ELECTROSTATIC BENDING ACTUATORS WITH A LIQUID FILLED NANOMETER SCALE GAP

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ABSTRACT

We report a considerable improvement in the electrostatic actuation of silicon-based nano electrostatic drive (NED) structures [1] via the insertion of a liquid into the nanosystem. The dielectric liquid provides an insulating, high dielectric constant deformable medium in the electrode gaps that enhances the generated force per unit-applied volt performance. The study demonstrates that small volumes of liquids (microfluidics/nanofluidics) can be inserted into micro and nanoelectromechanical systems (MEMS/NEMS) to enhance systems' performances up to 2.75.

INTRODUCTION

The electrostatic approach is an excellent choice for actuation of micro and nanoelectromechanical systems (MEMS/NEMS) for several reasons: MEMS/NEMS processes which are used for the fabrication of electrostatic actuators are standard and compatible with CMOS technology. Also, in respect with the pull-in problematic [2], the inverse square relation between the generated actuation force and the electrodes' separation distance enables one – with a downscaling of the gap – to expand actuation possibilities that has advantages over other physical driving principles. In this paper, we propose the development of a MEMS/NEMS NED actuator using a fluid as a gap medium in order to improve its electrostatic actuation capabilities.

DESIGN

The NED actuator (shown in Fig. 1) is composed of a number of facing electrodes, mounted on a cantilever and separated by electrically insulated spacer layers.

When applying a potential difference to the electrodes, the electrostatic force attempts to pull down the top electrode to the bottom electrode. Due to the V-shaped topography of the electrodes, a lateral mechanical force is generated which induces a lateral strain in the surface of the cantilever causing a cylindrical bending of the cantilever. The well-established electrostatic force equation is as follows:

$$F = \varepsilon_0 \varepsilon_r V^2 A / 2d^2$$

This gives the linear relationship between the generated force F between the two electrodes of surface A, facing each other at a distance d at a potential difference V, and the relative permittivity ε_r of the medium to the vacuum permittivity ε_0. The fundamental idea of this study is to increase the value of the relative permittivity in the electrostatic gap by using a dielectric fluid – the performance enhancement in terms of actuation force is thus $\varepsilon_{liquid}/\varepsilon_{air}$.

METHODS

The NED structure used to perform the study was produced using the fabrication process presented in Fig. 2. The MEMS/NEMS structure contains electrode gaps with a distance d of 200 nm. In order to perform the experiments, a suitable fluid with a dielectric constant higher than air has to be introduced into the electrode gap to enhance the electromechanical performance of the NED cells. A number of conditions need to be fulfilled to enable this: (1) The dielectric constant of the liquid should be larger than that of air to have an actuation enhancement effect. (2) The fluid has to be an insulating, dielectric liquid to avoid electrical shorting between the electrodes. (3) There should be no chemical reaction between the fluid and the solid parts of the NEMS/MEMS. (4) The liquid should have a relatively

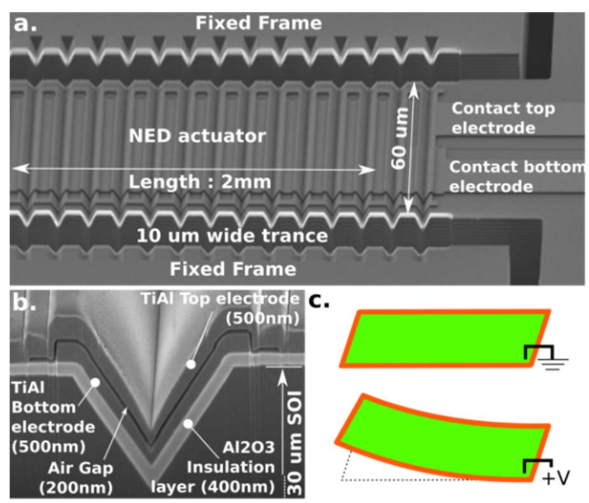

Figure 1: Scanning electron micrograph images (SEM) showing (a) the base of a NED actuator cantilever, (b) a zoom of a cross-section (obtained using focused ion beam) of a single actuation cell, and (c) a schematic diagram illustrating the bending behavior of the actuator.

low viscosity to enable structural deforming at kHz-range operation frequencies. (5) The liquid/structure combination must allow spontaneous capillary filling of the MEMS/NEMS gap by the liquid. (6) Capillary forces generated by the presence of liquid menisci should not cause a modification of the NEMS/MEMS structure. (7) Evaporation of the liquid should be neglectible and not affect the system's performance.

