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Suppression of the pull-in instability for parallel-plate electrostatic actuators operated in dielectric liquids

B. Legrand,^{a)} A.-S. Rollier, D. Collard,^{b)} and Lionel Buchaillet

Institut d'Electronique, de Microélectronique et de Nanotechnologie, IEMN CNRS, UMR8520, ISEN Department, 59652 Villeneuve d'Ascq, France

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We study electrostatic parallel-plate actuators operated in dielectric liquids. The stable operation zone of the actuators in common liquids is extended far beyond one-third of the initial gap, which is the typical limit of stability for such actuators operated in air. The pull-in effect can even be totally suppressed. In spite of higher dielectric constants in liquids than in air, which is expected to magnify the electrostatic forces, the required voltages to actuate are not significantly reduced and may even be larger. These results are discussed with regard to the dielectric constant of the liquids and to the electrical insulating layers of the parallel plates which appear to play a major role. Finally, the analytical approach is compared to experiments performed on fabricated devices. © 2006 American Institute of Physics. [DOI: 10.1063/1.2165282]

Electrostatic actuators are extensively used in silicon based microelectromechanical systems (MEMS) as they demonstrate simple fabrication, easy integration with integrated electronics, short response times, and proven reliability. In particular, parallel-plate actuators are commonly used in devices such as deformable membranes,¹ variable capacitors,² optical,³ and radio-frequency⁴ microswitches or electromechanical resonators.⁵ The voltage-displacement characteristic exhibits in air an instability called the pull-in effect, which limits the stable positioning of the mobile plate to one-third of the gap prior to collapse.⁶ This effect is a great advantage when a binary state actuation is required^{3,4} but represents a drawback for continuous mode actuation^{1,2} since the displacement is limited to one-third of the full gap. In spite of the wide-ranging use of electrostatic actuation in air or in vacuum, very few applications have been developed in microfluidic environments. Such applications are however very promising because direct integration of electrostatic actuators would simplify the design and fabrication of microfluidic MEMS and allow the integration of more complex components.⁷ Moreover, electrostatic actuation is expected to benefit from a much higher energy density in liquids due to the larger dielectric constant than in air (e.g., $\epsilon_r=80$ in water). Recent work⁸ has demonstrated that electrostatic actuation is feasible in many aqueous electrolytes and other dielectric liquids by counteracting electrode potential screening and undesirable electrochemistry⁹ using ac drive signals. In this letter, we study the voltage-displacement characteristics of MEMS parallel-plate actuators in dielectric liquids. Analytical approaches show that the electrical insulating layers of the plates play a major role in the actuator displacement characteristics and that the stable operation zone is extended far beyond one-third of the gap, even leading to the elimination of the pull-in effect. The analytical modeling is then compared to experiments performed on fabricated MEMS actuators.

An electrostatic parallel-plate actuator is typically modeled as shown in the inset of Fig. 1. It is considered as a

capacitor having a fixed electrode while the second electrode is mobile, connected to a mechanical spring of constant k , and free to move along the x axis when an electrostatic force is induced on the plate by applying a voltage V between the two plates. An electrical insulating layer of thickness e_1 [respectively, (resp.) e_2] and of dielectric constant ϵ_{r1} (resp. ϵ_{r2}) is deposited on the mobile (resp. fixed) plate so as to prevent any short circuit when the gap between the plates is closed. g is the initial gap value at zero voltage and the actuator is operated in a medium of dielectric constant ϵ_{rL} . The force F_{tot} along the x axis, acting on the mobile plate results from the capacitive electrostatic force¹⁰ and the spring restoring force. F_{tot} is given by

$$F_{\text{tot}} = \frac{\epsilon_0 \epsilon_{rL} S V^2}{2g^2(\gamma - u)^2} - kgu, \quad 0 \leq u < 1, \quad (1)$$

where $\gamma = 1 + (\epsilon_{r1}/\epsilon_{rL})(e_1/g) + (\epsilon_{r2}/\epsilon_{rL})(e_2/g)$, $u = x/g$, S is the area of the plates, and $\epsilon_0 = 8.85 \times 10^{-12}$ F m⁻¹. This result applies either in the limit of a high drive signal frequency or assumes no ions in the dielectric liquid.

