Electrostatically driven collapsible Au thin films assembled using transfer printing for thermal switching

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We report deterministic assembly of 100 nm thick suspended gold films using transfer printing that are mechanically collapsible. We demonstrate the latter using electrostatic force to establish and break physical contact between the film and a silicon dioxide substrate in a reversible and repeatable manner. Modeling the thermal conductance at the interface between the suspended film and the substrate, we show that the fabricated structure behaves as a thermal switch. The on-state corresponds to the collapsed film and the off-state to the fully suspended film. The on-to-off state ratio for thermal conductance exceeds $10^6$ in theory. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4720397]

Sub-micrometer thick suspended films find widespread use in micro/nano-scale transduction due to their large surface-area-to-volume ratio and ease of reversible deformation. On account of these characteristics, they are indispensable in sensing, actuation, and switching in micro/nano-devices. While a few devices can be fabricated using wafer-level direct bonding, most suspended films in such devices are fabricated by film deposition followed by etching of the sacrificial layers. Such fabrication is known to generate “fabrication stiction” problems, where thin films are pinned to substrates during aqueous rinse and dry cycles. A wide variety of processing, surface treatments, and physical schemes have been suggested for anti-stiction. However, existing approaches are limited by dimension and materials selection, process complexity, high pressure safety issues, or by the difficulty in scaling to dimensions larger than wafer size.

Here, we report deterministic assembly of a suspended gold (Au) film on supporting structures using transfer printing, inherently without any fabrication stiction. Deterministic assembly (few micrometer lateral resolution) using transfer printing enables not only homogeneous but also heterogeneous materials integration on large area substrates. Research over the last few years has demonstrated capabilities of this technique in fabricating unusual electronic devices for photovoltaics, lighting, chemical and biological sensing, and energy harvesting. One of the outstanding challenges of transfer printing is the deterministic assembly of nanometer scale thick suspended films due to the highly floppy and fragile nature of the thin film as well as a severely reduced contact area between the printed thin films and receiving supporting structures. In this letter, we present deterministic assembly of $100 \times 100 \, \text{µm}^2$ laterally, $100 \, \text{nm}$ thick Au films suspended over $800 \, \text{nm}$ air gap using an advanced form of transfer printing that was recently reported elsewhere. We demonstrate that the assembled thin film can be reversibly and repeatedly collapsed to establish contact with the substrate using electrostatic forces. We propose that this reversibility can be used in fabricating an electrically activated thermal switch and theoretically investigate such behavior.

We have recently reported measurements of the interfacial thermal conductance between transfer printed gold films and different substrates. The interfacial thermal conductance at room temperature ranges between 10 and 40 MW/m$^2$K. This is directly comparable to interfaces formed by sputtered Au films that exhibit thermal conductance of $\sim$65 MW/m$^2$K. The relatively high thermal conductance for transfer-printed films motivates their use in thermal applications where heat conduction can be electrically manipulated by forming and breaking physical contact between a transfer-printed suspended film and a substrate. We describe the design and the fabrication of this structure below, and then use contact mechanics and interfacial thermal transport modeling to predict the performance of the thermal switch based on the fabricated structure.

