Published in final edited form as:

J Micromech Microeng. 2009 June 1; 19(6): 1–9. doi:10.1088/0960-1317/19/6/065008.

Modeling and Characterization of Electrostatic Comb-drive Actuators in Conducting Liquid Media

Vikram Mukundan¹, Pierre Ponce², Holly E. Butterfield¹, and Beth L. Pruitt¹

¹ Department of Mechanical, Stanford University

² Department of Electrical Engineering, Stanford University

Abstract

Operation of electrostatic actuators in liquid media has various proposed applications, especially in biological environments. The devices are operated by modulating at a frequency higher than the relaxation rate of the ions in solution. We present circuit models based on electric double layer theories to obtain analytical expression for the frequency-dependent force response of electrostatic actuators in ionic media. The model has been compared with experimental measurements of actuation in media of conductivity spanning five orders of magnitude. Further, impedance spectroscopy is used to measure the values of the circuit models, which are compared with the experiments. These measurements also quantify the parasitic impedances in the devices. A conformal layer of Parylene-C is demonstrated as a passivation scheme for the electrodes in corrosive media. The heating effects due to parasitic impedances are also quantified by temperature measurements of devices in fluids.

1. Introduction

Microelectromechanical Systems (MEMS) electrostatic devices are found in a wide range of applications due to their various advantages such as large displacements and forces, speed, sensing and ease of on-chip integration [1,2]. Until recently, most applications are limited in dielectric media like vacuum, air or oil. Recent advances have enabled their operation in ionic and polar liquid media. The key limitations of operating electrostatic devices in conducting media are electrostatic shielding and electrochemical corrosion. Both of these problems can be overcome by the use of high frequency actuation signals in solutions [3,4]. Applications involving metal electrodes in conducting media have been widely used in high frequency techniques such as dielectrophoresis and AC electro-osmosis [5,6]. Such techniques overcome the limitations of electrostatic shielding and electrochemical corrosion by using high frequency signals that reduce the ionic concentrations at the immersed metal surface. The AC signals operate at frequencies such that the time between the cycles prevents the concentration of ions at the interface, reducing shielding and electrochemical reactions. Thus, appropriately chosen frequencies can be used to sustain electrostatic fields across electrode gaps in liquid media.

The use of AC signals to prevent the electrostatic shielding in polar solvents was first demonstrated by Sounart et al[4]. The technique was extended to operate in ionic solutions for studying cell mechanics[7,8], an application which may require devices to be immersed in biological solutions of high conductivity. This AC modulation technique, while suitable for single electrode pairs in solutions of low conductivity like polar solvents, requires some design changes to be applicable in solutions of higher conductivity. As seen in [8], solutions of higher conductivity require a higher frequency signal for significant actuation. However, at

frequencies above 1 MHz attenuation due to parasitic impedances prevents actuation. A differential drive electrode design was demonstrated to overcome these parasitic impedance losses, achieving close to full scale actuation in conducting biological media [9,10]. Other applications for liquid immiscible actuators include resonant sensors [11,12], parallel plate actuators [13,14] and microfluidic pumps [15]. Adrega et al [12] used viscous damping models to estimate the viscous effects on a micro-bridge resonator operating in conducting ionic liquids. Rollier et al [13] and Legrand et al [14] modeled the pull-in dynamics of parallel plate actuators in dielectric media, concluding that the effects of insulating native oxide become significant in media of high dielectric constants (like water).

Thus the operation and modeling of electrostatic actuators in *ionic* liquid media will extend their advantages into applications in biology. Here we present a model of electrostatic comb drive actuators in conducting liquid media to understand the frequency dependent actuation behavior. We present analytical expression for the frequency dependent electrostatic force in conducting media. The model has been verified with comparison to experiments in ionic solutions of conductivities varying from 10^{-1} to $10^4 \mu\text{S/cm}$. Circuit models of the electric double layer and device geometry are used to obtain the frequency response and transition frequency of operation. To further understand the impedance losses at high frequency we have conducted impedance spectroscopy measurements of immersed devices and test structures and fit them to the model. The circuit models are also used to understand the various parasitic effects that arise in a system immersed in liquid media.

We also demonstrate a conformal patterned Parylene-C layer to passivate metal electrodes and minimize the parasitic electric fields in the fluid. The electrodes are subjected to voltage bias in solutions of high ionic strength to test their behavior. Bare electrodes are compared with parylene protected electrodes under various voltage stresses. Further, temperature measurements of devices under actuation indicate the heating effects due to the actuation voltages. Conducting fluids show a much higher temperature rise over DI water as expected. The temperature measurements provide important constraints for the design and operating limits of such actuators.

