CONTROLLED FABRICATION OF NANOSCALE GAPS USING STICTION

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ABSTRACT

Utilizing stiction, a common failure mode in micro/ nano electromechanical systems (M/NEMS), we propose a method for the controlled fabrication of nanometer-thin gaps between electrodes. In this approach, a single lithography step is used to pattern cantilevers that undergo lateral motion towards opposing stationary electrodes separated by a defined gap. Upon wet developing of the pattern, capillary forces induce cantilever deflection and collapse leading to permanent adhesion between the tip and an opposing support structure. The deflection consequently reduces the separation gap between the cantilever and the electrodes neighboring the point of stiction to dimensions smaller than originally patterned. Through nanoscale force control achieved by altering device design, we demonstrate the fabrication of nanogaps having controlled widths smaller than 15 nm. We further discuss optimization of these nanoscale gaps for applications in NEM and molecular devices.

INTRODUCTION

As dimensions are continuously scaled down to achieve electronic, photonic and electromechanical devices with improved performance and novel principles, developing methods for the controlled fabrication of electrodes separated by nanometer-thin gaps is important to enabling reliably-functioning devices. Current methods of fabricating such nanogaps include oblique-angle shadow evaporation, electrochemical deposition, electromigration, mechanical break junctions, molecular junctions and etching of nanometer-scale sacrificial layers [1-5]. However, these approaches, mainly developed for two-terminal devices, commonly involve multiple processing steps and lack robustness and tunability, thus preventing effective incorporation into more complex multi-terminal designs. These limit their practical applications in integrated systems.

A common mode of failure in electromechanical systems is permanent adhesion between device components, referred to as stiction. Stiction arises due to the surface adhesion forces overcoming the elastic restoring force of a mechanically active structure, leading to its collapse and hindering its recovery. As surface adhesion forces increase with the decrease in gap dimensions, stiction becomes increasingly more challenging in NEM devices.

Here, we propose the use of stiction, typically considered an irreversible failure mode, to promote controlled fabrication of electrodes separated by nanoscale gaps of varying widths. The feasibility of this approach to form nanogaps with dimensions smaller than 15 nm, and their potential applications are investigated in this paper.

DESIGN PRINCIPLES

Capillary forces exerted on the mechanically-active structures of electromechanical systems by the drying of the liquid trapped in the small gaps of the devices after wet fabrication processing can readily lead to stiction [6]. Taking advantage of this stiction, our proposed method of fabricating nanogaps relies on control of the surface adhesion forces at the nanoscale to enable control of cantilever deflection that is used to tune the gap. The laterally-actuated cantilever and other device components are fabricated through a one-step lithography process. During the wet developing of the patterned structures, capillary forces induce deflection and eventual collapse of the cantilever. The stiction between the cantilever and a support structure enables formation of gaps smaller than originally patterned between the cantilever and additional electrodes located relative to the point of stiction. Through changes to the structural design and liquid phase processing step, surface adhesion forces caused by the capillary action can be adjusted to allow for precise control of the gap size.

FABRICATION

The fabrication scheme for stiction-induced formation of nanogaps is shown in Figure 1. Five layers of poly(methyl-methacrylate) (PMMA), a positive electron beam resist, are spun over a silicon (Si) substrate with 2 µm-thick thermal oxide (SiO_2). Each layer is spun at 2000 rpm for 45 s and baked at 180 ^oC for 90 s. The initial three layers of PMMA have molecular weight of 495 kg/mol (PMMA 495 A6) and the following two layers have molecular weight of 950 kg/mol (PMMA 950 A4). Next, the cantilever and other electrodes are defined by patterning the PMMA film using electron-beam (e-beam) lithography. The resist is developed in 1:3 dilution of methyl isobutyl ketone (MIBK) in isopropanol for 3 min, placed in an isopropanol bath to thoroughly rinse, and dried under a gentle stream of nitrogen normal to the surface. Finally, about 10 nm of chromium (Cr) and 100 nm of gold (Au) are deposited over the substrate using thermal evaporation to form the electrodes.

The five layers of PMMA of two different molecular weights with a total thickness of about 1.5 µm allow fabrication of large aspect ratio features with an undercut profile, a thinner base and a thicker top section. The undercut is achieved due to the differential dissolution rate of PMMA of varying molecular weights in MIBK; lower molecular weight PMMA has a faster dissolution rate than the higher molecular weight PMMA. The undercut prevents sidewall coverage during metal deposition and ensures electrical isolation between the electrodes. The undercut and the high aspect ratio of the PMMA cantilever also

enable the structure to freely deflect due to an applied force.

