Electrostatic Microgenerators

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Executive Summary

Just as the electromagnetic force can be used to generate electrical power, the electrostatic force can also be used to convert mechanical energy into an electrical form. Electromagnetic generators are used in large power stations because scaling laws show them to be superior at larger sizes. However, on the micro-scale, the electrostatic force becomes significant and so is suitable for electrical power generation. There are several different methods of operation in which the electrostatic force can be used to generate electrical energy. In this paper we discuss these methods and their relative merits in terms of power density, the suitability of the method to performing maximal power point tracking and difficulties of generator fabrication.

Introduction

Motion-driven microgenerators, which have applications in wireless sensor networks for security systems, military applications, structural condition monitoring and personal health systems, require work to be done on a transducer so that electrical energy can be generated. This requires a relative motion between either end of the transducer (referred to as rotor and stator in conventional generators) and is either achieved by fixing the stator and allowing motion of the rotor by connecting it directly to the source motion, or through the use of an inertial mass, as shown in Figure 1. The inertial method is preferred because only one attachment point is needed to harvest energy from the source.

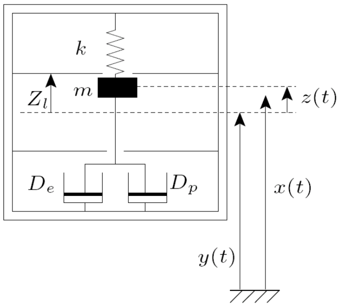

Figure 1 Typical inertial generator arrangement

As can be seen from Figure 1, the system comprises an inertial proof mass, a spring and two dampers. One of these dampers, the electrical damper D_e, represents the conversion mechanism between kinetic energy and electrical energy, and the other represents parasitic mechanical damping due to air damping and hysteresis losses in the spring (D_p). As has been shown in [1], the amount of energy that can be generated under specific operating conditions (the amplitude and frequency of the input vibration), is heavily dependent on the strength of the electrical damping force. In addition, as the operating conditions change, the damping force must be tuned to allow the generator to continue to work at its peak effectiveness. In other words, the generator must perform maximal power point tracking. One of the main design decisions, therefore, is what type of transduction mechanism should be used.

Transduction Types

There are essentially 2 transduction mechanisms that can be used to convert motion into electrical energy. These are:

- Electromagnetic (E.M.)
- Electrostatic (E.S.)

Electromagnetic microgenerators make use of permanent magnets moving in relative to a coil, inducing a voltage, and thus causing current flow according to Faradays' laws of induction. Electrostatic generators can make use of variable capacitor structures, or piezoelectric materials. The choice of transducer type for a particular generator application is made based on the following three main criteria:

- **Scaling laws:** Different quantities scale at different rates with size. An obvious example is that volume scales with the cube of length but area only scales as the square of length. In the same way, electrostatic forces and electromagnetic forces do not scale at the same rate as size changes. Electromagnetic forces scale somewhere between L^3 and L^4. Electrostatic forces scale somewhere between L^1 and L^2 [2]. Therefore, electromagnetic transducers are likely to be better at large sizes and electrostatic generators become superior once devices are miniaturised.

- **MEMS compatibility:** The potential for the enormous uptake of microgenerator powered devices means that they must be cheap to manufacture. They will always be integrated with some sensing and data transmission electronics. As a consequence, a very useful feature of a microgenerator is its ability to be manufactured in large numbers at low cost and that it can be easily integrated with electronics. It is therefore beneficial if the generator can be made using MEMS technology. Electrostatic transducers are often used as actuators in MEMS devices and thus variable capacitance structures are readily integratable using standard microfabrication technology.

- **Controllability:** Large scale energy harvesting devices, such as PV panels and wind turbines use maximal power point tracking techniques in order to harvest as much energy as possible as operating conditions change. An important aspect of microgenerators is that in order to maintain a high degree of effectiveness, it should be possible to apply maximal power point tracking techniques to these generators. This can be done by altering the electromechanical damping coefficient D_e, either by changing the load impedance (E.M. and E.S. generators) or by adapting the polarisation of the generator (E.S generators). In electrostatic generators this is readily achieved by changing the pre-charge on the capacitor.

Electrostatic Transducers

Having taken into account the above criteria, and bearing in mind that the ultimate aim for energy-harvesting devices is that they can be further and further miniaturised to power smaller and smaller devices, the electrostatic transducer provides a very attractive approach.

