We report a class of ‘wet’ MEMS elastomer–metal electrostatic actuators which can actuate in air, oil or water environments with no external fluidic connections, has actuation voltages lower than 15 V and is compatible with widespread PDMS microfluidics.

A wide variety of valving and pumping technologies have been developed for use in miniaturized systems for the life sciences. Among these, a family of elastomer-based (usually polydimethylsiloxane) devices and systems have become popular due to their simplicity of fabrication, low equipment costs and ready compatibility with existing life science lab equipment (i.e. they are actuated with laboratory pumps and valves as opposed to electrical equipment). Some of these devices, however, depend on pneumatically-actuated pumps and valves which require two-layer PDMS processes and many pressurized external gas lines (40–100 kPa) to operate, even when employing a variety of clever multiplexing techniques. The dependence on external pneumatic actuation is becoming increasingly problematic with the push towards integrated, high-density microfluidic systems which require thousands of independent valves. Additionally, the lack of low power actuation schemes has, in part, prevented the adoption of these polymer devices for use in vivo.

In this communication, we present a class of elastomer–metal devices which actuate due to electrostatic pull-in when presented with a high frequency sine wave signal. These valves can be readily integrated into existing single-level PDMS systems, can be actuated with no external valving and require low temperature processes. These valves can be grouped together to form classic peristaltic valves and pumps, or combined with pores to build low power, programmable drug dosing elements. Conceptually, these devices are scalable into nano-fluidic regimes and are compatible with CMOS processes.

The main aim of this communication is to present basic design theory with initial actuation and gating valving results.

Electrostatic actuation is a well known process in ‘dry’ MEMS. On applying a potential between two parallel plates, electrostatic forces pull both the plates together. If the plates are held apart by a linear spring, the maximum range of travel is limited to 1/3 of the original gap after which electrostatic force exceeds the spring force and the gap collapses (assuming the potential is held constant). This ‘pull-in’ voltage is given as:

$$V_{\text{PI}} = \sqrt{\frac{8k(g + (\varepsilon_\text{ox} \varepsilon_\text{rL})/\varepsilon_\text{ox})^3}{27\varepsilon_\text{ox} \varepsilon_\text{rL} A_{\text{cap}}}}$$ (1)

where $k$ is the mechanical spring constant of the spring holding the plates apart, $g$ is the initial distance between the plates, $\varepsilon_\text{ox}$ is the thickness of any solid insulating layer covering the plates, $\varepsilon_\text{rL}$ is the relative permittivity of the solid insulating layer, $\varepsilon_\text{L}$ is the relative permittivity of the material between the plates (e.g. air, water, oil), $A_{\text{cap}}$ is the area of overlap between the capacitive plates, and $\varepsilon_\text{ox}$ is the permittivity of free space.

Even though filling the space between the plates with water ($\varepsilon_\text{L} = 80$) would provide very low pull-in voltages, operation in water has historically been limited due to the problems related with electrolysis, and electrode polarization. This, of course, does not occur in oil filled plates and DC voltages are sufficient to close the plates. In order to operate in water, a high frequency AC drive wave with no DC bias is necessary to prevent double layer screening of the electrostatic forces. Note that as water has such a high dielectric constant, the thickness of any passivating dielectric cannot be ignored in the pull-in voltage calculations (eqn (1)).

The devices presented here use this phenomenon to collapse the ‘roof’ of a conventional PDMS or metal microchannel onto the ‘floor’. This collapse can be used as a valve in the same way that ‘Quake’ valves use pressure to collapse a PDMS roof and seal a microchannel. Two geometries were explored. In the first, an all-gold microchannel was patterned over oxide-insulated indium tin oxide (ITO) electrodes using resist as the microchannel mold (Fig. 1a). The roof served as one capacitive plate and the ITO electrode formed the other. In the second design, the channel was made from PDMS instead of gold, but a thin gold layer was patterned into a compliant electrode within (or below) the PDMS.

Gold has a maximum yield strength of 120 MPa; above that stress, metal devices would plastically deform and fail. It was thus important to ensure that the actuating stress did not deform the devices permanently. However, attempting to lower the pull-in voltage below 15 V resulted in devices that were so flimsy that Laplace–Young pressure collapsed the channel during conventional release.
Given a spring constant \( k \), an overall gap of \( g \) (4.95 \( \mu m \)) and a final remaining gap of \( t_{ox} \) (0.45 \( \mu m \)) after pull-in, the energy expended to close an actuator is:

\[
E = \frac{1}{2}k(g - t_{ox})^2
\]  

(2)

For the devices presented here, this corresponds to energies ranging from 0.55 nJ to 0.67 nJ.

Fig. 1 shows the fabrication process. The devices were fabricated on 4" glass substrates. Transparent indium tin oxide (ITO) electrodes were sputtered (1500 Å) and patterned through a lift-off process and annealed at 750 °C in a Rapid Thermal Anneal (RTA) oven (Fig. 1a). A thin layer of oxide (0.45 \( \mu m \)) was deposited via plasma-enhanced chemical vapor deposition (PECVD) and annealed in a RTA oven at 700 °C (Fig. 1b). Contacts were timed etched through the oxide in 49% BHF (0.1 \( \mu m \) min\(^{-1}\)) (Fig. 1c). A 5 \( \mu m \) resist (Shipley 1827) for all-gold devices or a 10 \( \mu m \) resist (AZ\( ^c \) 9260) for elastomer–metal devices was spun and patterned into desired microchannel geometries.