Table 1 shows the relevant parameters for the selected fluid (olive oil) for the demonstration here – although other dielectric liquids with optimized properties could be used in a final design.

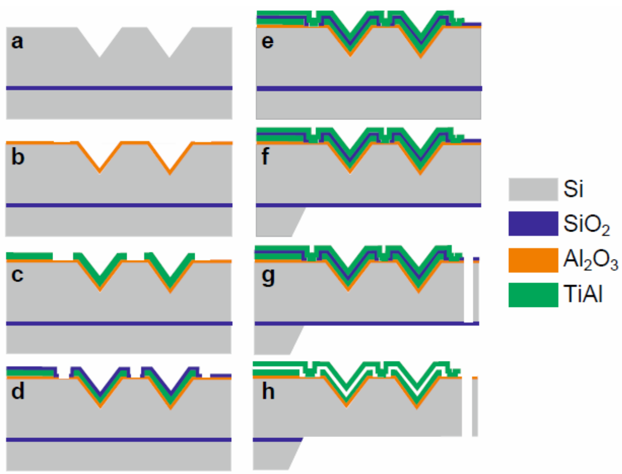

Figure 2: Fabrication process of the NEDs. (a) Wet etching (b) Atomic Layer Deposition of Al_2O_3 (c) Sputtering of 1st TiAl film (d) Chemical Vapor Deposition of SiO_2 (e) Sputtering of 2nd TiAl (f) Handle Silicon removal (wet etch) (g) DRIE etching and (h) HF vapor etch release.

Table 1: Properties of the oil (olive) used for the study (20 °C / 1 atm).

CA on TiAl	Θ	15.4 ± 0.3	deg
Surface tension	γ_{lv}	32	mJ m^{-2}
density	P	850	kg m^{-3}
Rel. permittivity	ε_{liquid}	2.75 ± 0.35	-
Evaporation flux	α_{vol}	-10.7	ml hr^{-1} m^{-2}

The effect of capillary forces on the NEMS structure

Another issue that needs to be considered in the design, the setup, and the measurements is the influence of capillary forces on the mechanical structures of the MEMS/NEMS. It is known that capillary forces can deform a MEMS structure – both in a negative way, e.g. stiction [5] and a positive way, e.g. dimension reduction [6]. This modification of the structure occurs because there are menisci present which generate a pressure difference and capillary forces which act on the solid mechanical parts. Here, the channels are closed along the structure but open at the actuator sides – the presence of menisci in combination with very narrow/wide gaps allows us to estimate the capillary pressure to be 0.3 MPa. This is considerable and implies that a small 'reservoir' of oil is favorable at the gap ends for functioning.

Evaporation of the liquid

Evidently evaporation of the liquid should not affect the performance of the NED actuator. Evaporation could have two consequences for device performance: (1) reduction of the effective dielectric constant of the gap, and (2) stiction of the electrodes. Microfluidic tests enable an estimation of the room temperature evaporation flux per surface of the oil. If we consider that the density of the oil to be 850 kg m^{-3} then the mass evaporation flux (α_{mass}) can be estimated to be -2.5×10^{-6} kg s^{-1} m^{-2} – compare this to the much higher value for water ~-5×10^{-4} kg s^{-1} m^{-2} [7] - implying that during the measurement time (hours), the system is unaffected by evaporation of a long period of time. FEA modelling (Ansys, USA) predicts a reduction of the gap volume of 1.43 % that for an excitation voltage of 30 V applied to the structure when the electrostatic gap is filled with oil.

Relative permittivity of the liquid

In order to evaluate the actuation enhancement ratio of curvature of the NED cantilever having electrostatic gaps filled with oil, the relative permittivity of olive oil has been measured. The measurement was achieved *in situ* over 6 different chips, by connecting the NED systems to an impedance meter (HP4284A Agilent, USA). A first measurement of the system with air-filled gap permitted, following the estimation of the impedance of the NED in air using finite element modeling (Ansys, USA), to estimate the parasitic capacity present aside the NED. The system was then filled with oil in order to perform a second impedance measurement. The permittivity of the olive oil was then measured as the ratio of impedance of the NED in case of air filled and oil filled gaps. The results of that measurement are reported in Table 1. A relative permittivity value of 2.75 ± 0.35 in the frequency range 1 kHz at 0.1 V was measured for the oil.

