Electrical Characterization of Traditional and Aerosol Jet Printed Conductors under Tensile Strain

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Motivation

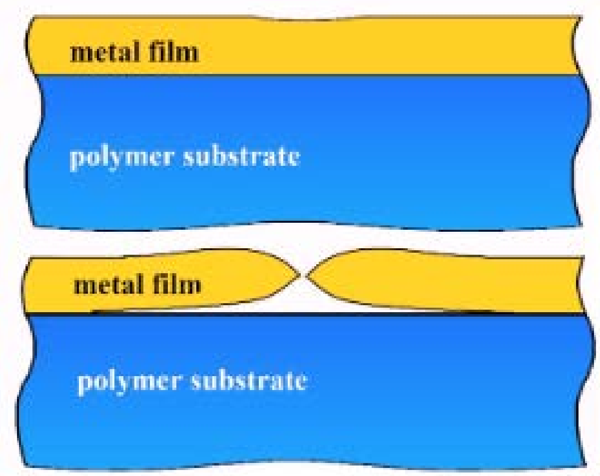
Address current hurdles within flexible and stretchable electronics development:

- ***How to overcome mechanical mismatch between conductor and dielectric?***
- ***What happens to electronics and interconnects under stain?***
- ***Which materials and fabrication methods best tolerate strain?***

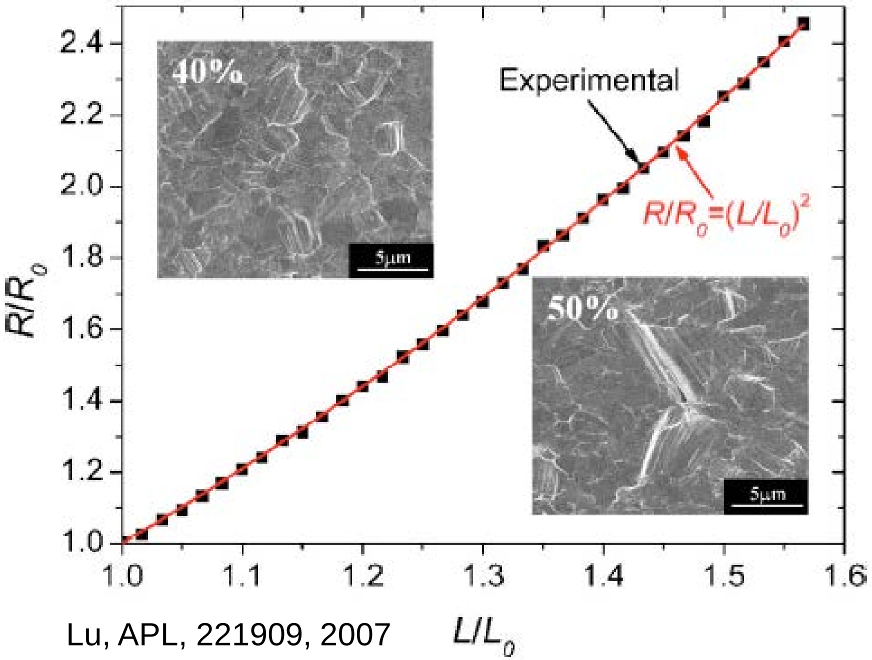
Chihaya Adachi & Hajime Nakanotani Lab

Prior Research: Metals Under Tensile Strain

Xiang, APL, 161910, 2005



Metals under strain { **Strong adhesion (top)** / **Weak adhesion (bot)**



Lu, APL, 221909, 2007

All resistance increase due to geometric change; no measurable discontinuities initiated in film

Strong adhesion at interface in data shown

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Resistance in Conductors Under Strain

$$R = \underline{R_C} + \underline{R_D} = \underline{R_0(1+\varepsilon)^2} + \underline{\left[\frac{\rho L(1+\varepsilon)}{A}\right] m^{\frac{1}{\alpha(1+\varepsilon)}}}$$

Continuous Resistance Increase
(material independent)

Lu, APL, 221909, 2007

Discontinuous
Resistance Increase
(material dependent)