In order to obtain a stable equilibrium position of the actuator versus voltage, the following conditions (2) have to be satisfied:

$$F_{\text{tot}} = 0 \text{ and } \left(\frac{\partial F_{\text{tot}}}{\partial u} \right)_V \leq 0. \quad (2)$$

From Eq. (2), we obtain in Eq. (3) the voltage V required to have a mechanical equilibrium at the position u and the range of values of u for which the system is stable:

$$V = \sqrt{\frac{2g^3k}{\epsilon_0 \epsilon_{rL} S}} (\gamma - u) \sqrt{u} \text{ and } u \leq \frac{\gamma}{3}. \quad (3)$$

From Eq. (3), we can deduce that if γ is greater than 3 then the system can be positioned at any location within the gap in a stable manner. If we first consider an actuator operated in air ($\epsilon_{rL}=1$), with a gap of a few micrometers [typically (typ.) $g=2 \mu\text{m}$] and insulating layers of a few hundreds nanometers (typ. $e_1=e_2=300 \text{ nm}$, $\epsilon_{r1}=\epsilon_{r2}=8$ for silicon nitride),¹¹ γ is very close to 1 so that the actuator is stable for $u \leq \gamma/3 \approx 1/3$; that is to say over one-third of the gap. Note

^{a)}Electronic mail: bernard.legrand@isen.fr

^{b)}Present address: LIMMS/CNRS-IIS, University of Tokyo, Japan.

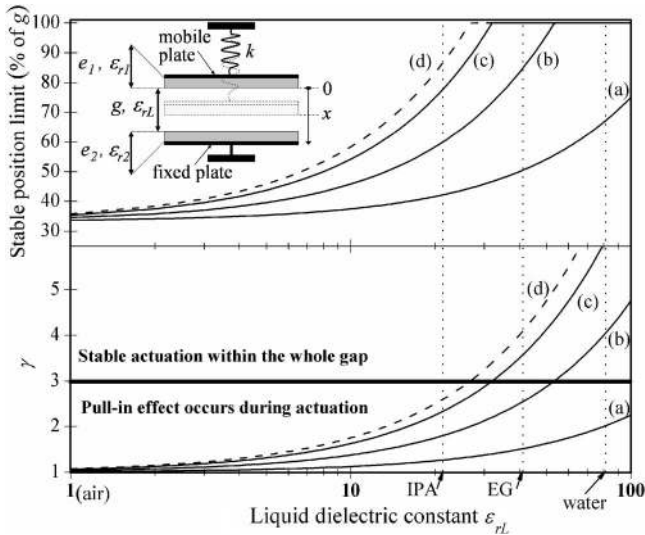


FIG. 1. Value of γ (lower) and extension of the stable operation range (upper) of a parallel-plate actuator operated in a liquid of dielectric constant ϵ_{rL} , for: (a) $e_1=e_2=0.05\text{g}$ and $\epsilon_{r1}=\epsilon_{r2}=8$, (b) $e_1=e_2=0.15\text{g}$, and $\epsilon_{r1}=\epsilon_{r2}=8$, (c) $e_1=e_2=0.25\text{g}$ and $\epsilon_{r1}=\epsilon_{r2}=8$, and (d) $e_1=e_2=0.15\text{g}$ and $\epsilon_{r1}=\epsilon_{r2}=4$. The inset shows a schematic diagram of the parallel-plate electrostatic actuator.

that in air, due to the low value of ϵ_{rL} , it is nearly impossible to avoid actuation instability using reasonable insulating layer thicknesses. Hence, the insulating layers are generally neglected in air for the calculations and using this assumption we can retrieve, using Eq. (3), the well-known value of the pull-in voltage $V_{\text{pull-in,air}}$ by considering the voltage V required to position the actuator at the limit of stability in air (i.e., $\gamma=1$ and $u=1/3$):

$$V_{\text{pull-in,air}} = \sqrt{\frac{8kg^3}{27\epsilon_0 S}}. \quad (4)$$

For voltages greater than $V_{\text{pull-in,air}}$, the electrostatic force becomes larger than the spring restoring force irrespective of the actuator position. As a consequence, the mobile plate collapses onto the fixed plate.