Sample preparation – 3 different configurations

In order to perform the study, the single test structure having three different microfluidic configurations has been used and is presented in Fig. 3.In the following of the paper, the standard NED, with its electrostatic gaps filled with air and actuated in the air is defined as **Sample 1**. Following the first set of measurements, the packaging containing the NED was filled with oil, allowing the entire NED to be fully dipped in the liquid. During this preparation, the electrostatic gaps of the NED cantilever are expected to be filled with oil due to the spontaneous capillary effect. This configuration will be referred to as **Sample 2**. Finally, using absorbent paper, the oil was carefully removed from the die to create a third sample having oil in the gaps only. The horizontal alignment of the NED cantilever with the surrounding frame was optically checked with an optical microscope (Leica DM8000M, Germany), thus confirming the absence of liquid under the NED cantilever. In this case, the electrostatic gaps are still filled with oil when the NED cantilever is freely moving in air. This configuration is referred to as **Sample 3**. A this stage, two important points should be mentioned: (1) The NED is based on electrostatic actuation. This implies the deformation of the electrodes during the actuation effectively reduces the volume of the gaps. The actuation of the NED with gaps filled with oil – considered an incompressible liquid – is only possible due to the openings that are present at each side of the electrostatic gap. (2) The low evaporation rate of oil at room temperature allows one to consider the gap permittivity to be constant during the measurements.

RESULTS

The measurements are obtained using a digital holographic microscope (Lyncee-Tech, Switzerland). Each sample has been tested at first from a quasi-static measurement, in order to measure the maximum deflection of the samples, and then from a dynamic measurement, in order to evaluate the evolution of the dynamic response. For the quasi-static analysis, a sinusoidal potential difference (maximum amplitude of 30 V at 20 Hz, no bias), has been applied between the electrodes over 4 periods. This analysis has been performed quasi-statically, i.e. at a low frequency that allows one to neglect the dynamic parameter of the system such as inertial or damping effects. It also allows one to evaluate the total amplitude of the actuator displacement. For the dynamic analysis, a frequency scan has been performed from 250 Hz to 4.3 kHz. In order to limit the amplitude of the excitation voltage above 4 kHz has been reduced from 30V to 5 V.

Fig. 4 plots the measured variation in curvature (normalized to actuation using an air gap) as a function of amplitude of the displacement at resonance frequency, the applied actuation voltage. The relative curvature ratio is ~4.1 in the case of Sample 2, corresponding to the actuators dipped in liquid and ~2.8 in the case of Sample 3, corresponding to liquid filled gap NED structures operating in air. In the case of Sample 3, the increase in the cantilever tip displacement amplitude (directly linked to the curvature along the NED actuator) is in excellent agreement with the theoretically expected enhancement derived from the previously presented and measured permittivity of the oil. In the case of Sample 2, the increase of curvature is 50 % higher than expected, indicating the influence of extra effects influencing the deflection in a constructive manner.
Fig. 5 shows the frequency response of the different samples demonstrating the effect of the external medium and the gap medium on the dynamic behavior of the structure. At low frequency (<1 kHz), sample 2 is presenting a loss in bending, strongly affecting the bending behavior at higher frequencies. Similarly, the bending of sample 3 is reducing till 3 kHz with a minimum of 65 % of the amplitude of sample 1, proving, due to the presence of oil, an internal damping of the cells increasing with the frequency. However, the resonance frequency is not significantly affected by the presence of oil as a gap medium. In contrast, when the NED is plunged in oil, no resonance peak can be observed – see Fig. 5 (left), justifying the large damping of the oil as a surrounding medium for the actuator.

