Sensors & Transducers


# Charge Pumped MEMS Actuation for High Force and Large Displacement

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**Abstract:** Charge-pumping represents an unusual approach to MEMS actuation with the potential benefits of large displacement coupled with high force, as well as simple out-of-plane motions, large-scale self-assembly, simple single contact and even the possibility of non-contact actuation. Charge pumping is conducive to energy scavenging techniques such as tribolectric harvesting, useful in aerospace and satellite applications, but it comes at the cost of modifications to the electronics control infrastructure now based on two-terminal (power/ground) voltage and current paradigms. Non-contact examples will be shown, including devices that can be used for microscale biomimetic optics. *Copyright © 2014 IFSA Publishing, S. L.*

**Keywords:** MEMS, Actuator, Out-of-plane, Charge-pump, Biomimetic accommodating lens, Energy harvesting.

## 1. Background

MEMS device actuation design can benefit from physical scaling laws that result in the large dominance of effects related to surface area, over effects related to volume, such as mass, gravitational and inertial effects. So instead of simply scaling down designs that worked well in the macro world, we envision a new class of devices specifically designed to take advantage of what *already* works well in the micro-scale world. This discussion represents a class of devices requiring a different mentality in both design and control methodology because they depend neither on the passage of current (the typical approach to electromechanical design) nor directly on capacitance or voltage, but rather on manipulation of the fundamental unit of charge. Not quite static, and not dynamic enough to be concerned with current, but focused on how materials and geometeries allow charge to be collected on a surface and redistributed in controlled fashion, in order to mechanically take advantage of fundamental coulombic repulsion and attraction effects, which have enormous relative capacity for both high force and large displacement at the micrometer scale and below. An outcome of this design approach is the setting aside of the two-terminal (power/ground) thought process in favor of a single point of contact and control, and even the possibility of non-contacting methods, using field emitters, beta particle emitters, or triboelectricity [1-6].

All reported devices were designed at the University of Utah and built at Sandia using the SUMMiT-V five-level polySi architecture [7].

## 2. Charge Pumping Applications

Recent work in our group [8-15] can be categorized in terms of efforts to realize large-force, high-displacement radial motion that would be compatible with the demands of a biomimetic accommodating lens. It had become clear that traditional MEMS actuation would not be capable of providing these attributes, at least with any reasonable speed.

First we discuss the benefit of out-of-plane actuation, then describe efforts to convert out-of-plane motion to in-plane actuation of a radial lens-pulling device.

### 2.1. Out-of-plane Displacement

We previously demonstrated large-force and high displacement in a simple coiled spring, deployed out-of-plane using coulombic repulsion by charge pumping [8]. Whereas most MEMS actuators are capable of only a few percent displacement compared to their size, this device was easily capable of out-of-plane displacement equivalent to the size of the device footprint on the silicon chip, without contacting the device. See Fig. 1.

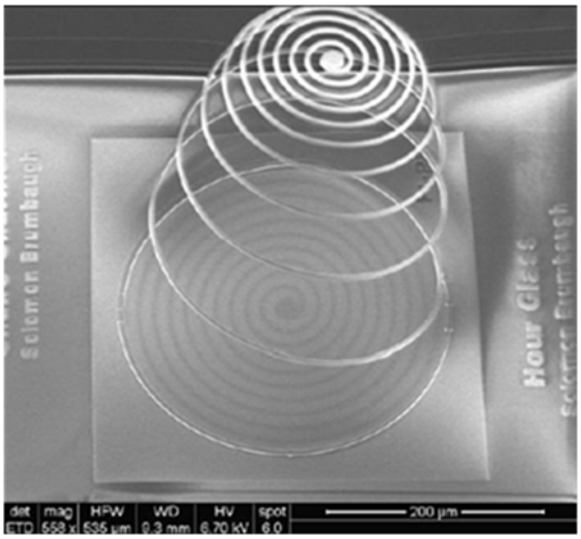


**Fig. 1.** Scanning electron micrograph showing deflection of the spiral beam actuator as observed during SEM imaging. The measured deflection was greater than 1:1 aspect ratio compared to the device footprint (220 μm out-of-plane corresponding to an equivalent point load of 2 μN) [8].