2. Theory and Modeling

2.1. Gouy-Chapman-Stern theory

The electrode-electrolyte interface is described by the Gouy-Chapman-Stern model to be comprised of two layers: the Stern layer and the diffuse layer which are collectively termed as the electric double layer (EDL). The Stern layer is a sheet of adsorbed ions at the interface with the adjacent diffuse layer of ions away from the surface. The Stern layer is taken to be one hydrated ionic radius in thickness and the diffuse layer is characterized by the Debye length (λ_d). A circuit schematic of the gap between the fingers is presented in Figure 1(b). The electrode gap is modeled with an interface capacitance comprised of the native oxide (thickness t_{ox}) and EDL in series. In the cases considered, the EDL is assumed to be very thin ($\sim 1 \text{ nm}$) compared to the gap sizes ($\sim 1 \mu\text{m}$) allowing the media between the electrodes to be represented by the bulk properties of the solution (σ_M , the conductivity and ϵ_M , the dielectric constant). The unit area resistance and capacitance of the medium are $R_M = d/\sigma_M$ and $C_M = \epsilon_M \epsilon_0/d$. The series interface capacitance is represented by C_{INT} .

2.2. Characteristic time constant

The characteristic time constant determines the frequency where electrostatic shielding can be minimized between the electrodes. The transition frequency is evaluated from the time constant of the ionic system. Bazant et al [16] proposed that the electrode-electrolyte system is governed by the dominant time constant of the circuit model. The circuit model of the device has a time

constant RC , where R is the resistance of the gap between the electrodes (determined by the media conductivity σ_M and gap distance d) and C is the interface capacitance determined by the insulating dielectric layer (the native silicon dioxide), Stern layer and diffuse layer of ions in series. The time constant may be expressed in terms of the relative permittivities of the oxide (ϵ_{ox}), Stern layer (ϵ_s) and media (ϵ_M) and the thicknesses of the oxide (t), Stern (λ_s) and double layers (λ_d):

$$\tau = \frac{\epsilon_o d}{2\sigma_M} \left[\frac{1}{\frac{t_{ox}}{\epsilon_{ox}} + \frac{\lambda_s}{\epsilon_s} + \frac{\lambda_d}{\epsilon_M}} \right] \quad (1)$$

The characteristic frequency is evaluated from the time constant as $f_c = 2/(2\pi C_{INT} R_M)$. Since C_{INT} is determined by the capacitances in series, the lowest value dominates. The values of the capacitances are compared in Table 7. For the systems in consideration, the insulating native oxide layer ($t_{ox} \approx 2$ nm [17]) has the lowest capacitance. The higher the capacitance, the lower the frequency required to actuate the device.

2.3. Frequency-dependent Electrostatic Force

For a comb-drive electrostatic actuator (Figure 1(a)) with N pairs of combs, thickness b , gap distance d in a dielectric medium of relative permittivity ϵ , under static equilibrium the electrostatic force F is balanced by the suspension of stiffness k and depends on the applied voltage V as

$$kx = \frac{Nb\epsilon\epsilon_o}{d} V^2. \quad (2)$$

However, this is not true in the case of a conducting liquid medium where the electric field is shielded by the interface capacitance due to the formation of the EDL. The effect of the double layer can be captured by accounting for the voltage drops across the interface. The electrostatic force then depends upon the frequency of the actuation signal since the extent of shielding depends on the time available for the mobile ions to form the shielding layer during each cycle. This dependence is obtained from the linear circuit model as shown in Figure 1(b), under the assumption that the electrode-electrolyte interface can be modeled as a thin layer of capacitance and the medium as a conducting dielectric. Since all components of the circuit are linear, the overall impedance of the electrode system (Z) and that of the actuator gap (Z_M) are expressed as,

$$Z = \frac{2}{j\omega C_{INT}} + \frac{R_M}{1 + j\omega R_M C_M}, \quad (3)$$

$$Z_M = \frac{R_M}{1 + j\omega R_M C_M}. \quad (4)$$

The voltage drop across the actuator gap in terms of the total electrode impedance Z under an AC excitation $V_{AC} = V_o \exp(j\omega t)$ is,

$$V_M = \operatorname{Re} \left\{ \frac{Z_M}{Z} V_o \exp(j\omega t) \right\}, \quad (5)$$

or

$$V_M = \operatorname{Re} \left\{ \left| \frac{Z_M}{Z} \right| V_o \exp(j\omega t + \varphi) \right\}, \quad (6)$$

where $\varphi = \arg \left\{ \frac{Z_M}{Z} \right\}$. From this expression, we evaluate

$$V_M = \left\{ \left| \frac{Z_M}{Z} \right| V_o \right\} \cos(\omega t + \varphi). \quad (7)$$