During the wet-developing process, a capillary force is exerted on the cantilever (Electrode 1) in Figure 1. This force can cause deflection of the cantilever. If sufficiently large to overcome the spring restoring force, the cantilever collapses on to an opposing PMMA support structure (Electrode 2) and undergoes stiction. The deflection and stiction reduce the gap between the cantilever and other electrodes positioned along the length of the cantilever away from the point of stiction, leading to the formation of nanogaps smaller than originally patterned. The spring constant of the cantilever can be adjusted by altering its geometry and the relative positioning of counter electrodes. Then, by adjusting the surface adhesion forces, one can control the extent of deflection and its profile such that desired gap dimensions are achieved. The formed nanogaps can further be reduced in size by evaporating a thin-film of metal onto the PMMA structures to define the conductive electrodes. The reduction in gap size during this processing step is dependent on the thickness of the deposited film.

RESULTS AND DISCUSSION

The feasibility of utilizing stiction to develop nanogaps smaller than patterned in a single lithography step is shown in Figure 2. To promote stiction, the capillary forces must overcome the elastic restoring force of the cantilever, causing the irreversible collapse of the structure. By altering the design and processing conditions, including the dimensions of the cantilever, the patterned gap size, and the liquid used, the surface adhesion forces can be altered to ensure collapse of the active structure during the wet processing. The nanogap fabrication presented above is not limited to the material sets used in our proof-of-concept approach. Similar results are expected in cases where materials other than PMMA and Au are used. Furthermore, different materials selections provide an additional means of controlling the surface adhesion forces and the stiction process [8]. In the cantilever of Figure 2, fabricated using the scheme in Figure 1, stiction is promoted by decreasing the gap size between Electrode 1 and Electrodes 2 and 3 by approximately 30 nm. Once collapsed, an effective gap of ~50 nm between Electrodes 1 and 3 at the point closest to the stiction region is achieved compared to the 200 nm gap in a similar cantilever that has not undergone stiction.

Through engineering of the spring constant of the cantilever, and the geometry and relative placement of the opposing electrodes, the size of the nanogaps can be controlled. An example ~35 nm gap fabricated is shown in Figure 3. Figure 3b illustrates the reduction in the gap size to ~10 nm by positioning Electrode 3 closer to the point of stiction. The tunability of the gap dimension is further demonstrated in Figure 4 where gaps ranging from about 10 nm to 170 nm are formed. As shown, the process is not limited to two-terminal structures. Further, through the same lithography step, devices with multiple electrodes can be fabricated. These multi-terminal devices are more relevant to applications in integrated systems and allow

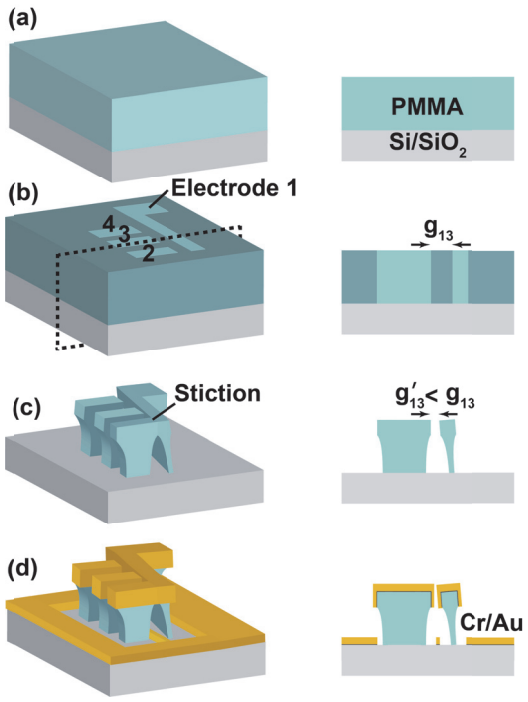

Figure 1: Controlled fabrication of nanoscale gaps using stiction; (a) multilayer PMMA e-beam resist is spun onto Si/SiO_2 substrate and baked after each spin, (b) resist is patterned using e-beam to define cantilever and opposing electrodes separated by a defined gap "g", (c) resist is developed in 1:3 solution of MIBK in isopropanol, rinsed in isopropanol bath and dried under a stream of nitrogen, (d) ~10 nm of Cr and ~100 nm of Au is evaporated onto the patterned structures defining the electrodes.