![Fabrication process flow.](image)

Fig. 1 Fabrication process flow.

![Unactuated elastomer–metal device after the sacrificial channel photoresist has been removed.](image)

(A) Unactuated elastomer–metal device after the sacrificial channel photoresist has been removed. (B) Unactuated elastomer–metal device filled with DI water. fluorescent ruthenium compound is added for visualization. (C) Actuated elastomer–metal device. Deflection is clearly visible as the dark region. (D) All-gold devices after release. (E) All-gold devices with DI water and fluorescent compound. (F) An actuated all-gold device. (G) Profilometry cross section along dashed line in D confirming pull-in. (H) Profilometry cross section along dashed line in A. Unlike all-gold devices, most elastomer–metal devices experienced some sagging after release. Valve profiles completely flatten against the bottom electrode at voltages above 30 V (all-gold) and 20 V (elastomer–metal). Scale bar is 100 \( \mu m \).

![Deflection graphs.](image)

Fig. 2 (A) Unactuated elastomer–metal device after the sacrificial channel photoresist has been removed. (B) Unactuated elastomer–metal device filled with DI water. Fluorescent ruthenium compound is added for visualization. (C) Actuated elastomer–metal device. Deflection is clearly visible as the dark region. (D) All-gold devices after release. (E) All-gold devices with DI water and fluorescent compound. (F) An actuated all-gold device. (G) Profilometry cross section along dashed line in D confirming pull-in. (H) Profilometry cross section along dashed line in A. Unlike all-gold devices, most elastomer–metal devices experienced some sagging after release. Valve profiles completely flatten against the bottom electrode at voltages above 30 V (all-gold) and 20 V (elastomer–metal). Scale bar is 100 \( \mu m \).
the valve and accumulated at the valve boundary, as pointed out by the arrows. This indicates that the flow was stopped. (C) As the valve was opened at

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microchannel. Beads flow under an unactuated valve. (B) At $t = 50$ s the elastomer–metal valve was closed, stopping flow; microspheres were expelled by the valve and accumulated at the valve boundary, as pointed out by the arrows. This indicates that the flow was stopped. (C) As the valve was opened at $t = 100$ s, the liquid flow resumed and the microspheres moved again. The eight rectangular posts around the actuating area (dark boxes) are crucial for pinning the deflection boundary during vertical dosing devices (see Fig. S3†), but are unnecessary in the case of horizontal gated valving and have been removed in newer designs. Scale bar is 50 μm.

(Fig. 1d). Cr/Au (150 Å/5000 Å) was then evaporated onto the chip to form the top electrode (Fig. 1e). For elastomer–metal devices electroplating was not needed (Fig. 1f) and the gold flexures were patterned via wet etching (Fig. 1g). The patterned resist was word exposed, developed and a new resist was spun on the wafer. The wafer was then diced. The resist was word exposed once again and developed. Cr was removed from individual dies with standard Cr etchant. 16 μm of Dow-Corning WL-5150 photopatternable PDMS was then spun on. The sacrificial channel photoresist was then removed by immersing the chip overnight in acetone. Standard critical point drying (CPD) was performed to release devices (Fig. 1h2). Contact pads were wire-bonded to a carrier PCB board and soldered. Microscopy and electrical setup are provided in the ESL†

Both all-gold (Fig. 1h1) and elastomer–metal (Fig. 1h2) devices were fabricated. For the elastomer–metal devices, the gold layer was patterned into a variety of common flexures to provide different spring constants and pull-in voltages (e.g. spirals, linear springs, crab legs, etc.). Fig. S1A and S1B† show representative fabricated devices. Fig. 2A and 2B show an inverted optical and an inverted fluorescent micrograph, respectively, of an unactuated elastomer–metal device. On applying a potential between the top gold electrode (ground), and bottom ITO electrodes, the device actuates and closes. Fig. 2C shows the same device under actuation at 16 V. Fig. 2D–F show the same results for an all-gold device. Peak currents were limited to 1 μA. All-gold devices closed within 1 s; elastomer–metal devices took 5 s to close completely. Using eqn (2) and the definition of power ($P = \delta E / \delta t$), this corresponds to an average power consumption of 110 pW. Fig. 2G and 2H show the deflection profiles for unactuated and actuated valves of both types obtained in water with the Zygo non-contact profilometer. Measured values of deflection vs. voltage are given in Fig. S2‡ pull-in voltages are marked by dashed lines.

Fig. 3 demonstrates the operation of the device as a valve. For visualization purposes, fluorescent water mixed with microspheres (0.5 μm diameter) was used to fill a 6 mm microchannel. The liquid flow was observed by detecting the movement of the microspheres. Flow was established by evaporative pumping across the microchannel. Upon valve actuation, the microsphere movement stopped, the microspheres were expelled from between the electrodes, and piled up against the boundary of the ITO electrode as shown in Fig. 3B. Once unactuated, the valve opened and the microspheres continued their flow.

Fig. S3† shows how the device can be used for programmed chemical delivery. Simply, a single 10 μm pore is etched into the center of the microchannel roof. Unactuated, the contents of the microchannel can diffuse through the pore and into an aqueous medium above the channel. If actuated, the pore is sealed shut against the floor of the microchannel, preventing diffusion. We recently demonstrated that arrays of these pores can be used to pattern programmable diffusible gradients into cell culture.19

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Notes and references

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