In deriving this harmonic response to AC excitation we assume that the voltage drops across all components are sinusoidal without non-linear distortions [18], which we believe holds for the range of concentrations and frequency considered here. Substituting V_M as the fraction of the total applied voltage across the device electrode in Eq. 2 we obtain the electrostatic force as

$$F = \frac{Nb\epsilon_M\epsilon_o}{d} \left\{ \left| \frac{Z_M}{Z} \right| V_o \right\}^2 \cos^2(\omega t + \varphi). \quad (8)$$

Since the electrostatic force is proportional to V_M^2 , the force has a DC component superposed with second order harmonics ($\cos^2\theta = (1 + \cos 2\theta)/2$). If we consider mechanical systems with natural frequencies much less than the actuation signal, the mechanical response filters out the higher harmonics (2ω). For such systems the actuator responds quasi-statically to the average force determined by the root-mean square voltage. This is true in particular for the class of actuators tested in this paper where the natural frequencies are lower than 1 KHz while the actuation signals are above 10 KHz. Note that for the particular case of a sinusoidal excitation $V_{RMS} = V_o / \sqrt{2}$.

$$F = \frac{Nb\epsilon_M\epsilon_o}{d} \left| \frac{Z_M}{Z} \right|^2 V_{RMS}^2 \quad (9)$$

Comparing Eq. 9 to Eq. 2 we notice that while V_o is replaced by V_{RMS} , the factor containing the impedances gives rise to the frequency dependence. Here we represent the frequency dependent factor $|Z_M/Z|^2$ as a function ' f ' of the angular frequency ω .

$$F = \frac{Nb\epsilon_M\epsilon_o}{d} f(\omega) V_{RMS}^2 \quad (10)$$

From this representation we can replace $\tau_1 = R_M C_{INT}$ and $\tau_2 = R_M C_M$ to emphasize the dependence on the two time constants of the circuit. For the device geometries tested here, $C_{INT} \gg C_M$ (Table 7), which implies that $\tau_1 \gg \tau_2$ and τ_1 is the dominant time constant. $f(\omega)$ is a function that varies from zero to unity depending on the frequency,

$$f(\omega) = \frac{(\omega\tau_1/2)^2}{1 + (\omega(\tau_1/2 + \tau_2))^2}. \quad (11)$$

This expression allows us to look at some special cases. When $\omega \rightarrow 0$ the function goes to zero implying that the voltage drop across the gap is zero. As discussed earlier this is due to the shielding effect of the EDL causing all the voltage to drop across the interface. At $\omega \rightarrow \infty$ the function approaches unity for $\tau_1 \gg \tau_2$. At this frequency the shielding effects are overcome allowing a potential drop across the gap and an electrostatic force to be set up across the electrodes. Yet another special case is when $\omega = 2/\tau_1$ where we find $f = 1/2$ (once again for $\tau_1 \gg \tau_2$). This value defines the transition frequency as the half displacement point in frequency. We also note that this time constant is identical with Eq. 1 which was defined as the characteristic time constant of the circuit model. For a device with gap $d = 2 \mu\text{m}$, a native oxide of thickness 2 nm ($\epsilon_{ox} = 3.5$), the plot of $f(\omega)$ in Figure 2 describes the normalized force response for different values of the time constant τ_1 from 0.1–100 μs . The form of the function $f(\omega)$ compares well with experiments [4,9].

2.4. Non-linear interface

While the classical theory discussed in the previous section describes the phenomena of ionic screening and charging, the linear model is typically relevant only when the voltage drop across the double layer are less than $k_b T/e$ (25 mV at room temperature). The voltages used in electrostatic actuation are on the order of several volts, which may lead to effects that are not captured in the linear interface model described so far. The number of ions attracted to the surface to shield the electric field caused by high voltages leads to very a high concentration near the interface. Such concentrations are limited by the finite size of the ions in the solution. A model accounting for the steric limits of concentration at the interface has been proposed for this case [19,18]. The model proposes that as the voltage increases beyond a critical value, a condensed layer of tightly packed ions are formed at the interface. Based on this model the total capacitance (C_D) including the condensed layer of ions is introduced as follows [18],