An electrostatic transducer uses the force between charges stored on electrodes to couple the energy from the mechanical domain into the electric domain. The charge separation Q on the electrodes depends on the potential difference V between them through the constitutive equation of a capacitance: $Q = C_{var} V$. The capacitance, C_{var},is a function of the geometry of the electrodes and the characteristics of the materials surrounding them,. As the mass moves over $z(t)$, as defined in Figure 1, the capacitance changes between C_{max} and C_{min} . The energy that is extracted from the mechanical motion then depends on how the variable capacitance is connected to the electronic circuitry. There are, in effect, two main techniques which have been used to realise the electrostatic transducer mechanism. These are switched systems and continuous systems. The different methods of operation will now be described.

Switched Systems

The switched type of connection between the transducer and the circuitry involves a reconfiguration of the system, through the operation of switches, at different parts of the generation cycle. Switched transducers can further be split into 2 main types:

Constant charge:

If a variable capacitor is pre-charged at maximum capacitance and then disconnected from any external circuitry before the geometry of the capacitor is changed by the motion, additional energy will be stored in the electric field between the electrodes as work has been done against the electrostatic force. This additional energy can then be used to power a circuit. The most common way in which this approach is implemented is as shown below:

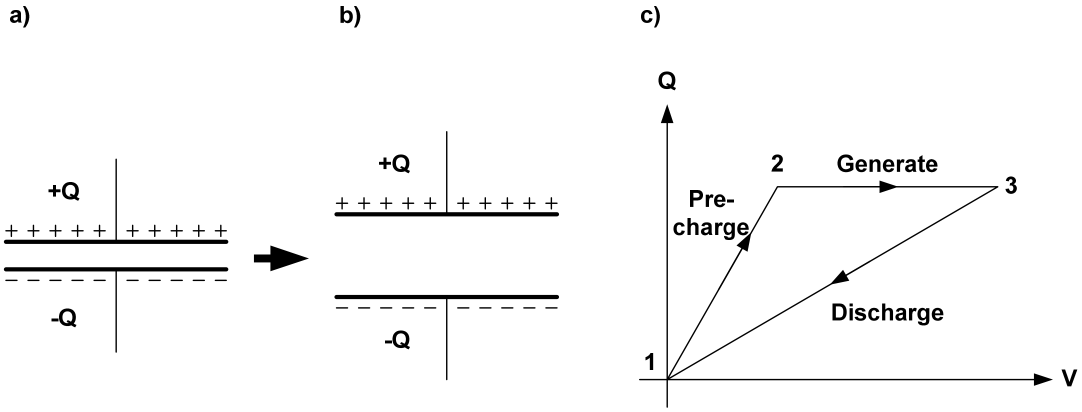

Figure 2 Operation of an electrostatic generator in constant charge. a) and b) show the two conditions of the capacitor and c) shows the QV diagram of the cycle

Two parallel plates are arranged so that they can separate, increasing the gap between them. This type of motion, under a constant charge, creates a constant force between the two electrodes. The diagram of Figure 2c shows a QV diagram of the operation of the generation cycle [3]. The device is pre-charged to a low voltage in the first part of the cycle by making a connection to a voltage source (1-2). Then, the plates are disconnected from the source and separated under constant charge during the generation part of the cycle (2-3). Finally, the capacitor is discharged in the third part of the cycle (3-1). The capacitance is then increased ready for the cycle to restart. The area traced out by the QV diagram represents the electrical energy generated.

Constant Voltage:

If the capacitor is pre-charged and then, whilst the capacitor is connected to a constant voltage (possibly provided by a battery), a reduction in capacitance between the electrodes caused by relative motion of the plates would result in charge being removed from the capacitor and being pushed back into the voltage source, thus increasing the energy stored in that source. If the plates are operated in a sliding motion, as indicated in Figure 3a and b, the force between the plates in the direction of relative motion remains constant.