Let us now consider operation of parallel-plate actuators in liquids where ϵ_{rL} is of the order of 1–100, which is the case for common liquids, such as water ($\epsilon_{rL}=80$ at low frequency). In this case, γ can be greater than 3, even with reasonable insulating layer thicknesses e_1 and e_2 , leading to the elimination of the pull-in effect and to the possibility of positioning the actuator at any location within the gap. In order to illustrate this effect, Fig. 1 shows the extension of the actuator stable operation regime and the variation of γ with the liquid dielectric constant and the thickness of the insulating layers. For common liquids—such as isopropyl alcohol (IPA), ethylene glycol (EG) or water—stable operation of the actuator is obtained far beyond one-third of the gap. When condition (5) is fulfilled:

$$\frac{e_1}{\epsilon_{r1}} + \frac{e_2}{\epsilon_{r2}} \geq \frac{2g}{\epsilon_{rL}}, \quad (5)$$

which corresponds to $\gamma \geq 3$, the pull-in effect is avoided and actuator stability is achieved within the whole gap g . We note that for example in Fig. 1(b), a parallel-plate actuator with 300 nm thick silicon nitride insulating layers ($\epsilon_r=8$) and $g=2\ \mu\text{m}$ does not exhibit the pull-in effect in water ($\epsilon_{rL}=80$) any longer, whereas the instability still occurs in

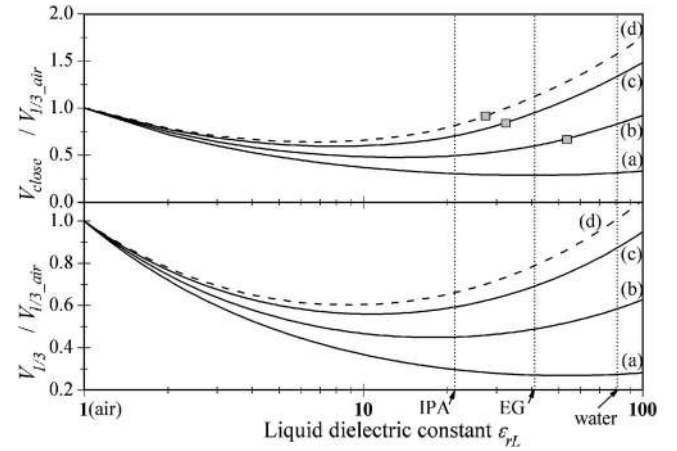


FIG. 2. Voltage values required to close one-third of the gap (lower) and to completely close the gap (upper) in a liquid of dielectric constant ϵ_{rL} , for: (a) $e_1=e_2=0.05\text{g}$ and $\epsilon_{r1}=\epsilon_{r2}=8$, (b) $e_1=e_2=0.15\text{g}$ and $\epsilon_{r1}=\epsilon_{r2}=8$, (c) $e_1=e_2=0.25\text{g}$ and $\epsilon_{r1}=\epsilon_{r2}=8$, and (d) $e_1=e_2=0.15\text{g}$ and $\epsilon_{r1}=\epsilon_{r2}=4$. The voltage required to close one-third of the gap in air is taken as the reference voltage. Squares show the limit between the pull-in and no pull-in regimes. When the pull-in effect occurs, the pull-in voltage is used to plot V_{close} .

IPA ($\epsilon_{rL}=21.3$) or EG ($\epsilon_{rL}=41.2$). The role of the insulating layer material is shown in Fig. 1(d), where the silicon nitride layer material is replaced by silicon dioxide ($\epsilon_r=4$) for the same thicknesses as cited before. In this case, the pull-in effect is eliminated at lower ϵ_{rL} than for silicon nitride, and no pull-in effect is expected in either water or EG. Actually, as the gap decreases in a dielectric liquid, a greater percentage of the potential drop is partitioned into the insulating layers. This effect is all the more significant as ϵ_{rL} is large, and it slows the increase in electrostatic force with decreasing gap. This is a stabilizing mechanism that leads, at large ϵ_{rL} values, to the suppression of the pull-in instability as shown in Fig. 1. In Fig. 2, the voltages needed to close one-third $V_{1/3}$ and the entire gap V_{close} are plotted from Eq. (3) versus ϵ_{rL} for different insulating layers configurations. When ϵ_{rL} is increased, $V_{1/3}$ and V_{close} first decrease as one expects since electrostatic forces are, neglecting the effect of the insulating layers, proportional to ϵ_{rL} . Subsequently, lower voltages are needed to induce the same actuator displacement. However, $V_{1/3}$ and V_{close} curves exhibit a minimum, and ultimately the required voltages increase with ϵ_{rL} . This behavior is explained by the fact that, for a given actuator displacement, the potential drop in the insulating layers increases with ϵ_{rL} , and is significant enough at large ϵ_{rL} values to reduce the electrostatic force. As a consequence, when ϵ_{rL} increases, a larger voltage is required to compensate for the potential drop and to produce the same actuator displacement. In practical cases, such as that represented in Fig. 2, actuation voltages are typically in the range of 25% to 150% of the required voltages in air, depending on the liquid dielectric constant value.