$$C_D = \frac{\frac{\epsilon_M \epsilon_0}{\lambda_d} \left| \sinh \left(\frac{zeV}{k_b T} \right) \right|}{\left[1 + 2v \sinh^2 \left(\frac{zeV}{2k_b T} \right) \right] \sqrt{\frac{2}{v} \ln \left[1 + 2v \sinh^2 \left(\frac{zeV}{2k_b T} \right) \right]}} \quad (12)$$

where k_b is the Boltzmann constant, T is the absolute temperature, V is the voltage drop across the double layer and v is the packing density of ions in the bulk, defined in terms of the mean ion spacing a and bulk concentration C ,

$$v = 2a^3 C. \quad (13)$$

The value of v is considered as a reference point at which the non-dilute characteristics of ions need to be included [18]. With the introduction of the condensed layer the interface capacitance is no longer a strong function of the bulk concentration at very high voltages. However the

native oxide or any other dielectric coating at the electrode surface is in series with the condensed layer capacitance. Importantly the lowest of the capacitances will dominate when they are in series. For the silicon electrodes considered here, the native oxide capacitance is lower than the condensed layer capacitance by a factor of 10–100. Thus it is reasonable to assume a linear capacitance at the interface.

3. Fabrication

The devices are fabricated on a Silicon-On-Insulator (SOI) wafer with 15 μm device layer (p-type Boron doped to 0.008–0.01 $\Omega\text{-cm}$) and 4 μm of buried oxide (BOX) layer as seen in Figure 7(a). The electrodes and comb-drive features are first patterned in the silicon by a Deep Reactive Ion Etch (DRIE) process. A composite metal layer comprising Chromium (Cr 25 nm)/Platinum (Pt 50 nm)/Gold (Au 300 nm) is deposited by e-beam evaporation and patterned by photo-resist lift-off. Gold is chosen for the electrode for its resistance to corrosion and bio-compatibility, Chromium acts as an adhesion layer while Platinum provides a diffusion barrier. Here we introduce a conformal Parylene-C coating as a passivation for the electrode. The wafers are cleaned in a ‘Piranha’ solution (4:1 H_2SO_4 : H_2O_2) at 90 $^\circ\text{C}$. A buffered oxide etch (6:1 BOE) is used to etch the buried oxide layer without releasing the suspended components. This step serves the dual purpose of isolating the electrodes from the actuator and removing the native oxide to improve the parylene adhesion during deposition. After rinsing and drying, the wafers are immediately treated with Hexamethyldisilazane (HMDS) to further promote parylene adhesion. HMDS keeps the surface hydrophobic and keeps moisture off, helping the adhesion of parylene coatings [20]. Without this treatment, parylene is found to delaminate easily during processing. Parylene-C ($1.5 \pm 0.5 \mu\text{m}$) is deposited immediately after by a room temperature vapor deposition polymerization process in a PDS 2010 Labcoater (Speciality Coating Systems, Indianapolis, IN).

The Parylene layer is patterned to selectively coat the metal electrodes and removed from the comb fingers and the suspended components since it would interfere with the actuation of the device. For patterning parylene, 10 μm SPR 220-7 positive photo-resist is spun onto the wafer and patterned under 365 nm ultraviolet (UV) radiation. Since parylene reacts and degasses under high doses of UV radiation [21,22], it is critical at this step that the parylene layer is not overexposed. Otherwise, the bubbles released in the parylene layer and the stresses caused during deposition over topography could lead to severe delamination of the parylene layer. Wafer cleaning, adhesion promoter coating and slight underexposure of the patterning resist contribute to stronger adhesion of the parylene film. This process allows us to create a conformal parylene film over 15 μm topography in silicon. After developing the resist, the exposed parylene can be etched away in a number of plasma processes [20]. Since our parylene structures do not have any high aspect ratio features we use an oxygen plasma asher to etch the parylene. At 150 W power and a chamber pressure of 5 mTorr, parylene-C etches at a rate of about 100 nm/min. For this process a photoresist:parylene thickness ratio of 10:1 provided sufficient selectivity to etch the parylene. After patterning the parylene, the wafer is diced in a wafer saw. The individual dies are then released in a timed buffered oxide etch (BOE). The devices are dried and released in a liquid carbon-dioxide critical point dryer (CPD) to avoid stiction of the suspended components. A scanning electron micrograph (SEM) of the finished device is shown in Figure 7(b).