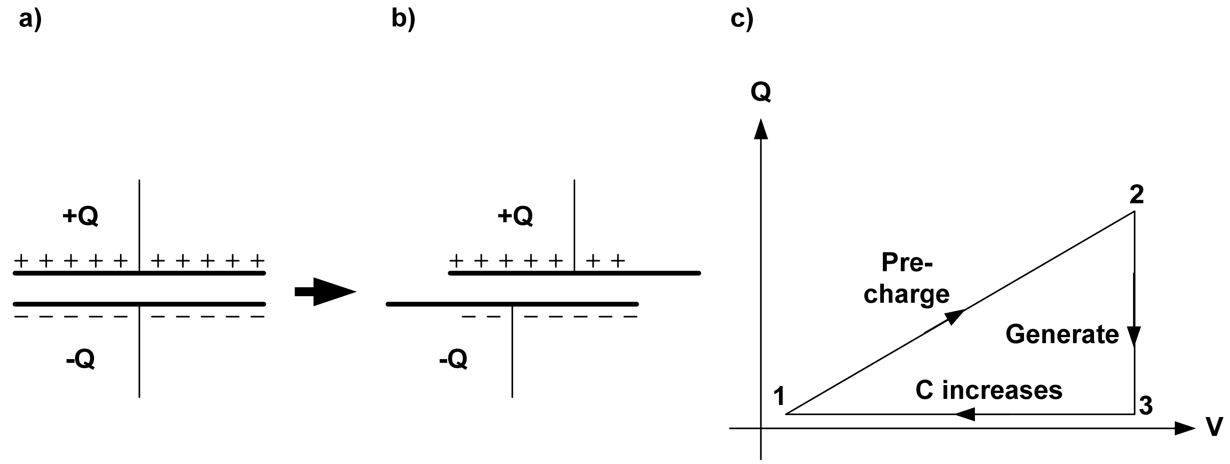

Figure 3 Operation of an electrostatic generator in constant voltage. a) and b) show the two conditions of the capacitor and c) shows the QV diagram of the cycle

Figure 3c shows the QV diagram for this approach. The capacitor is pre-charged to a set voltage whilst at high capacitance (1-2). Then, whilst connected to a voltage source, the capacitance is reduced, forcing charge back into the voltage source (2-3). This is the generation part of the cycle. Switches then disconnect the capacitor from the voltage source before the capacitance is increased at constant charge (3-1) ready for the cycle to start again. Again, the area enclosed by the QV diagram represents the energy generated.

Continuous Systems

A third mode of operation exists when the variable capacitor is continuously connected to the load circuitry, and this load circuitry provides the capacitor with a polarisation voltage. A simple example of this is a voltage source, a resistor and a variable capacitor wired in series. A change in capacitance will always result in a charge transfer in between the electrodes through the load resistance causing work to be done in the load.

The switched generators previously discussed are special cases of this continuous mode generator: a constant charge generator is equivalent to a continuous generator operated with an infinitely high load impedance, whilst the constant voltage generator corresponds to a continuous generator which is short circuited. Because no work can be done when either the generated current or the generated voltage is zero, these extremes of operation require a switching circuit to make them operate.

The use of controlled switches complicates the implementation of the generator and the circuitry required to control them consumes a minimum amount of the generated power and so in some circumstances the use of a continuous system is preferred. The design can be based on a variable capacitor with a constant polarisation source $(Q=C(z(t))\ V_{pol})$, or could combine a position dependent polarisation source with a fixed capacitor $(Q=C\ V(z(t)))$. A well-known example of the use of built-in polarisation sources is given by piezoelectric generators (which are discussed elsewhere in this issue). The capacitance between the electrodes of the generator is then virtually constant, but the polarisation voltage changes as a function of the displacement. A current then passes through the load and work is done. A QV-diagram is drawn for piezoelectric generators in Figure 4b, however in this case the loop integral on this plot is zero because the piezoelectric capacitance is constant.

If piezoelectric materials are not available in the chosen technology or are not applicable for the target application, *electrets* can be used. These dielectric materials have the ability to fix charges quasi-permanently. In silicon-based technologies it is straight-forward to use a SiO_2/Si_3N_4 double-layer, similar to the structures used for flash memory cells. If the use of these layers is not compatible with the design of the capacitor, polymers like Teflon or Parylene are applied [4]. By subjecting the *electret* to an ion flow (e.g. by corona charging) it can be charged to close to its breakdown field strength, resulting in surface potentials up to 300V. *Electrets* have expected lifetimes of 50 years.