Cairns, et al., APL, 76, 2000

- ✧ **Discontinuities include cracks, buckles, losses of adhesion, etc.**
- ✧ **For ideal conductor, $R_D \rightarrow 0$, $R = R_C$**
- ✧ **Novel addition to previous work: α = discontinuity-percolation factor**
- ✧ **α quantifies tendency of discontinuities to propagate and unify at higher strain**

R_0 = initial resistance
ε = engineering strain
ρ = resistivity of underlying conductor
L = characteristic discontinuity length
A = characteristic discontinuity area
m = number of discontinuities
α = discontinuity-percolation factor

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Lu, APL, 221909, 2007

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Resistance Increase
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$$m\,(R,\varepsilon) = \left\{\left[\frac{R}{R_0} - (1+\varepsilon)^2\right]\frac{R_0 A}{\rho L(1+\varepsilon)}\right\}^{\alpha(1+\varepsilon)}$$

- ✧ **Determine α from m at known R, ε**
- ✧ **Describe microscale phenomenon**
- ✧ **Preference is for α to be close to 1 (no discontinuity percolation)**

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ε = engineering strain
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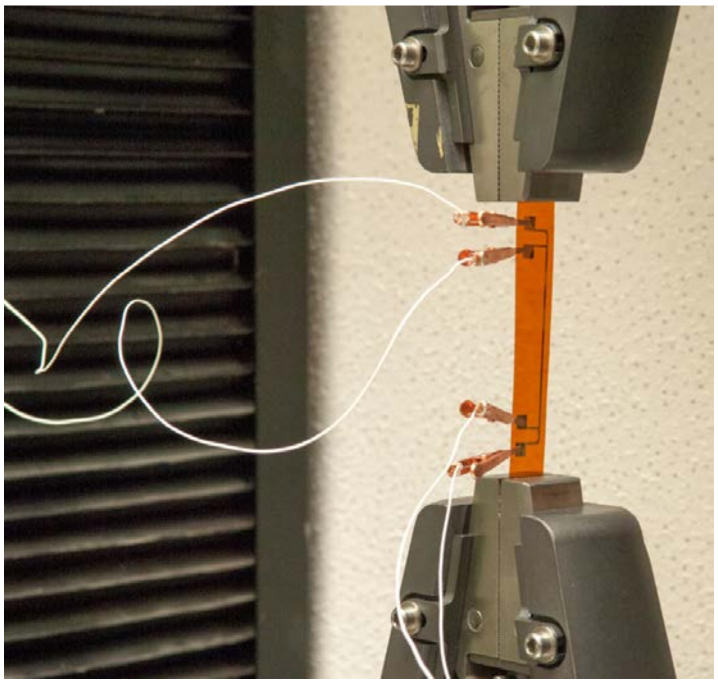
Methods and Materials: Sample Preparation

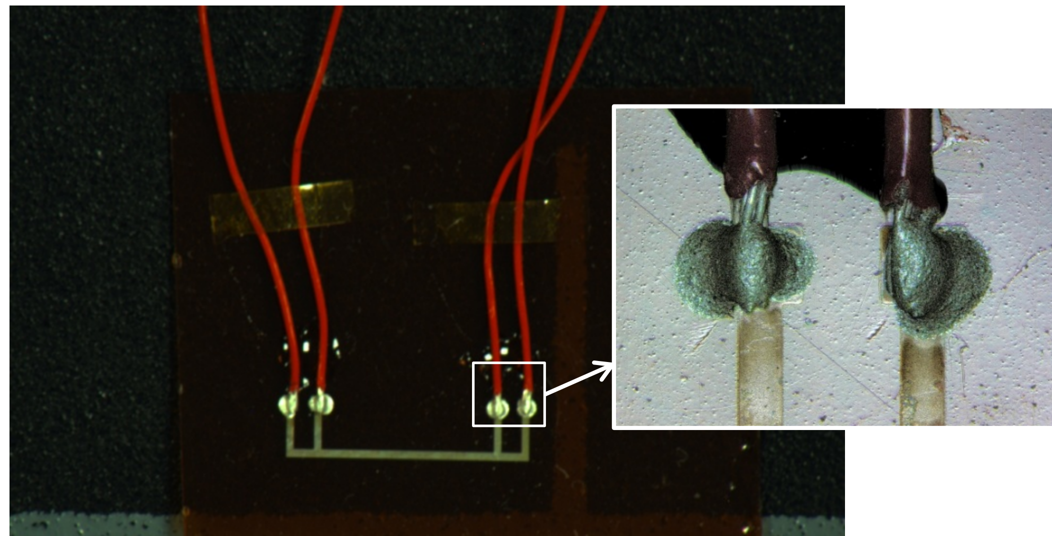
- ✧ Substrates: PDMS, Kapton
- ✧ Conductors: Silver (evaporated), Gold (evaporated), Silver ink (printed)
- ✧ Evaporated samples deposited to 100nm target thickness (100-110nm actual thickness) in TEMESCAL electron beam evaporator at P = 2-3 x 10^{-7} Torr
- ✧ Printed samples deposited in Optomec aerosol jet printer (2μm thickness) and laser sintered