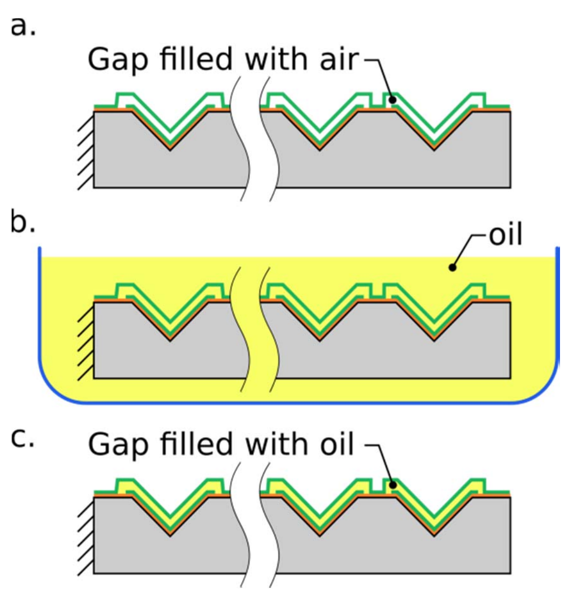

Figure 3: Schematics diagram showing the three set-ups used for the experiment with (a) the original NED clamped-free cantilever, *(b) the structure dipped in the oil and (c) the structure with oil in the gaps, only*

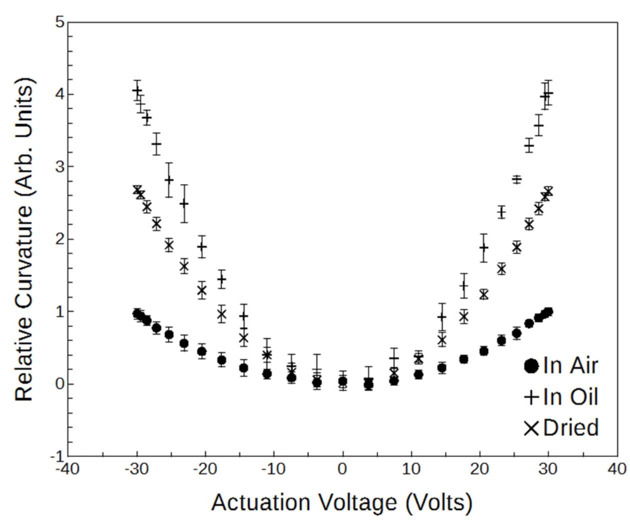

Figure 4: Experimental results of the bending response of the actuator over a [-30V to +30V] voltage sweep, sample 1, in air, (●), sample 2, in oil ambience (+), and, sample 3, with oil in the gaps, only (×), relative to the maximum curvature achieved in air.

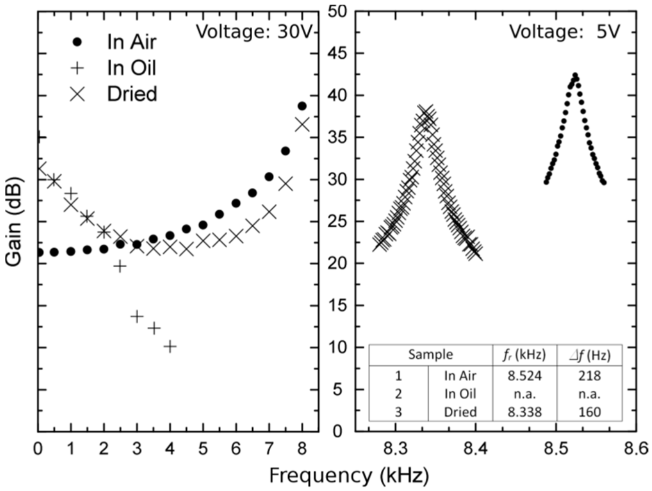

Figure 5: Experimental results of the dynamic response of sample 1, in air, (●), sample 2, in the oil (+), sample 3, with oil in the gap (×).

CONCLUSIONS

The already highly performant NED actuators have been shown to be improved via the insertion of a suitable dielectric liquid into the electrode gap. At low frequency, the actuation enhancement is related to the ratio of the dielectric constant of the liquid compared to that of air. This operation has an effect on the damping of the structure. However, the structure is still showing a resonance behavior without significant frequency variation. The amplitude at resonance is reduced by 35%. It is hoped that higher dielectric constant/low evaporation rate liquid (e.g. ethylene glycol, $\varepsilon_r = 37$) can further improve such systems' actuation. Finally, the study clearly demonstrates that smallvolumes of liquids (microfluidics/nanofluidics) can be used in conjunction with micro and nanoelectromechanical systems (MEMS/NEMS) to enhance systems' performances at low frequencies.

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