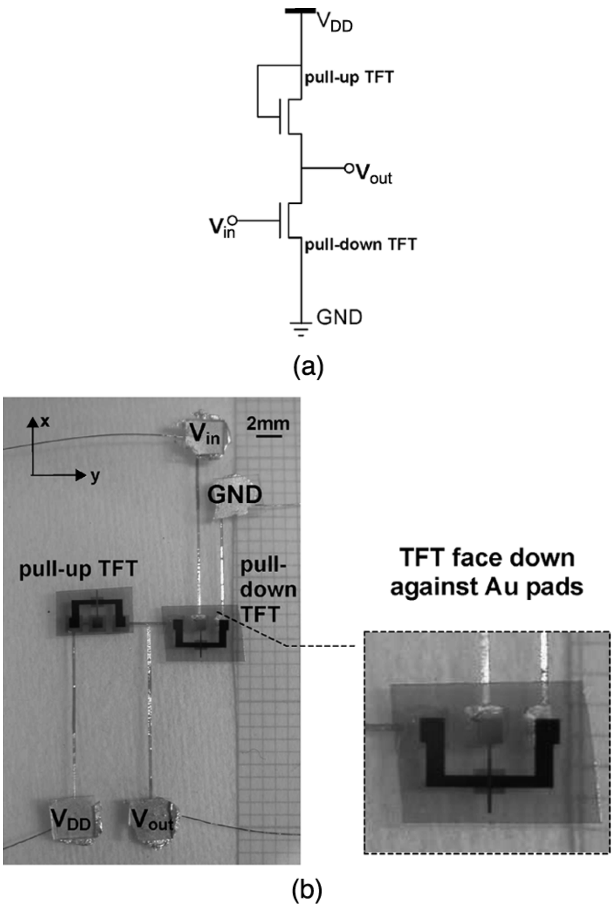

Fig. 8. (a) Circuit diagram and (b) photograph of the stretchable inverter. Amorphous silicon TFT's made on polyimide foil are mounted face down on contact pads and interconnected with the stretchable Au conductors. The clear silicone membrane covers the entire field-of-view. (c) One TFT mounted face down on the Au pads on the PDMS membrane [23].

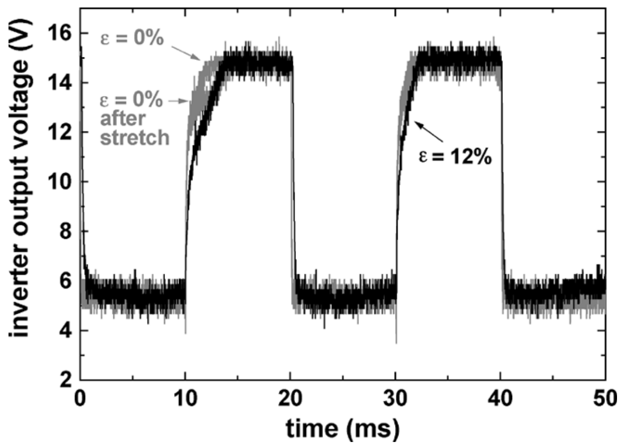

Fig. 9. Output voltage of the inverter driven with a 14-V square wave at 50 Hz while relaxed ($\varepsilon = 0\%$) prior to and after a 12% elongation, and while stretched by 12% [23].

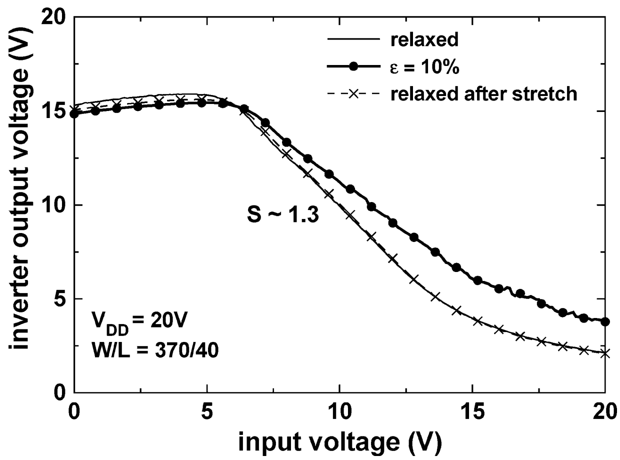

Fig. 10. dc voltage transfer characteristic of the elastomeric inverter in its relaxed state, prior to, while, after stretching by 10%. The supply voltage V_{DD} is 20 V. S is the inverter gain. The TFT channel is $L = 40\mu\text{m}$ long, and $W = 370\mu\text{m}$ wide [23].

was stretched in 1-mm steps ($\Delta\varepsilon_x \sim 2.5\%$), held stretched for 1 minute, and released to its initial position for 5 minutes; the same sequence was repeated for 2–5 mm of elongation, so that the 40mm long circuit was stretched by up to 12%. While the circuit is stretched by up to 12% in the X direction of Fig. 8, it contracts by up to 6% in the Y direction, because the elastomer's Poisson's ratio is 0.5. In a way, we can say that the substrate "breathes" while it is stretched.

Fig. 9 presents the AC responses of a stretchable inverter driven with a 14 V amplitude 50 Hz square wave in the initial (0% strain), stretched (12% strain) and relaxed (0% strain) states. The AC response is seen to be little affected by the mechanical deformation. The circuit kept operating oven the ten stretching cycles that we applied.

We also evaluated the DC electrical performance of the inverters prior to, during, and after uni-axial stretching by up to 10%. The stretching procedure was identical to that described above. The relaxed inverter begins to switch at $V_{IN} \sim 5\ V$. The circuit has a gain S of ~1.3, in agreement with a circuit model based on the TFT characteristics. The gain was low because the pull-up and pull-down TFTs are identical. At 10% tensile strain the transfer characteristic (Fig. 10) is seen to be affected somewhat by the mechanical deformation. The circuit gain is slightly reduced because of shearing of the electrical contacts between the TFT/Au contact pads during the stretching. Improving the mechanical stability of contacts is now one of our priorities. The transfer characteristics in the relaxed state, prior to and after elongation, are identical.

Clearly, this circuit is fully elastic, electrically as well as mechanically.

VII. Conclusion

We are now able to fabricate stretchable interconnects for elastic electronic surfaces. Experiments illustrate the astonishing stretchability of thin gold conductors on PDMS membrane as well as the complex and rich nature of this new electrical component. The mechanisms of deformation, and the electrical and mechanical properties of thin metal films on polymer substrates are only beginning to be understood. Substrate preparation, film growth and bonding, the built-in strain in stiff films on compliant substrates, the mechanisms of stretching, and of electrical conduction particularly across fractures, need careful study.

We cannot decide yet which interconnect fabrication technique (relaxed or pre-stretched conductors) is better. Both techniques produce highly stretchable interconnects. But it is certain that conductors which can double their length and maintain low electrical resistance will be integrated to electronic packages and to large area and elastic circuits. Achieving fully elastic integrated circuits will require the development of novel fabrication and evaluation techniques including micro-patterning, contacting, and electrical testing.

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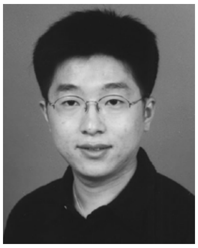

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