Methods and Materials: Strain Conditions and Data Acquisition

- **Resistance monitored using 4-wire measurements while stretching in Instron tensile tester at rate of 10% strain/minute**

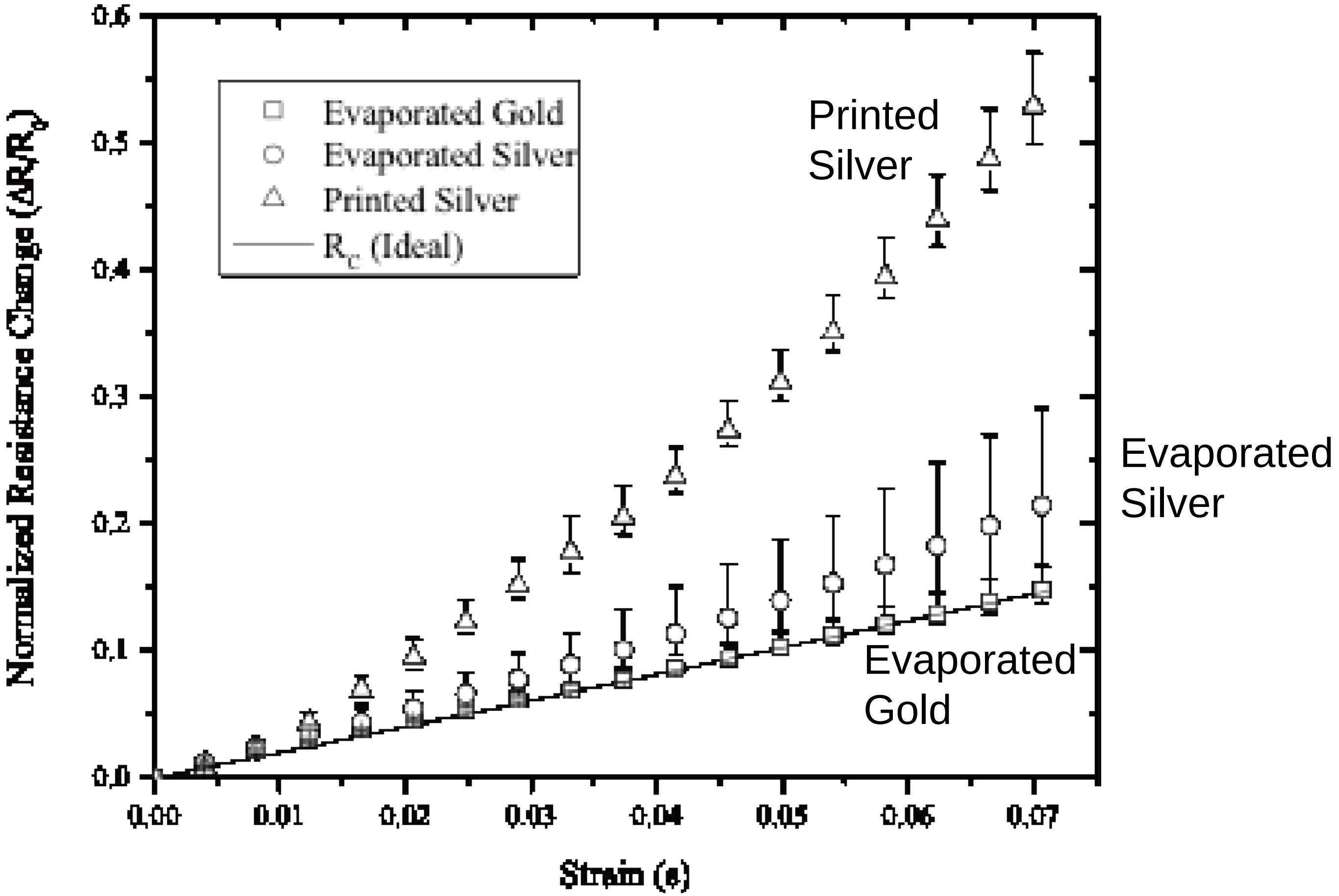


Alligator clips to output from evaporated films



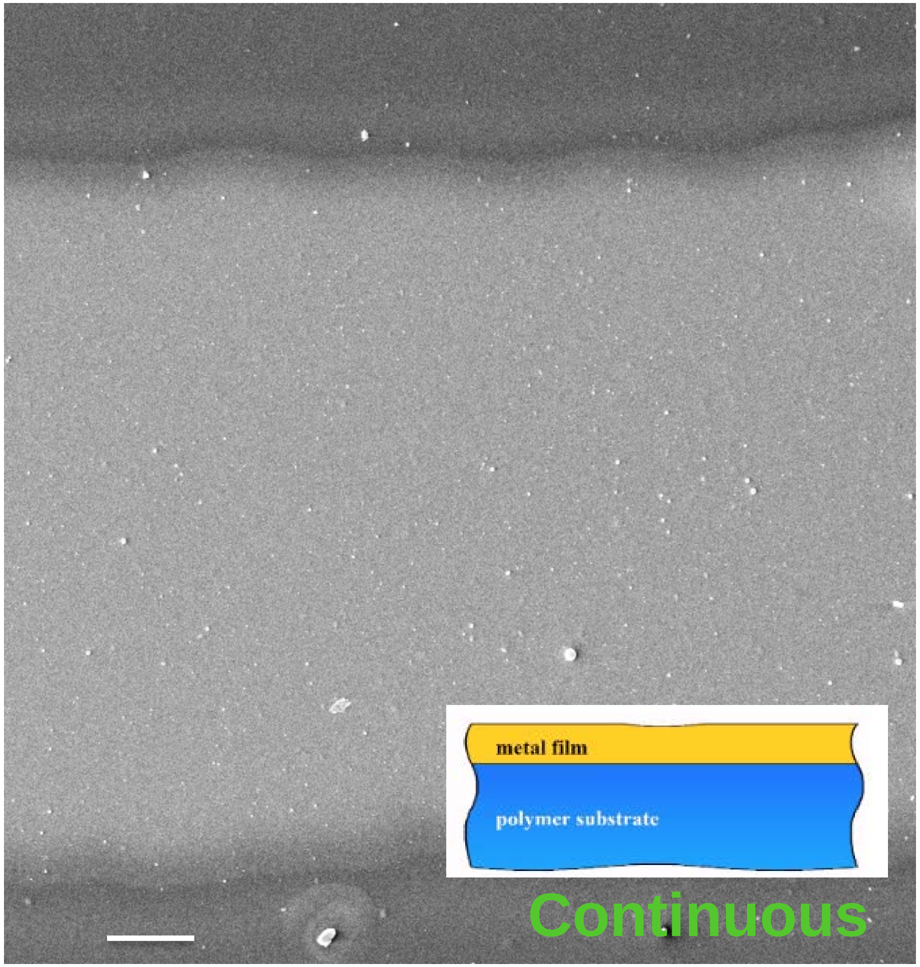
Silver epoxy to output from printed films