### 2.2. Demonstration of Coulomb's Law

The best demonstration of Coulomb's Law is the same one used in Freshman Physics: The Braun Electroscope is a device with a needle pivoting on a rigid vertical bar. When amber and hair are rubbed together, the amber accumulates a net excess charge through triboelectric effects, and when discharged to the electroscope, the ungrounded conductor re-distributes the charges across the surface. The pivoting needle then responds by being repelled from the rigid vertical shaft, into a position perpendicular to the shaft. In our micro-scale implementation of the Braun demonstration, the ring of the Braun electroscope was fabricated in-plane with the substrate, hinged for effect to two other rings. Upon actuation by charge injection, the rings self-deployed perpendicular to the substrate, and the needle responded perpendicular to the rigid shaft (Fig. 2).

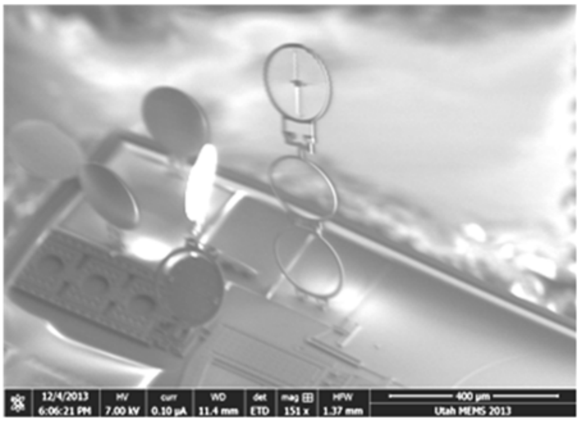


**Fig. 2.** Micro-scale Braun electroscope, fabricated in-plane and deployed by charge pumping from the SEM, showing coulombic effects.

While the electron beam is useful for simultaneously (and in a non-contact mode) embedding charge *and* visualizing the resulting dynamic effects, other sources of charge pumping are effective for simply actuating the devices. In the lab, a Van der Graaff generator was used effectively both in contact mode and in non-contact mode by holding a probe over the device to shower the device with electrons escaping from the tip. Manual triboelectric charging is also effective, such as with an amber rod and hair.

### 2.3. Biomimetic Accommodating Lens

Several design implementations (Fig. 3) were directed at translating strong out-of-plane motion into radial in-plane actuation. Out-of-plane motion is desired due to the large opposing surface areas that can be used to maximize the advantage of coulombic effects. Two sail-based designs are shown with the sail parallel to the substrate. The sails are constructed of doped (conductive) polysilicon, but none of the structures have electrical contact to ground. As charge is applied through the action of scanning an energetic electron beam over the device, accumulated charges redistribute over the available surface in order to create as much separation as possible. At some point, the crowded charges begin to face each other across the gap between the lower part of the sail and the underlying substrate, and tremendous forces are exerted on the sail. There is some difficulty in modeling these effects as commercial multi-physics software is not set up for these effects and requires definition of a ground plane per the traditional two-terminal electrical model.