A generator using electrets is presented in [5]. In these designs the movable electrode of the capacitor is patterned, while the other electrode is not; the total capacitance is thus constant. The *electret* built in the device is patterned too: the relative position of the patterned electrode to the *electret* determines the polarisation of the capacitor and the change in polarisation results in a current through the load.

Electrets are often used in combination with a variable capacitance to make a continuous generator. The fixed charges of the *electret* induce an electric field between the electrodes of the capacitor, corresponding to a potential of several tens of volts. Three possible QV diagrams showing the operation of a continuous electret generator are shown in Figure 4a. If the capacitor is operated in a constant voltage mode, a change in capacitance will result in a current through the load circuitry along curve (1-3-1). A high impedance load forces the generator to operate in constant charge as the high impedance obstructs the charge transport between the electrodes (1-2-1). In both of these cases, the area of the QV loop integral is zero as the transition from maximum to minimum capacitance occurs on the same trajectory. An optimised load for a continuous generator will operate the generator in between these extremes along (1-4-1), and as can be seen, work is now done and the loop integral has a finite value. This class of generators is referred to as velocity damped generators because the damping force is approximately proportional to the relative velocity between the proof mass and the frame.

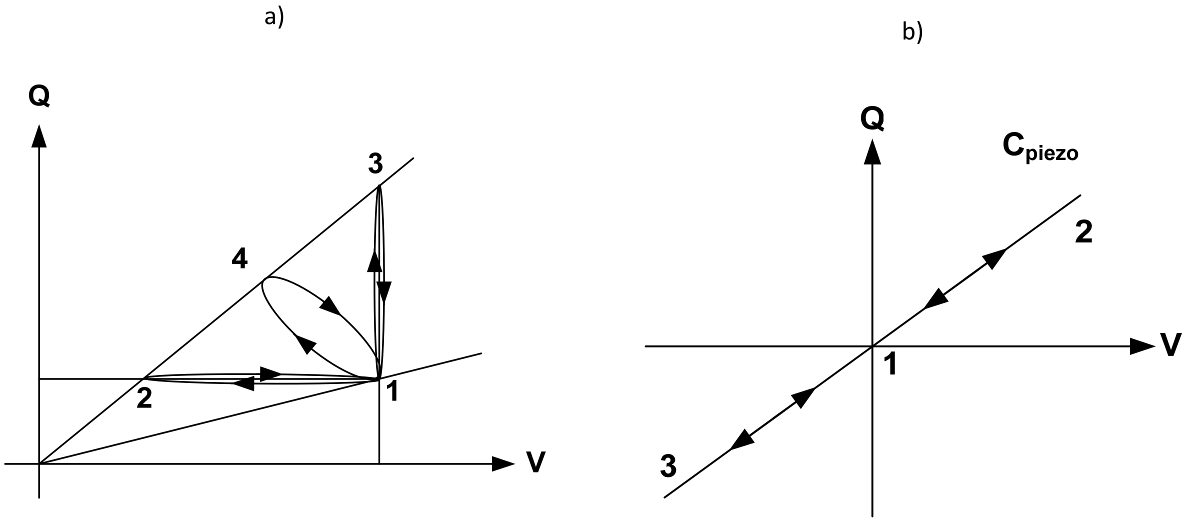

Figure 4 Operation of an electrostatic generator in continuous mode (a) or using a piezoelectric polarisation (b)

Transducer Designs

There are four main designs of electrostatic transducers that have been reported in the literature that are used to implement miniature prototype generators:

- Parallel Plate – gap closing
- Parallel Plate – variable overlap
- Comb drive
- Rolling Rod