Conductor-Kapton Systems Under Strain



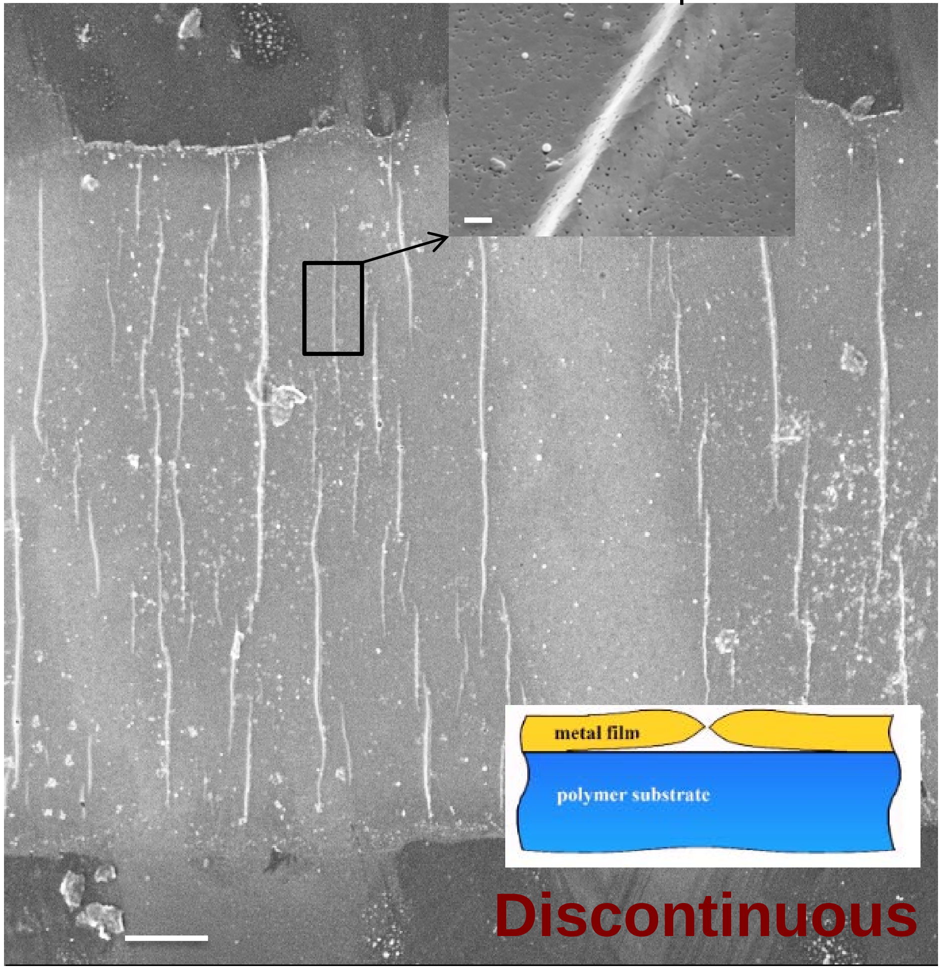
- ✧ Only continuous resistance increase in gold sample
- ✧ Evaporated silver superior to printed silver