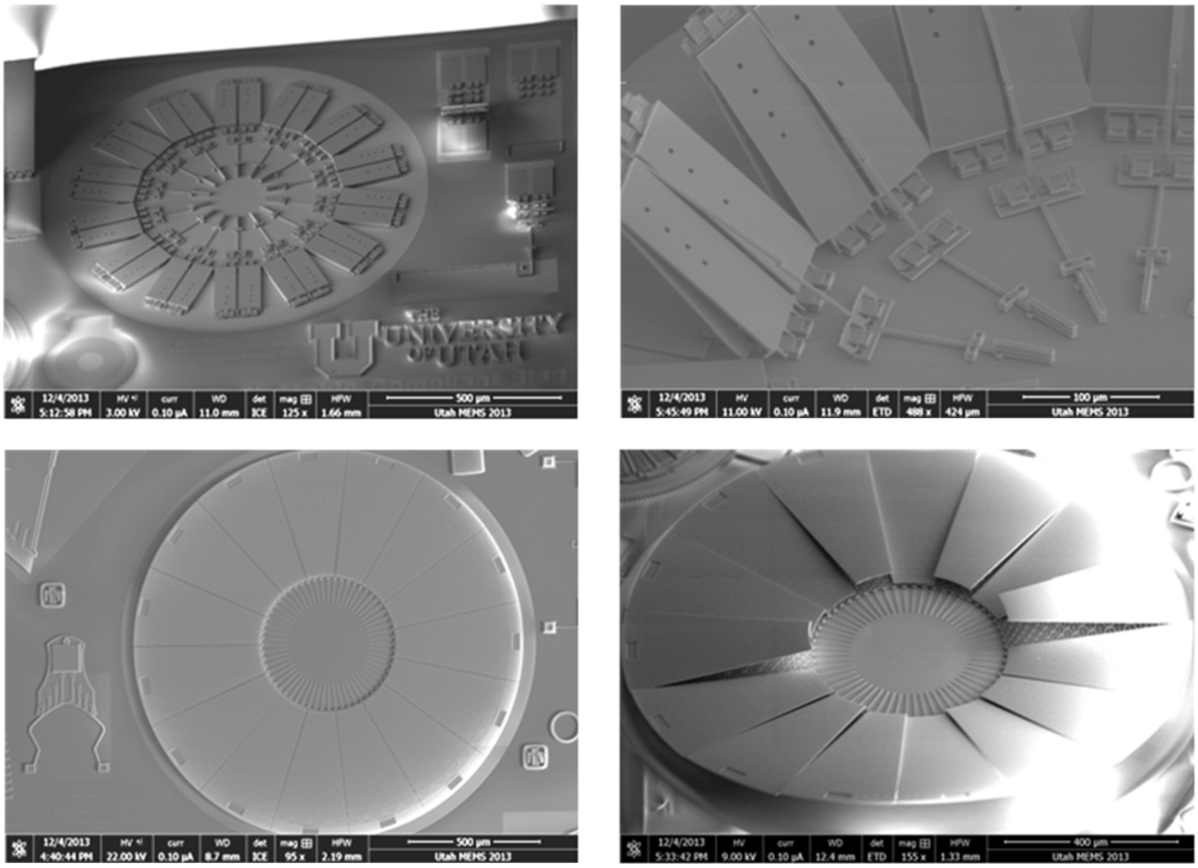


**Fig. 3.** Two versions (upper and lower) of biomimetic lens stretching actuators, (left) base state as-built in-plane; (right) biomimetic lens stretchers actuated out-of-plane by charge pumping. In these cases, the charge pump is the electron beam also used to image the devices. Note the differences in accelerating voltage (HV) between L and R.

We previously described [8-9] the electron beam conditions under which a MEMS designer may choose to create a net-positive charge condition, or a net-negative charge condition. This permits designers to create conditions of both attractive forces between separated unlike charge states on design elements, or repulsive forces between design elements due to the presence on each mechanical element of like charges, per Coulomb's law.

The upper design of Fig. 2 was created with multiple parallel sails in an attempt to multiply the applied force. The design shown in the lower part of the figure took advantage of a negative poisson compliant mesh [11], arranged to accommodate radial expansion, in order to avoid mechanical hinges. Both designs unfortunately had insufficient tolerances between individual sails, creating pinch points and wedging the sails together as the devices deployed. The effects of out-of-plane deployment by charge pumping were thus demonstrated without the benefit of creating a working accommodating lens actuator.

### 2.4. "Traditional" In-plane MEMS Actuation

Remarkably, the conditions we used for e-beam charging of the devices shown in Fig. 3, were also effective in continuously driving the Sandia-designed torsional ratcheting actuator (TRA) [17]. It was unusual since no attempt was made to ground either terminal. Under the action of the electron beam, the floating nodes differentially charged to the point where the interdigitated fingers attracted to each other, touched and discharged, then sprung back to the base state to begin another cycle, engaging the ratchet with each step. Fig. 4 shows the device under charging conditions that produced voltage contrast between the sets of opposing fingers.

## 3. MEMS Actuator Comparison

Table 1 provides a relative reference for several actuation techniques. We show typical success metrics of force and displacement, but also take into account the cost efficiencies of how much real estate the design consumes on the chip. This is the origin of what looks like a unit of pressure (force per unit area). It is not an actual pressure comparison, but rather is a measure of force efficiency per unit chip real estate. This table tells us some of what we already know: that chevron actuators based on thermal expansion provide an extremely high force over a very low displacement. Using chevrons in practical applications involves gears and ratchets, which increases design complexity, takes time for full actuation, and reduces the favorable calculation of real estate use. The charge pumped hinged plate was calculated to be the next most efficient use of real estate for the applied force, carrying the benefit of extremely fast reaction times.