A $100 \times 100 \, \text{µm}^2$ square and $100 \, \text{nm}$ thick Au film was assembled on an $800 \, \text{nm}$ thick supporting Au layer deposited on a $150 \, \text{nm}$ thick SiO$_2$ layer, both of which were formed on a highly doped Si wafer. The Au layer was patterned to make an open area of $50 \times 50 \, \text{µm}^2$ square and a $10 \, \text{µm}$ wide channel. The open area was covered by the Au film as shown in Fig 1(a). In such configuration, the Au film is suspended on an $800 \, \text{nm}$ air gap and can be mechanically collapsed on the SiO$_2$ layer by electrostatic force when a bias voltage is applied between the Si wafer and the Au layer. The dimensions of the Au film, the Au layer, the SiO$_2$ layer, and the air gap were chosen by studying the mechanical collapse of suspended films under uniform electrostatic attraction. To determine the force for the unit area required to collapse the Au film, we assumed that all sides of the thin film are simply supported on the edge of the $50 \times 50 \, \text{µm}^2$ square opening of the Au layer. Mechanical deflection ($\omega_{\text{max}}$) of the Au film, at the moment the Au film starts to contact with the SiO$_2$ layer, by uniformly applied vertical force per unit area ($P_{\text{mech}}$) is calculated with $\omega_{\text{max}} = c_1 \frac{P_{\text{mech}} L^4}{E h^3}$, where $E$, $h$, and $L$ are Young’s modulus, thickness, and lateral length of the suspended square Au film, respectively, and $c_1$ is a geometric dependent value of 0.0444. Since $\omega_{\text{max}}$ is the air gap, fixed at 800 nm, isolating the force required per unit area ($P_{\text{mech}}$)

\[ c_1 = \frac{3}{2} (1 - \nu^2) \left( \frac{1}{2} \right)^{3/2} \left( \frac{1}{E h^3} \right) \]

\[ E = \frac{3P_{\text{mech}}}{h^3} \]

\[ h = \frac{P_{\text{mech}} L^4}{E} \]

\[ \omega_{\text{max}} = \frac{3}{2} (1 - \nu^2) \left( \frac{1}{2} \right)^{3/2} \left( \frac{1}{E h^3} \right) \]

\[ L = \frac{1}{2} \left( \frac{1}{2} \right)^{1/2} \]

\[ P_{\text{mech}} = \frac{3}{2} (1 - \nu^2) \left( \frac{1}{2} \right)^{3/2} \left( \frac{1}{E h^3} \right) \]

\[ \omega_{\text{max}} = \frac{3}{2} (1 - \nu^2) \left( \frac{1}{2} \right)^{3/2} \left( \frac{1}{E h^3} \right) \]

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\[ L = \frac{1}{2} \left( \frac{1}{2} \right)^{1/2} \]

\[ P_{\text{mech}} = \frac{3}{2} (1 - \nu^2) \left( \frac{1}{2} \right)^{3/2} \left( \frac{1}{E h^3} \right) \]
yields a constant value. The SiO2 layer and the air gap are located in series between the Au film and the Si wafer. Thus, the total capacitance in this combined dielectric layer is

$$C_{\text{tot}} = \frac{C_{\text{oxide}}}{C_{\text{oxide}} + C_{\text{air}}}$$

where $C_{\text{oxide}}$ and $C_{\text{air}}$ are the capacitance of the SiO2 layer and the air gap on 50 $\times$ 50 $\mu$m area, respectively. Each capacitance can be written in terms of thickness ($d$), area (A), and permittivity ($\varepsilon$) of the capacitors as:

$$C = \frac{\varepsilon d}{A}$$

Total potential energy in capacitor is determined by $U = \frac{C^2 V^2}{2}$ or $U = \frac{\varepsilon d A V^2}{2}$. Taking derivatives of this function with respective to thickness ($d$) and dividing by total area yields the function of electrostatic force per unit area, $F_{\text{elec}} = \frac{\varepsilon V^2}{2 (\varepsilon_{\text{oxide}} + \varepsilon_{\text{air}})}$. Substituting $F_{\text{elec}}$ with $F_{\text{mech}}$ and solving for $V$ results in required threshold voltage to induce enough electrostatic force for the mechanical deflection ($\theta_{\text{max}}$) of the Au film. Figure 1(c) is the plot of the threshold voltage and SiO2 breakdown voltage as a function of the thickness of the SiO2 layer. The figure implies that increasing thickness of the SiO2 layer increases the threshold voltage required for collapse. However, the increment of oxide breakdown voltage is much stiffer, resulting in a larger window for us to operate before failure of the device. The breakdown of the 800 nm thick air gap is not a concern since, experimental breakdown voltages of sub-micron ranges at around 70–120 V, according to Hourdakis et al., which is a factor of several times higher than breakdown voltage of the 150 nm thick SiO2 layer.