Evaporated Silver-Kapton After Strain



Scale bar: 100 μm

Scale bar: 2 μm



Scale bar: 100 μm

✧ 1.1 < α < 2.1; exact value not attainable, crack depth unknown

✧ In discontinuous section, adhesion loss led to buckling

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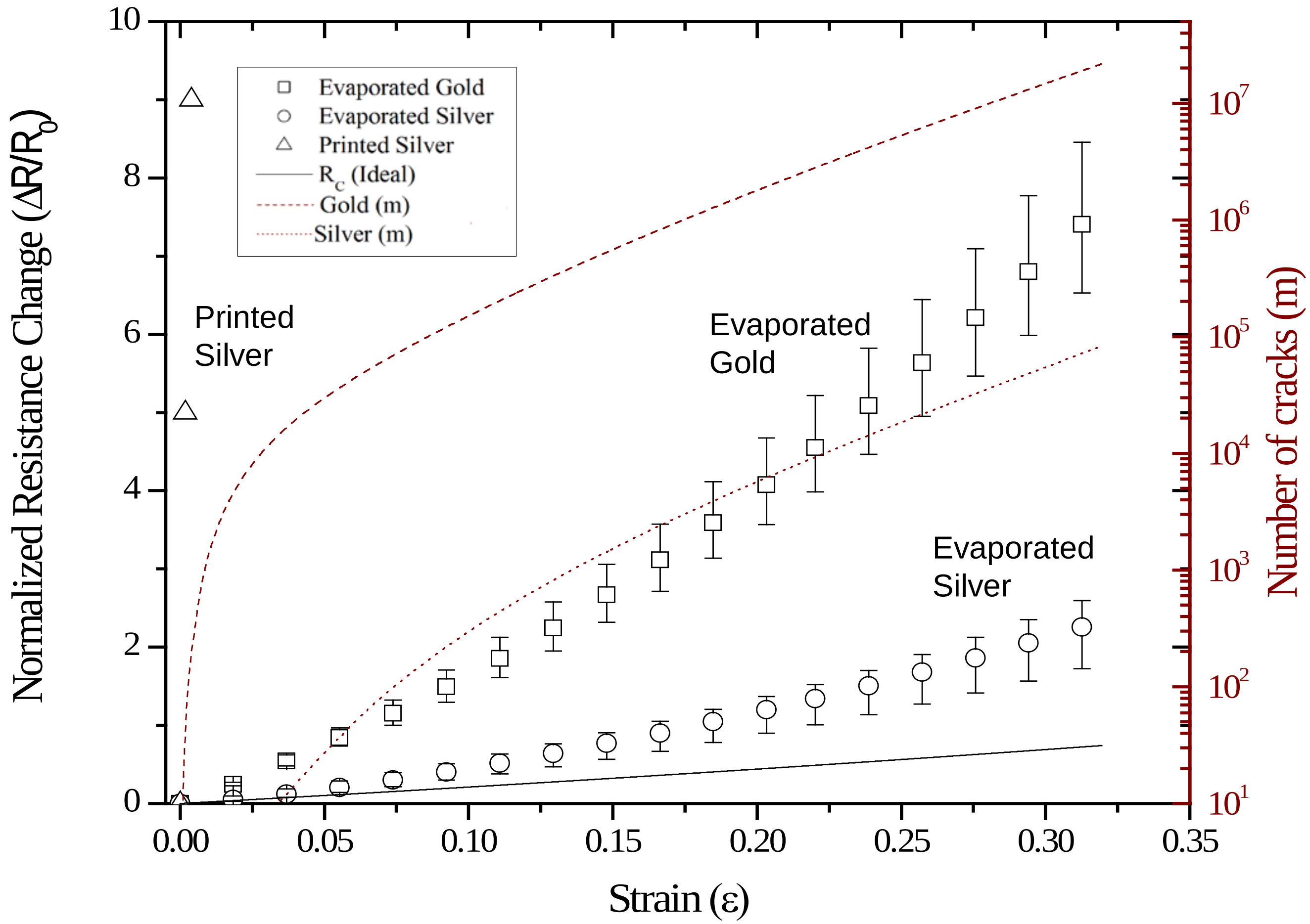
Conductor-PDMS Systems Under Strain



- ✧ Significant discontinuity induced resistance across all materials
- ✧ Printed silver completely inelastic
- ✧ Evaporated silver “best”

$$m\ (R, \varepsilon) = \left\{ \left[\frac{R}{R_0} - (1+\varepsilon)^2 \right] \frac{R_0 A}{\rho L (1+\varepsilon)} \right\}^{\alpha(1+\varepsilon)}$$