Experiments have been performed on a MEMS actuator as described in Figs. 3(a) and 3(b). The cantilever-type actuator is fabricated using a $2\ \mu\text{m}$ thick structural layer of polycrystalline silicon. The fixed and mobile plates are encapsulated in 300 nm thick layers of silicon nitride in order to prevent any short circuit when the gap is closed. The detailed fabrication process has been presented elsewhere.¹² The device is actuated in air, IPA, deionized (DI) water [Figs. 3(c) and 3(d)] and ordinary water. In order to prevent charge screening that would disable the actuator, an ac volt-

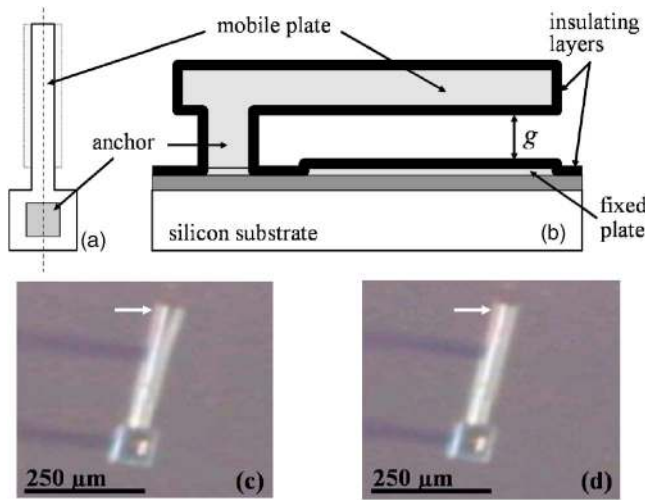


FIG. 3. (a) Schematic top view of the cantilever type actuator. (b) Schematic cross section along the dashed line in (a). The mobile (resp. fixed) plate is 250 μm (resp. 200 μm) in length and 30 μm in width. Electrodes are coated by 300 nm thick silicon nitride layers ($\epsilon_r=8$). Gap value is 2 μm . (c) Optical microscope image of the actuator in DI water when zero voltage is applied. (d) Optical microscope image of the closed position in DI water when the actuation voltage is applied. The images (c) and (d) are taken at an angle of 25° relative to the substrate normal. The arrow indicates the free end of the actuator.

age is employed to drive the device as reported in Ref. 8. The closed position of the actuator is detected from optical images. Table I reports for each liquid the voltage V_{close} required to close the gap. These values are compared to theoretical values calculated as in Fig. 2. We note good agreement between experimental and theoretical values.

In conclusion, we have studied stability and displacement-voltage characteristics of parallel-plate electrostatic actuators operated in dielectric liquids. Stable operation is extended far beyond one-third of the gap, and the pull-in effect can even be totally eliminated in common liquids. On the other hand, actuation voltages remain roughly in the same range as in air in spite of the fact that the electrostatic forces are expected to be magnified by the dielectric constant of the liquids. This is explained by considering the plate insulating layers which play a major role in the actuator capacitance for large ϵ_{rL} values. This work gives guidelines to design MEMS actuators operated in liquids, and to optimize the pull-in effect and actuation voltages depending on the targeted application.

TABLE I. Comparison of theoretical and experimental actuation voltages of the MEMS actuator in different dielectric liquids. In air, the actuator is driven by a dc voltage. In the liquids, the actuator is driven by an ac signal at 1 MHz. In the theoretical calculations, a value of 1.2 N m⁻¹ is assumed for the spring constant k .

Liquid	ϵ_{rL} ^a	σ ^a ($\mu\text{S cm}^{-1}$)	f_C ^b (kHz)	Theoretical V_{close} (V)	Experimental V_{close} (V_{rms})
Air	1	7.6 ^c	8±0.1
IPA	21.3	0.09	17	3.9 ^c	4±0.1
DI water	80	0.07	13	6.3	6±0.1
Water	80	5	950	6.3	6±0.1

^aDielectric constant and conductivity data taken from Ref. 13.

^bMinimum signal frequency required to prevent potential screening (calculated from Ref. 8).

^cGap is closed due to the pull-in effect.

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