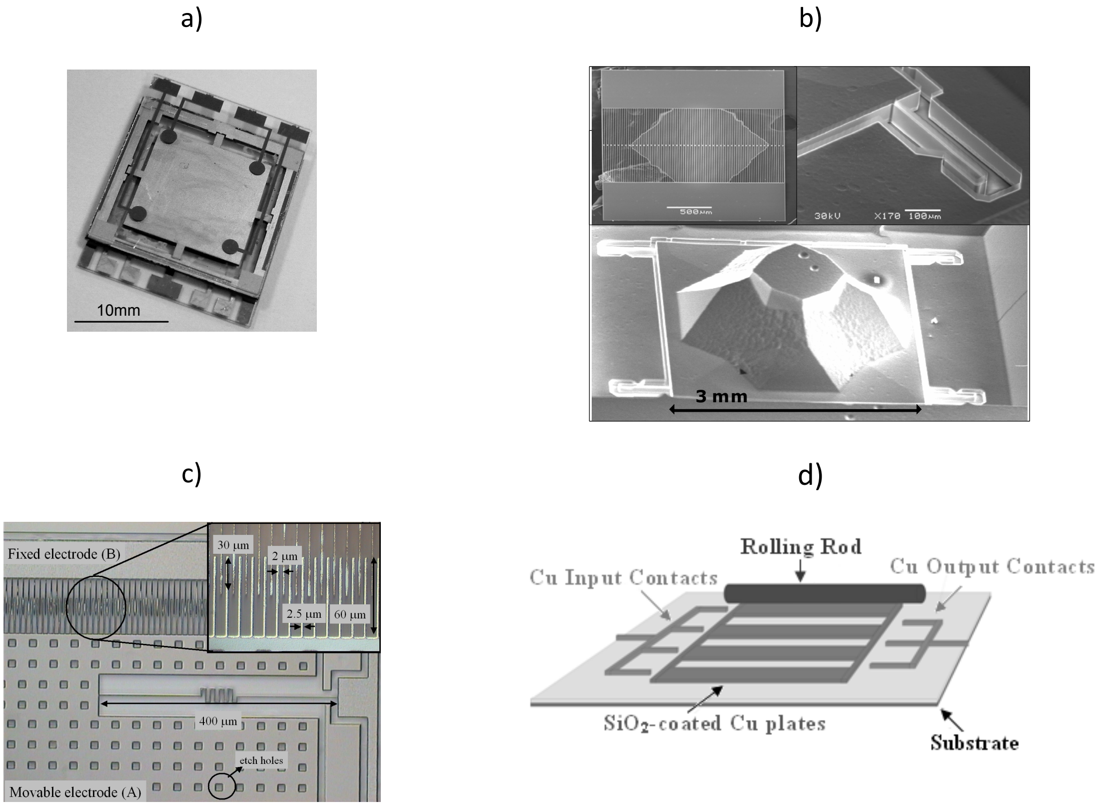

Figure 5 Four Types of transducers as reported in the literature : a) parallel plate – Gap closing from [6], b) parallel plate – variable overlap, c) Comb drive, d) rolling rod

The device shown in Figure 5a is a parallel plate design, where a capacitance is formed between two parallel electrodes stacked on top of each other. The device is operated in constant charge and generates high voltage spikes when primed with a low voltage.

The device in Figure 5b is a parallel plate design too, however in this case the motion of the seismic mass is now in-plane with respect to the bottom wafer. Multiple electrodes have been patterned on the mass that form 200 capacitors connected in parallel. As the mass moves, the overlap between the electrodes changes, varying the capacitance. This type of continuous mode generator is typically combined with electrets [7].

The third type of transducer is again composed of multiple capacitors in parallel, only this time the electrodes are located on the same wafer, forming a comb drive. This type of capacitor originates from micromachined accelerometer designs. The mass of the generator moves in plane when motion occurs, changing the overlap of the electrodes. They can be operated either in a continuous mode [8,9] or in a switched mode [10].

When analysed, it can be shown that the maximum possible output power from these systems is proportional to the value of the proof mass. If these systems are to be made in a cost effective way they must be manufacturable using batch production using standard MEMS silicon processing, hence the popularity of devices shown in Figure 5b and c in the literature, in both switched or continuous implementation. However, this makes it difficult to integrate a large value of proof mass: as silicon is not a dense material, a mass of 0.1 g consumes approximately one square centimetre of silicon on a typical wafer. Therefore this approach is not very cost-effective.

The device pictured in Figure 5d, previously reported in [11], aims to overcome this problem. By using a proof mass that is not fixed to the structure, an external mass can be used whilst not incurring the problems associated with the alignment and fastening of an external mass to the MEMS device. This structure comprises a metal rod rolling on top of a layer of dielectric, acting as the movable electrode, and a set of strip electrodes underneath the dielectric, acting as the static electrodes. The rod and the strip electrodes form a variable capacitor while the rod moves. The device operates in a constant charge mode.