4. Displacement Characterization

The released devices are mounted on a ceramic dual in-line package (DIP) and wirebonded with gold interconnects. The devices are actuated with the required frequency using a Tektronix AFG 3102 function generator. As described earlier, a differential drive is required to overcome the attenuation effects at high frequency. The TEKA FG 3102 can generate two independent

signals with user defined phase differences. We note again that the device responds with a static deflection for the excitation frequencies considered here. The devices are observed under a Leica DMRXA2 upright microscope and the images are captured with a Leica DFC350x CCD camera. The displacements are measured by an optical centroid tracking algorithm written in Matlab. At a frame capture rate of 100 ms, the displacement resolution is about 20 nm (pixel/10) under a 50x objective.

To validate the model we test the displacement response of devices in potassium chloride (KCl) solutions of concentrations varying from 100 μM –100 mM. KCl is chosen because of its properties as a symmetric monovalent solutes with well characterized conductivity properties. For the same device and electrolyte, we vary the characteristic time constant by varying the concentration. The displacement is measured for actuation signals at frequencies from 100 Hz–10 MHz. The curves from the displacement measurement are fitted with the model predictions from Eq. 11 in Figure 4(a) to obtain values of the time constant τ_1 in various electrolytes. The model trend for the electrostatic force agrees well with the measured values. We note that the displacement is not a strong function of τ_2 since $\tau_1 \ll \tau_2$. The error bars indicate variations over repeated measurements on the same device. The transition regions in each solution display the most variation, which is believed to be due to changes in concentration or interface properties between each run.

We also obtained the time constant values from similar measurements on devices of different gap widths (2 and 5 μm) and compliances (0.02–0.3 N/m) in solutions of varying conductivities to study the variation in the behavior. A total of 17 devices have been tested with at least 3 for each conductivity value. These values are plotted in Figure 4(b). The error bars at each conductivity represent the minimum and maximum variation across different devices. The time constant values compare closely with the theoretical value given by Eq. 1 for different solutions (Ethanol, DI water and KCl solutions) spanning a wide range of conductivity values (10^{-1} – $10^4 \mu\text{S/cm}$) for devices of varied electrode geometries.

5. Electrical Characterization

5.1. Impedance analysis

Test structures resembling the actuator designs are used for impedance characterization across the frequency range 100 Hz–10 MHz in solutions including De-Ionized (DI) water, ethanol and KCl solutions (100 μM –150mM). The measurements are carried out with an HP 4192 LF impedance analyzer. The impedance spectrum is fit to a form predicted from the circuit model (Z) to obtain values for R_M , C_{INT} and C_M . The parylene layer ensures that the role of parasitic components is minimized in the impedance and the measured values correspond to those of the device electrodes. This is particularly important in the low frequency range where the capacitance of the electric double layer increases due to the large surface area of the immersed wirebonds and bond pads. The dielectric coating keeps the parasitic capacitances at low frequencies much lower than the interface capacitances measured. However the parasitic capacitances are still prominent in the high frequency limit since the device capacitances are much smaller in this case. The data in Figure 5 show the conductance and capacitance of the measured device impedance. Table 2 shows a summary of time constant measurements by displacement and impedance and comparisons with theory. The tolerance limit on the circuit parameters are about 50 % (for 95 % confidence limit), allowing the estimation of time constants to well within a order of magnitude. The circuit time constant values from displacement and impedance measurements compare well with the predicted model frequency.

5.2. Electrochemical corrosion

Parylene is known to be an excellent passivation and protection layer for electrodes in ionic media due to its high dielectric breakdown ($\sim 1000 \text{ V}/\mu\text{m}$ [23]) and low porosity to diffusive ions. To test the effectiveness of parylene as a passivation layer, we conducted tests by subjecting the electrodes to a voltage while submerged in a highly conducting ionic solution of 150mM KCl. A comparison of the passivation performance to unprotected electrodes is shown in Figure 7. Even at as low voltages as 3 V, we see electrolysis bubbles released from the unprotected electrodes while the metal lines are seen to peel off the silicon. As the bias is increased to 3 V, corrosion happens quickly and the metal layer delaminates completely from the silicon within a few seconds. Since gold is electrochemically passive, we believe that the underlying Chromium adhesion layer is being corroded in the solution. Similar events also occur when the experiment is carried out in 150 mM KCl solution. In this case, the electrodes are visibly discolored before being delaminated. As the frequency is increased, the rate of corrosion decreases since the surface concentration and the reaction time of the ions at the surface are both reduced. Thus actuation at high frequency mitigates the corrosion effects. In the case of electrodes in DI water, bubble generation was greatly reduced above 100 Hz and the electrode discoloration in KCl solution stopped above 10 KHz. However electrode damage in the form of discoloration is visible in KCl solutions.