Au thin films, mechanically collapsible by electrostatic force, were fabricated with chosen dimensions by transfer printing of Au films prepared on a donor substrate onto a target area on a receiver substrate. To fabricate Au films on a donor substrate, we deposited 100 nm gold by sputtering on 1.1 $\mu$m thick thermally grown SiO2 as the sacrificial layer on a Si wafer. After patterning of the 100 $\mu$m $\times$ 100 $\mu$m Au film, the SiO2 layer was selectively etched to define a square area of 120 $\mu$m $\times$ 120 $\mu$m in a concentric alignment with the patterned Au film. Photoresist was spun and patterned on them to form anchors and frame. Final wet etching with HF eliminated the remaining SiO2 layer and the Au film was then suspended on the donor substrate with supporting photoresist anchors. The fabrication of a receiver substrate started with a RCA (standard wafer cleaning steps to remove organic and ionic contaminants) cleaned highly doped silicon (Si) wafer (Ultrasil; $\rho = 0.001–0.006$ $\Omega$cm) and deposited a 150 nm thick SiO2 using plasma enhanced chemical vapor deposition (PECVD; PlasmaTherm). We then sputtered (AJA international, INC) an 800 nm thick Au layer on the SiO2 layer. The deposited Au layer was patterned to define an open area of 50 $\times$ 50 $\mu$m square and a 10 $\mu$m wide channel. The channel allows air to escape when a film suspended on top of the patterned Au layer is electrostatically collapsed on the SiO2 layer. On top of the fabricated receiver substrate, a 100 $\times$ 100 $\mu$m square, 100 nm thick Au film, prepared on the donor substrate, was transfer printed using a microtip stamp, allowing the printed film suspended on the deposited gold layer and over 800 nm air gap (Fig. 1(a)). Figure 1(b) shows a scanning electron microscope image of the Au film assembled on the substrate.

Figure 2(a) shows an illustrative cross section and optical microscope images of the assembled Au film when bias voltage was on and off, respectively. After printing the Au film on the receiver substrate, the film remained free standing in the absence of any voltage across the Au layer and the Si wafer. When a voltage of 12 V was applied across them in a sweep mode, the central air gap region of the Au film, defined by the 50 $\times$ 50 $\mu$m square opening of the Au layer, collapsed mechanically due to the electrostatic force between the Au film and the Si wafer as microscopic images in Fig. 2(a) exhibit. Moreover, the Au film reversibly restored its original flat shape immediately after removing the bias voltage. However, when excessive voltage (approximately 15 V) was applied, central region of the thin film stuck to the SiO2 layer. To test reversibility, we applied bias voltage within a reasonable range (<13 V) and observed the thin film return to its original suspended state for more than 30 times without any observable hysteresis in both mechanical and/or electrical behavior. During applying bias voltage, the capacitance change due to collapsing of the Au film, was measured to demonstrate its deformation in a quantitative way. As the input voltage increases, the capacitance raises and reaches a non-specific certain saturation value, which indicates that the Au film was fully collapsed, thus the total capacitance does not change significantly before a breakdown occurs in the SiO2 layer. The capacitance difference between bias voltage on and off states is about 0.35 pF, which is reasonably lower than the theoretical maximum difference ($C_{\text{oxide}} - C_{\text{tot}}$: 0.55 pF). Collected microscopic images and measured capacitance change obviously demonstrate that the assembled suspended Au film is reversibly collapsible via electrostatic force depending on the bias voltage in a completely controllable fashion.
An application of interest for the fabricated structure is a thermal switch that provides tunable interfacial thermal conductance. In the off-state, an air gap limits heat conduction between the substrate and the Au film. For the geometry considered here, the thermal conductance per unit area (heat transfer coefficient) is the ratio of the thermal conductivity of air to the thickness of the air gap and is \( \frac{1}{C^2} \) kW/m²K. In the on-state, the Au film establishes physical contact with the substrate and heat conduction is limited by interfacial phonon transport. Thermal transport at the Au/SiO₂ interface is complicated due to the involvement of electrons in addition to phonons. Here, we first use the diffuse mismatch model (DMM) to evaluate the thermal conductance at the interface between Au and SiO₂ due to phonons. The DMM assumes phonons scatter diffusely at the interface. The transmission probability is independent of the phonon wave vector and polarization and depends only on the mismatch between the phonon density of states at the interface. Due to the lower Debye temperature, \( \theta_d \), of Au (165 K) compared to that of SiO₂ (492 K), phonons with frequencies higher than the cut-off frequency of Au, \( \omega_d^0 = k_b \theta_d^0/h \), cannot be transmitted across the interface if elastic scattering is considered. At room temperature (295 K), the predicted thermal conductance due to phonon transport is 89.4 MW/m²K, assuming both materials behave as isotropic Debye solids. This is slightly higher than the measured thermal conductance of 65 MW/m²K for sputtered Au on SiO₂. Assuming perfect contact, the discrepancy can be partially attributed to the extra resistance posed in the metal by electron-phonon coupling. The conductance, \( h_{ep} \), can be assumed to be of the form \( h_{ep} = \psi T^{-1/2} \), where \( \psi = 4.09 \times 10^9 \) using the measured value.