The power density achievable with each design of electrostatic transducer is dependent upon whether the optimal value of electrostatic force can be achieved. This value is dependent upon the dimensions of the generator, the proof mass and the operating condition. Generally speaking, it is more difficult to achieve high electrostatic forces using constant voltage comb drive structures than constant charge structures, because the constant voltage case requires the control of a high voltage source. The constant charge case only requires the control of a relatively low voltage source. For this reason, constant charge designs may be advantageous when large electrostatic forces are required.

Reported Measurements

Measurements have been reported for several prototype electrostatic microgenerators. Some of these are shown below in Figure 6. The first results are from the constant charge generator described in [6]. The operation of the generator, and its behaviour in comparison with the QV diagram of Figure 2c can be seen. At around 0.01s, the capacitor is pre-charged, at maximum capacitance, to around 30V. After some time, the source motion causes the plates to separate. This operation is done under constant charge and so a large increase in voltage can be seen. Once the electrodes reach maximum separation, the capacitor is discharged. This generator was shown to generate around 12 μJ from an input motion of 40 Hz and 6 mm amplitude.

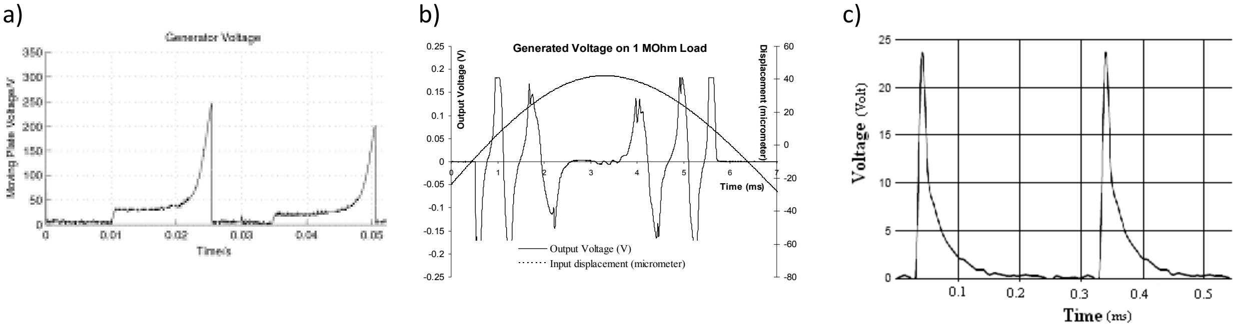

Figure 6 Measured results from E.S. generators

The measurement in Figure 6b illustrates the operating principle of the parallel-plate variable overlap micromachined generator. As the mass moves (sinusoidal curve), the parallel capacitors change in value. Because the amplitude of the motion is larger than the pitch of the capacitors, multiple generation cycles like the ones indicated in Figure 4a occur. Note that the amplitude of the generated voltage decreases as the displacement increases, due to the decreasing velocity of the mass. A 10 V electret polarisation was used in this experiment.

Results from a rolling-rod generator are shown in Figure 6c. While the rod rolls across the dielectric, the capacitance varies periodically. Maximum capacitance occurs when the rod is aligned with any of the opposing strip electrodes whereas minimum capacitance occurs when the rod lies in the middle of two adjacent strip electrodes. Just like any other constant charge transducer, pre-charge takes place at maximum capacitance positions and discharge at minimum capacitance positions. As the rod rolls from one side of the substrate to another, a series of output pulses can be observed at the output stage.

Conclusions

To date, the microgenerator community has concentrated its work with a relatively even distribution on each of the three main transducer types, electrostatic, electromagnetic and piezoelectric generators. However, as microgenerators become further and further miniaturised, the requirements for MEMS compatibility increase. In addition, due to the nature of the scaling of electrostatic and electromagnetic forces, at some level of miniaturisation, the electromagnetic force will become weaker than the electrostatic force and thus electrostatic microgenerators will be able to achieve greater power densities. Therefore, it is likely that in medical applications, where it is necessary to implant self-powered sensors into the human body, electrostatic generators are likely to dominate. So far, there have been three main types of electrostatic microgenerators presented, these being the constant voltage and constant charge switched type and the electret based continuous type. The switched types are more easily controlled to perform maximal power point tracking, but have the added complexity of the associated circuitry to control those switches. In addition, constant charge designs are preferable when a large electrostatic force is required in the application.

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