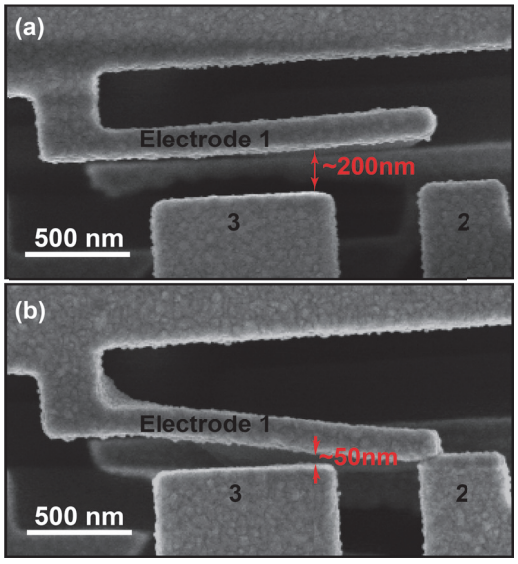

Figure 2: Stiction promotes formation of nanogaps smaller than patterned; (a) Scanning electron micrograph (SEM) of a cantilever with a gap of ~200 nm, (b) SEM of the same cantilever positioned closer to electrodes 2 and 3. Larger capillary force in (b) causes collapse of the cantilever, leading to stiction and reducing the gap between 1 and 3.

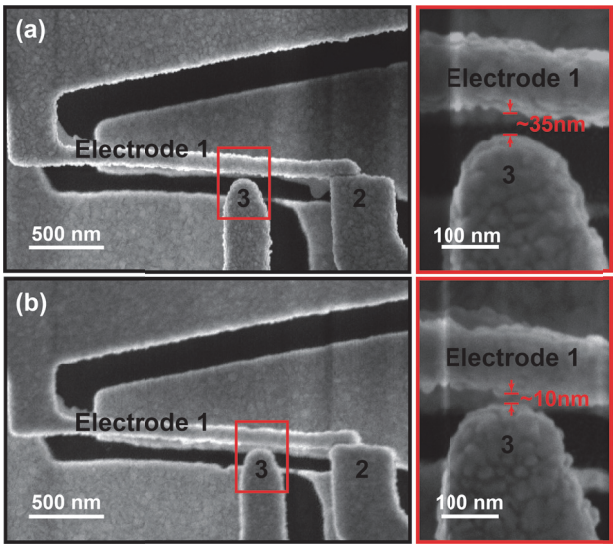

Figure 3: SEM of nanogaps fabricated using the scheme in Figure 1. Capillary forces during wet developing of the pattern cause stiction between Electrodes 1 and 2, while forming a gap of ~35 nm (a) and ~10 nm (b) between Electrodes 1 and 3. The smaller gap in (b) is achieved by positioning Electrode 3 closer to 2.

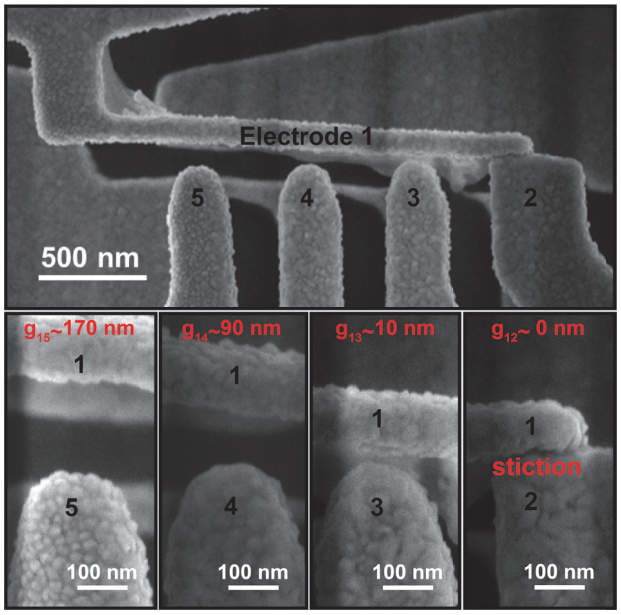

Figure 4: Optimizing device architecture and electrode placement relative to the point of stiction allow achieving nanogaps with controlled width, useful for fabrication of various multi-terminal devices.

exploration of more complex device designs and concepts.

A potential application of the proposed nanogap fabrication scheme is in the development of NEM switches, which, with their large on-to-off current ratios, abrupt switching and near-zero leakage currents have emerged as technology competitive with complementary metal-oxide-semiconductor transistors [8]. However, the need for large actuation voltages is among the main challenges preventing integration of NEM switches into widely used systems. To reduce the operating voltage, decrease in the size of the switching gap is necessary, as it leads to an increase in the electrostatic force of actuation. The reduction of the nanogap size to the few-nanometer regime, however, has been a fundamental fabrication challenge. Typically, as the size of the switching gap decreases, the yield of functional devices lowers due to failure modes such as stiction during fabrication. In contrast, in our proposed approach the stiction is used to benefit nanogap formation. Depending on device design, the collapsed electrode can be made to remain stationary or undergo mechanical motion with an applied voltage. As shown in Figure 5, a smaller gap and a more flexible cantilever allow electromechanical modulation of the gap. In this two-terminal example a current modulation of 10^{11} is achieved within 3 V applied bias. The desired switching performance can be achieved through the optimization of the fabrication technique. This approach can also be extended to three terminal NEM switches that more closely resemble the conventional transistors. A prototype design is shown in Figure 5b.