The parylene coated electrodes on the other hand display very little electrochemical damage both at DC and higher frequency. The electrodes show a much reduced amount of bubble generation compared to the bare electrodes. The prevalence of the bubbles at the edges indicates some leakage through gaps between parylene and silicon surfaces. In conducting KCl solution, there is no damage to the electrode due to the presence of the parylene layer even though some electrolysis is seen at the outer edges. Since the actuation signals are expected to be at frequencies higher than 10 KHz, the damage to the electrodes is minimal. The parylene layer also acts as an electrostatic shield reducing the fringing fields at high frequency. Thus the patterned parylene coating proves to be a successful passivation scheme for electrostatic actuators for operation in highly conducting media.

6. Temperature measurements

Electrostatic actuation in liquids results in joule heating of the media. This is due to the mobility of ions in the bulk media, as represented by the parallel resistor R_M in Figure 1(b) and the conductivity measurements shown in Figure 5. At low frequency signals, most of the voltage drops across the shielding capacitances but at higher frequencies, the power is dissipated through the resistive components of the media. Thus temperature increase is one of the important considerations for such a device especially for applications in biology. We measured the temperature rise in the media during actuation using a thermocouple inserted in the media, while providing the actuation signal with a function generator. The temperature rise was below the measurement resolution in low conducting solutions such as DI water. However the temperature rise was significant in solutions of higher conductivity as indicated in Figure 7. When the actuation voltage is turned on the temperature begins to rise and reach a steady state. The cavity with the aqueous media has a typical rise time of about 300s. All temperature measurements are made after ensuring steady state. At maximum signal strength of $20 V_{pp}$ which corresponds to a dissipated power of about 50 mW at 10 MHz, the steady state temperature increase in the fluid (150 mM KCl) is $7.2 \pm 0.1^\circ\text{C}$. For a baseline room temperature at 20°C the media is within the range suitable for biological samples. Of course, the actual voltages applied will depend on the required displacement, but with suitably designed compliant structures low operating temperatures are ensured for samples which may be sensitive to high temperature.

7. Conclusion

We have presented a linear circuit model to describe the electrostatic force as a function of actuation frequency. This model provides an analytical expression for the frequency dependent electrostatic force in conducting media and compares well with the measured displacement spectrum in KCl solutions. We also estimate the characteristic time constants from a fit to the the measured displacement spectrum. The time constants also compare well with the theoretical values and the model provides a good estimate of the operating frequency. Impedance spectroscopy measurements are used to analyze the electrode impedances at different frequencies and observe that parasitic impedance is particularly significant at high frequencies in highly conducting liquids. Due to the high currents, the operation of devices in such conducting medium leads to thermal power dissipation and heating in the media. The temperature rise in the conducting media was measured to be around 7.2 °C at an actuation power of 50 mW (20 V_{pp}) in 150 mM KCl. The temperature rise sets an important design constraint for operation of such devices since many of the proposed applications are in biology. We note that a device with higher compliance would require lower actuation voltages, which would enable lower operating temperatures.

Acknowledgments

This work is supported by NSF CAREER award ECS 0449499 and NIH grant R01EB006745-01A1. Fabrication was done at the Stanford Nanofabrication Facility, which is supported by NSF under grant ECS 9731293. VM was supported by a Stanford Graduate Fellowship and HEB by the National Defense Science and Engineering Graduate Fellowship, sponsored by the Air Force Office of Scientific Research.