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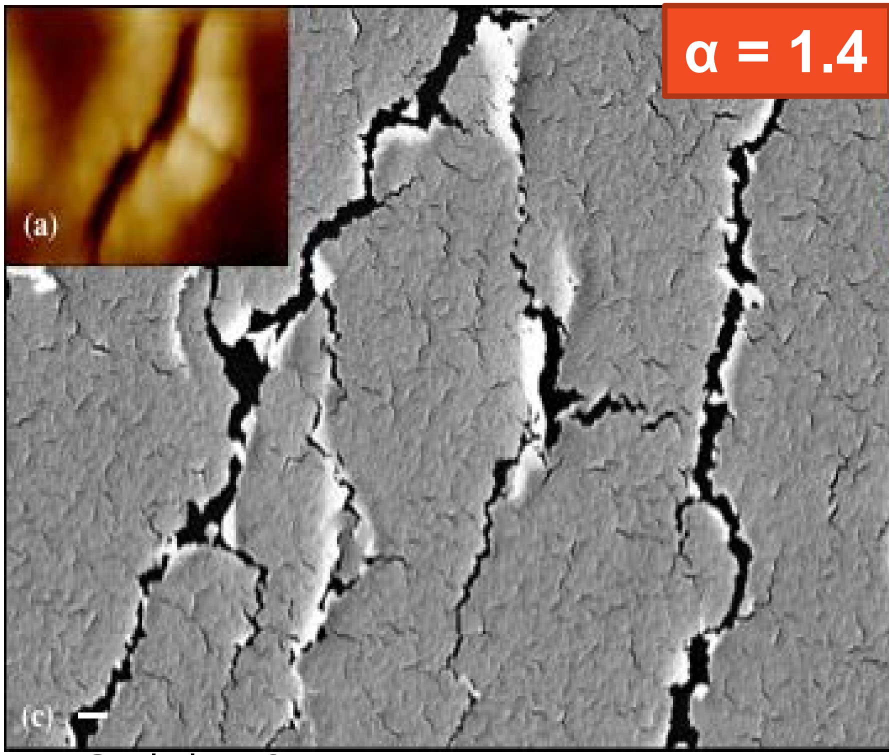
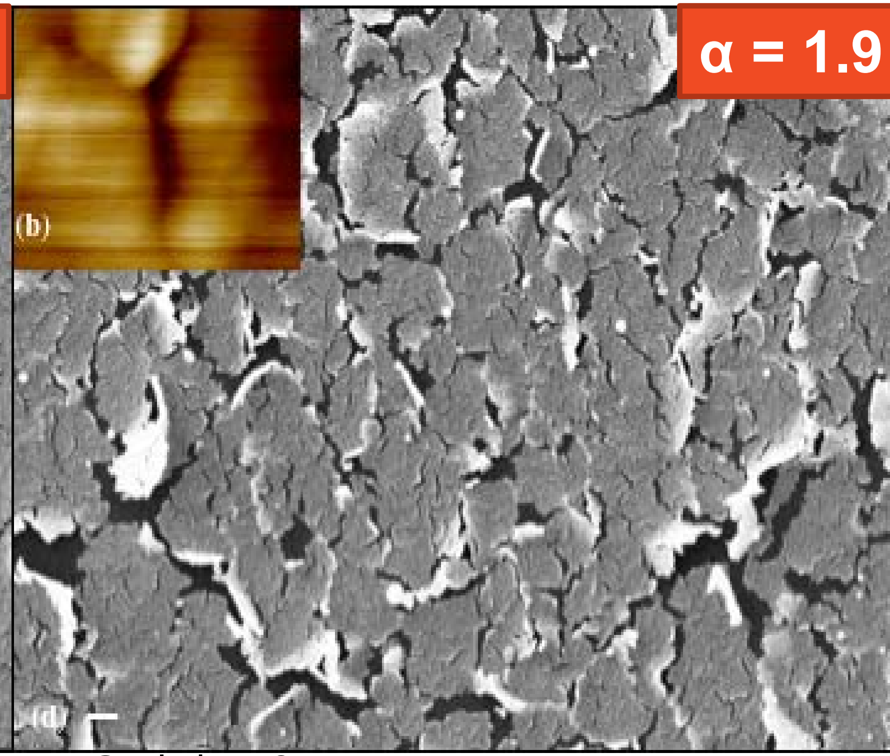
Conductor-PDMS Systems Under Strain

Gold (100nm) on PDMS



Scale bar: 2 μm

Silver (100nm) on PDMS



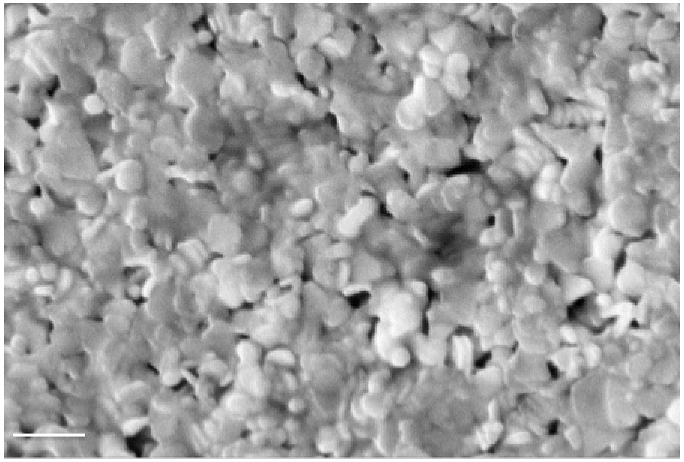
Scale bar: 2 μm

- ✧ AFM (a,b) → discontinuity depth; SEM (c,d) → discontinuity length, width
- ✧ Qualitative inspection supports quantitative α determination