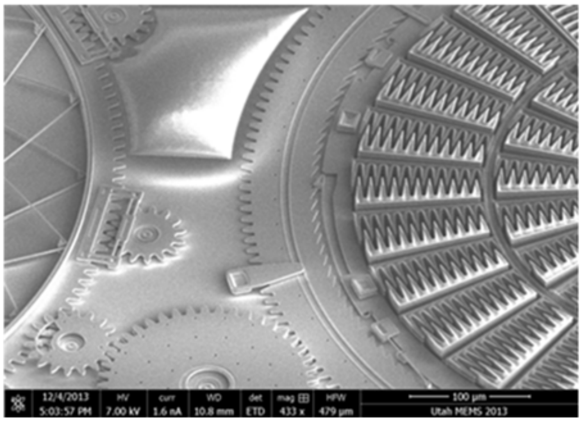
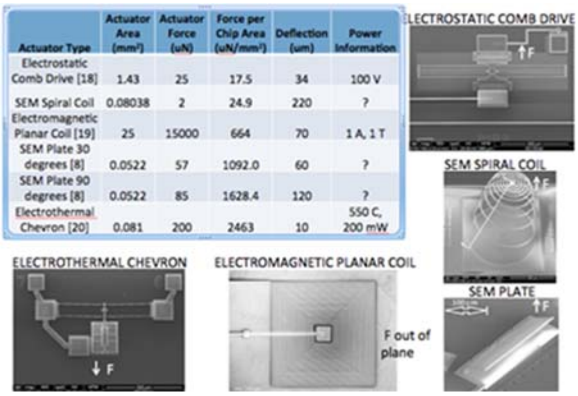



**Fig. 4.** Sandia-designed torsional ratcheting actuator [17] showing voltage contrast in the comb fingers, actuated here by non-contact (SEM) continuous charge pumping.

**Table 1.** MEMS Actuator Efficiency.



| Actuator Type | Actuator Area (mm²) | Actuator Force (uN) | Force per Chip Area (uN/mm²) | Deflection (um) | Power Information |
|---|---|---|---|---|---|
| Electrostatic Comb Drive [18] | 1.43 | 25 | 17.5 | 34 | 100 V |
| SEM Spiral Coil | 0.08038 | 2 | 24.9 | 220 | ? |
| Electromagnetic Planar Coil [19] | 25 | 15000 | 664 | 70 | 1 A, 1 T |
| SEM Plate 30 degrees [8] | 0.0522 | 57 | 1092.0 | 60 | ? |
| SEM Plate 90 degrees [8] | 0.0522 | 85 | 1628.4 | 120 | ? |
| Electrothermal Chevron [20] | 0.081 | 200 | 2463 | 10 | 550 C, 200 mW |



## 4. E-Harvesting Applications

We have demonstrated the power of charge pumping in actuating micromachines both in-plane and out-of-plane. This source of powering MEMS is unique in the ability to provide large displacement without the traditional sacrifice of high force. Manipulation of discrete charges is perfectly suited for energy harvesting approaches based on triboelectricity. This effect is familiar to each of us in day-to-day living, in how clothes cling due to static buildup, as well as the shocking discharge when touching a conductive object.

## 5. Future Work

Our objective in publishing this work is to seek development partners interested in capitalizing on abundant and free energy sources readily attainable through triboelectric effects. Challenges to be overcome include learning how to convert charge stored in a single terminal trap, into current that can be applied in traditional electric applications. Otherwise, it involves how to invent the machines and control systems of the future that operate strictly on discrete bursts of relocated charge, in preference to performing work via continuous or alternating current. Future work will concentrate on development of high-surface area, mechanically stable charge traps and the system of both trapping and controlled releasing discrete amounts of charge.

## 6. Summary and Conclusions

It is truly a paradigm shift to begin thinking in terms of applying force and performing work, directly using the fundamental unit of charge, designing how charges interact with each other, in preference to the traditional engineering of power using secondary effects of charge: charge in motion (current), charge in storage (voltage) or induced charge (capacitance).

The ability to accumulate charge from the ambient environment could lead to the elimination of batteries and allow MEMS to operate indefinitely. A triboelectric MEMS trickle charge pump could enable the powering of an entire cell phone or other mobile electronic devices, by dumping the collected charge into a single terminal supercap that acts like an infinitely rechargeable battery. In space-based MEMS, this would give advantages in weight, form factor, and energy storage. The trickle charger would replenish on-board power supplies for electronic function and it would alleviate the static charge build-up that occurs in normal space operation, where charging is otherwise a nuisance.

The infrastructure for these devices is not batteries, converters, power supplies, and function generators. It is rather triboelectric generators, single-terminal capacitors, MEMS switches, and a host of new power management tools that allow the control circuitry to be managed through classical, two-terminal voltage switching. In other words, while the "work" is done by controlled positioning and repositioning of static charges, yet the control is managed through classical electrical interfaces.

This potential saving of space (form factor), weight, and energy efficiency are of great interest in space based applications, where triboelectric charge can be "harvested" simply by nonmechanically collecting the abundant charge on high surface area storage media (single-terminal supercaps). This factor also applies in terrestrial applications, wherein charge-pumped MEMS can be powered simply by appropriate harvesting of charge through rubbing materials together with differing triboelectric tendencies.

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