In order to proceed with the estimation of the interfacial thermal conductance in the on-state, we need to evaluate the actual contact area depending on the applied force. Here, we use a static model for contacting rough surfaces presented by Kogut and Etsion (KE model), which combines elastic and plastic deformations and the improved Lennard-Jones potential adhesion model originally developed by Derjaguin et al. (DMT model), and extends them to include highly plastic deformation. Briefly, the KE model predicts the contact and the adhesion forces due to asperities in different deformation regimes, which are determined by the degree of the transition from elastic to plastic deformation based on Finite element analysis results. In addition to the adhesion forces considered in the KE model, we include the capillary force due to the water molecules in atmosphere. We assume that the surface is completely covered with a monolayer of water. We note that we have assumed the suspended film to have a similar surface morphology as the SiO₂ substrate. However, the Au film can undergo higher plastic deformation than the model predictions due to ductility. Furthermore, capillary forces may vary substantially based on humidity and condensation at the interface. These considerations limit the quantitative accuracy of the model at present. Despite these limitations, the model provides insight into the possible range of thermal conductance in idealized structures.

Figure 3 shows the change in expected thermal conductance as a function of external electrostatic load applied. The inclusion of capillary forces yields higher thermal conductance by increasing the area of contact. The on-state thermal conductance exceeds 20 GW/m²K. Based on the previous calculation of conductance through the air gap, we find the on-state to off-state conductance ratio to be on the order of 10⁶, suggesting the feasibility of such a structure as a thermal switch. This will be investigated experimentally in future research. We note that we have neglected convection and radiation in considerations of thermal transport and provide justification for this. We do not consider convective transport.
since the sub-micrometer air gap is much smaller than the scale needed for convection cells. Further, we are interested in applications close to room temperature such as in electronics cooling where radiative effects do not dominate.

In summary, nanometer scale thick gold films (~100 nm) over air gap (~800 nm) were deterministically assembled using large area scalable transfer printing technique instead of sacrificial layer or wafer bonding based approaches. Since the suspended films were constructed without any wet process, potential capillary force based stiction or any additional complex process for anti-stiction were eliminated. It was demonstrated that the assembled gold thin film was mechanically collapsible via input voltage bias and its collapsing behavior was very reversible and repeatable. We hypothesize that the fabricated structure can be used as a thermal switch. Our modeling predicts that the on-state to off-state thermal conductance in such a switch exceeds 10^6. Future experimental work will focus on thermal characterization of the structure to verify the potential for thermal switching.

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