References

1. Tang WC, Nguyen TCH, Judy MW, Howe RT. Electrostatic-comb drive of lateral polysilicon resonators. *Sensors and Actuators A: Physical* 1990;21(1–3):328–331.
2. Legtenberg R, Groeneveld AW, Elwenspoek M. Comb-drive actuators for large displacements. *Journal of Micromechanics and Microengineering* 1996;6:320–329.
3. Sameoto D, Hubbard T, Kujath M. Operation of electrothermal and electrostatic mumps microactuators underwater. *Journal of Micromechanics and Microengineering* 2004;14:1359–1366.
4. Sounart TL, Michalske TA, Zavadil KR. Frequency-dependent electrostatic actuation in microfluidic mems. *Journal of Microelectromechanical Systems* 2005;14(1):125–133.
5. Ramos A, Morgan H, Green NG, Castellanos A. Ac electrokinetics: a review of forces in microelectrode structures. *Journal of Physics D: Applied Physics* 1998;31
6. Voldman J. Electrical forces for microscale cell manipulation. *Annual Review of Biomedical Engineering*. *Annu Rev Bioeng* 2006;8:425–454.
7. Panchawagh, HV.; Serrell, D.; Finch, DS.; Oreskovic, T.; Mahajan, RL. Design and characterization of a biomems device for in-vitro mechanical simulation of single adherent cells. *ASME International Mechanical Engineering Congress and Expedition*; Orlando, FL. 2005.
8. Mukundan, V.; Pruitt, BL. Experimental characterization of frequency dependent electrostatic actuator for aqueous media. *Solid State Sensors, Actuators and Microsystems workshop*; Hilton Head Island, SC. 2006.
9. Mukundan, V.; Pruitt, BL. Differential electrode design for electrostatic actuator in conducting media. *The 14th International Conference on Solid-state Sensors, Actuators and Microsystems*; Lyon, France. IEEE; 2007.
10. Mukundan, V.; Ponce, P.; Butterfield, H.; Pruitt, BL. Modeling and validation of electrostatic actuation in aqueous ionic media. *21st International Conference on Micro Electro Mechanical Systems*; Tucson, AZ. IEEE; 2008. p. 467-470.
11. Adrega T, Chu V, Conde JP. Electrostatically actuated resonance of amorphous silicon microresonators in water. *Applied Physics Letters* 2006;89

12. Adrega T, Chu V, Conde JP. Resonance of electrostatically actuated thin-film amorphous silicon microelectromechanical systems microresonators in aqueous solutions: Effect of solution conductivity and viscosity. *Journal of Applied Physics* 2007;101(094378)
13. Rollier AS, Legrand B, Collard D, Buchaillet L. The stability and pull-in voltage of electrostatic parallel-plate actuators in liquid solutions. *Journal of Micromechanics and microengineering* 2006;16:794–801.
14. Legrand B, Rollier AS, Collard D, Buchaillet L. Suppression of the pull-in instability for parallel-plate electrostatic actuators operated in dielectric liquids. *Applied Physics Letters* 2006;88(3)
15. Bansal T, Chang MP, Maharbiz MM. A class of low voltage, elastomer-metal ‘wet’ actuators for use in high-density microfluidics. *Lab on a Chip* 2007;7(2):164–166. [PubMed: 17268616]
16. Bazant MZ, Thornton K, Ajdari A. Diffuse-charge dynamics in electrochemical systems. *Physical Review E* 2004;70(021506):1–23.
17. Lukes F. Oxidation of si and gaas in air at room temperature. *Surface Science* 1972;30(1):91–100.
18. Kilic MS, Bazant MZ, Ajdari A. Steric effects in the dynamics of electrolytes at large applied voltages, i. double-layer charging. *Physical Review E (Statistical, Nonlinear, and Soft Matter Physics)* 2007;75(2):021502.
19. Borukhov I, Andelman D, Orland H. Adsorption of large ions from an electrolyte solution: a modified poisson-boltzmann equation. *Electrochimica Acta* 2000;46(2–3):221–229.
20. Meng E, Li P-Y, Tai Y-C. Plasma removal of parylene c. *Journal of Micromechanics and Microengineering* 2008;(4):045004. 0960–1317.
21. Bera M, Rivaton A, Gandon C, Gardette JL. Comparison of the photodegradation of parylene c and parylene n. *European Polymer Journal* 2000;36(9):1765–1777.
22. Fortin JB, Lu TM. Ultraviolet radiation induced degradation of poly-para-xylylene (parylene) thin films. *Thin Solid Films* 2001;397(1–2):223–228.
23. Noordegraaf, J. C-shield parylene allows major weight saving for em shielding of microelectronics. In: Hull, H., editor. *The First IEEE International Symposium on Polymeric Electronics Packaging*; Norrkoping, Sweden. 1997. p. 189-196.

Figure 1.

(a) A comb-drive actuator operates by applying a voltage between a fixed electrode and a suspended electrode anchored through a flexible suspension. The electrostatic force between the combs is balanced by the spring stiffness. (b) Schematic circuit model of the comb-drive electrode gap indicating the interface capacitance (C_{INT}), gap resistance (R_M) and capacitance (C_M).

Figure 2.

Frequency dependent electrostatic force function plotted for various values of τ_1 from 10^{-7} - 10^{-4} s. The model indicates that higher frequency signals are required to actuate in higher conducting solutions, while shielding takes place at low frequencies.

(a)

(b)

Figure 3.