Nanogaps have also been widely desired for applications in molecular electronics that rely on metal-molecule-metal junctions. These gaps are conventionally formed using techniques such as direct deposition of metallic contacts, which has the potential to damage the fragile organic molecular layer, leading to low yields of working devices and structures that lack robustness. Through the proposed stiction-induced nanogap fabrication, damage to the molecular layer can be avoided as the molecules are introduced into the gap after electrode formation through techniques such as vapor deposition or liquid-phase self-assembly. In self-assembly molecules are functionalized with terminal groups that enable selective attachment onto the electrode surfaces. For example

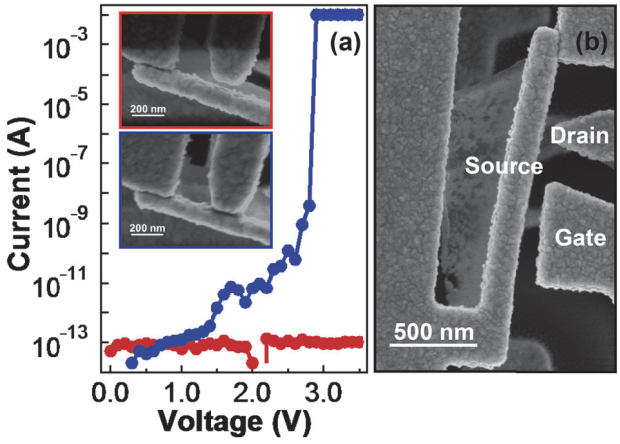

Figure 5: (a) Through altering device geometry to achieve smaller gaps and more flexible cantilevers, nanogaps can be fabricated to undergo electromechanical modulation (blue compared to red), useful for applications in NEM switches. Insets show corresponding devices with the bottom cantilever (blue) ~20 nm thinner than the top (red). (b) Prototype design of a three-terminal NEM switch.

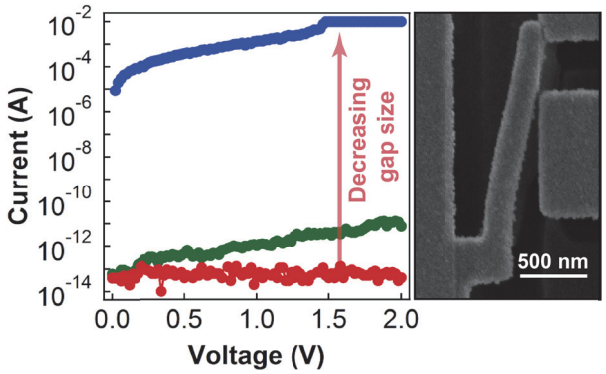

Figure 6: The current-voltage characteristics of three gaps of different sizes with molecular layers of fluorinated decanethiols self-assembled on the Au electrodes (left). Representative SEM image of the devices tested (right). Nanogaps of different sizes are achieved using the same design while changing the size of original gap patterned.

thiolated molecules self-assemble onto gold [9]. Figure 6 shows the current-voltage characteristics of nanogaps of different sizes with thin-films of fluorinated decanethiol self-assembled on the Au surface using vapor phase deposition. As expected, a general increase in current is observed with the decrease in gap size. Further interpretation of the data to extract information about the nature of the molecular junction requires more detailed experimentation. We speculate that as molecular layers are formed, further decrease in gap size can be achieved through changes in surface adhesion forces imposed by changes in surface properties. This approach is also valuable to form anti-stiction coatings in NEM devices to enhance operation reliability, and to form molecular switching gaps for quantum tunneling NEM switches [10].

Although providing a promising platform for fabrication of nanogaps, the proposed technique faces some challenges that must be addressed. As observed through the SEM images, the as-deposited metal electrodes have a large surface roughness, which introduces inhomogeneity in the gap size, makes the devices susceptible to electrical shorting and can alter device performance. This can be overcome by exploring materials alternative to Au and PMMA or through use of techniques such as atomic layer deposition to form atomically smooth surfaces. In addition, functional devices that require nanogaps with asymmetric metal electrodes of different materials can be envisioned. Enabling such structures requires modifications to the fabrication scheme that may increase its complexity.

CONCLUSION

A method for controlled fabrication of nanometer-scale gaps is proposed that utilizes stiction, a common source of failure in electromechanical systems. Capillary forces induced during liquid phase processing of the sample cause deflection of a movable electrode and consequent stiction. The deflection leads to reduction in the size of the gaps patterned. The experimental results support the feasibility of the proposed method to fabricate nanogaps, with controlled widths smaller than 15 nm, through the engineering of surface adhesion forces. Further optimization of this versatile fabrication platform allows nanogap development for various applications including electromechanical and molecular devices.

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