$$m\ (R, \varepsilon) = \left\{\left[\frac{R}{R_0} - (1+\varepsilon)^2\right]\frac{R_0 A}{\rho L(1+\varepsilon)}\right\}^{\alpha(1+\varepsilon)}$$

Printed Silver

- After inspecting post-strained printed silver samples, there were **no discernible discontinuities**
- **Initial resistivity 10x bulk silver resistivity**
- Current additive manufacturing techniques have intrinsic discontinuities



Scale bar: 1 μm

- **Applying tensile strain intensifies discontinuities**; lower modulus polymer does as well
- Applying small strain and returning polymer to initial length restores resistance to R_0

Conclusions

- ✧ Evaporated metals are likely more tolerant to tensile strain than any additively manufactured conductor
- ✧ Developed model to describe conductor resistance during strain
- ✧ Validated model via experimental and qualitative analysis as way to describe microscopic phenomenon with easily attainable data
- ✧ Achieved through α – material dependent "discontinuity percolation factor" (e.g. propagation of cracks, delamination, buckles, etc.)

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I would like to thank the following individuals, without whom the work could not have been completed: Brian Smith, Peter Standley, Joseph Louis, Joseph Ricker, Abigail Spencer

Conductor-Polymer Systems Under Tensile Strain

- Unstretched state: $R_0 = \frac{\rho L_0}{A_0}$
- Stretched state: $R = \frac{\rho L}{A}$
- Assuming volume maintained: $AL = A_0 L_0$

$$\frac{R}{R_0} = \left(\frac{L}{L_0}\right)^2 = (1+\varepsilon)^2 = R_C$$

- R_C is the ideal case; resistance increase ***only*** caused by changing geometry, ***no*** material failure

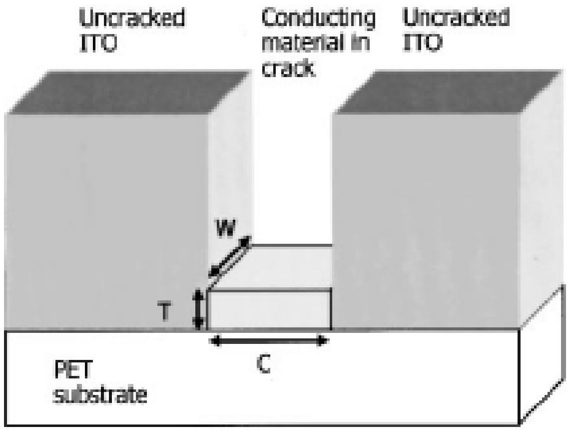
R_D: Discontinuity Induced Resistance

ITO under tensile strain

$$R_D = \frac{\rho\lambda^2}{V}\sum_{i=1}^{m}(\varepsilon - \varepsilon_{ci})^2$$

Conductor-polymer systems under tensile strain

$$R_D = \left[\frac{\rho L(1+\varepsilon)}{A}\right] m^{\frac{1}{\alpha(1+\varepsilon)}}$$



Cairns, et al., APL, 76, 2000

Problems:

1. All ITO discontinuities were cracks that traversed the width of the film
2. Rapid loss of electrical continuity

Solutions:

1. More adaptable
2. α = "discontinuity-percolation factor"

R_D = discontinuity induced resistance
m = number of discontinuities
ρ = resistivity of underlying conductor
λ = length scale of discontinuity
ε = strain
ε_{ci} = strain at initiation of discontinuity 'i'
V = volume of underlying conductor
L = characteristic discontinuity length
A = characteristic discontinuity area
α = discontinuity-percolation factor