(a) Fabrication steps for the underwater electrostatic comb-drive actuators with a conformal parylene passivation layer (b) A scanning electron micrograph (SEM) of the fabricated device.

(a)

(b)

Figure 4.

(a) A plot of the measured displacement with the theoretical fit in solutions of 0.1–100 mM KCl. The measurements are made at a constant signal of 5 V_{pp} while varying the frequency. The error bars indicate variations in the same device over repeated measurements (n=5). (b) The dominant time constant as observed in experiments is plotted with the solution conductivity. The measured values show good comparison with the theoretical prediction with an interface native oxide. At these frequencies, the non-linear double layer capacitances are not significant. Each data point is an average measurements over different devices, with all values normalized to an electrode gap distance of 2 μm for comparison.

Figure 5.

Capacitance and conductance measurements on parylene coated device used as a fit for extracting the model values. The capacitance values at low frequency reflects the interface capacitance due to ionic shielding, while at high frequency it is the parasitic values. The high conductance at high frequency is also the spreading bulk resistance between the actuation electrodes. These spectra are fit to the circuit model to estimate key parameters of the system.

Figure 6.

(a) Bare electrodes under a DC bias in DI water lead to rapid delamination of the metal layer due to corrosion. (b) Bare electrodes in 150 mM KCl solution under a $5 V_{pp}$ 1 KHz signal show electrode damage by discoloration (c) When the frequency is increased to 10 KHz, there is reduced corrosion. (d–f) Parylene protected electrodes do not show any damage in (d) DI water or (e) KCl at 1 KHz and (f) 10 KHz. The electrolysis bubbles seen at the edges are likely due to leaks in the parylene adhesion.

Figure 7. Temperature measurements on a device in 10, 100 and 150 mM KCl solution. All measurements are taken after reaching a steady state from the time of applying the actuation voltage. The steady state temperature increases in solutions of higher conductivity due to greater power dissipation.

Table 1

Properties of interface oxide, stern layer and device capacitance

	Native oxide	Stern layer	Electrode gap
Thickness	$t_{ox}=2$ nm	$\lambda_s=0.5$ nm	$d=2$ μm
Relative permittivity	$\epsilon_{ox}=3.5$	$\epsilon_s=5$	$\epsilon_M=78$
Capacitance (F/m ²)	$C_{ox}=0.015$	$C_s=0.088$	$C_M=3.4\times 10^{-4}$

Table 2

Comparison of time constant (τ_1) from displacement and impedance measurements with the model.

Media	Impedance fit		τ_1 (s)	
	$R_p(\Omega)$	$C_{pVT}(nF)$	From model	From Impedance
DI water	1442000	0.118	7.7×10^{-5}	1.7×10^{-5}
100 μ M KCl	44640	0.094	2.56×10^{-5}	4.21×10^{-6}
1 mM KCl	10160	0.096	2.56×10^{-6}	9.7×10^{-7}
10 mM KCl	840	0.101	2.56×10^{-7}	8.48×10^{-8}
10 mM KCl	140	0.115	2.56×10^{-8}	1.61×10^{-8}
150 mM KCl	124	0.121	1.72×10^{-8}	1.5×10^{-8}

Nomenclature		
Symbol	Name	Units
a	Ion interaction length	m
b	Device thickness	m
C	Concentration	m^{-3}
C_D	Condensed layer capacitance	F/m^2
C_{INT}	Interface capacitance	F/m^2
C_M	Device gap capacitance	F/m^2
C_{ox}	Native oxide capacitance	F/m^2
d	Comb-drive finger gap	m
e	Electronic charge	C
k	Spring constant	N/m
k_b	Boltzmann constant	J/K
F	Electrostatic force	N
f	Frequency dependent force function	-
N	Number of comb finger pairs	-
R_M	Resistance of electrode gap	Ω/m^2
T	Absolute temperature	K
t	Time	s
t_{ox}	Native oxide thickness	m
V_o	Voltage amplitude	V
x	Displacement	m
Z	Total impedance of electrode	Ω/m^2
Z_M	Impedance of electrode gap	Ω/m^2
z	Ion valence	-
ϵ_o	Permittivity of free space	F/m
ϵ_M	Relative permittivity of media	-
ϵ_{ox}	Relative permittivity of oxide	-
ϵ_s	Relative permittivity of stern layer	-
λ_d	Debye length	m
λ_s	Thickness of stern layer	m
v	Packing density	-
σ_M	Bulk conductivity of media	S/m
τ, τ_1, τ_2	Time constants	s
ϕ	Phase difference	rad
ω	Angular frequency	rad/s