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Applications of MEMS in power sources and circuits

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Abstract
Power supply for electronics is one of the more recent application areas which has been explored for MEMS devices and techniques. Within this field, the most actively researched application has been MEMS power sources, particularly to replace batteries for portable electronic devices such as wireless sensor nodes. In addition, there are possibilities for MEMS devices in circuit protection, and power conversion and conditioning. This paper reviews these applications. More detailed descriptions are presented of work at Imperial College on motion scavenging power sources and MEMS circuit breakers, and examples of work in power applications by other groups are also given. Finally, some possible future directions are discussed.

1. Introduction

The field of MEMS applications is very diverse, both in terms of the functions provided by the MEMS devices, and the application areas to which these are applied. In the area of electronic systems specifically, a major application has been the integration of MEMS sensors (such as accelerometers) with the associated circuits. More recently, the incorporation of micro-mechanical devices, such as switches and resonators, in radio frequency circuits and sub-systems has been a major area of research.

Another growing application area within electronic systems is that of power supply. Particularly with the proliferation of portable electronic products, provision and efficient use of power is a key concern. The most explored application of MEMS in this field is the generation of power from motion and vibration, something to which an integrated electro-mechanical technology is ideally suited. However, MEMS switches also have benefits for circuit protection, and the use of micro-mechanical structures for energy storage results in potential uses in power conversion and conditioning.

2. Power generation

In portable electronic products the batteries often represent the largest contributing element to both size and cost, and their capacity sets the useful operation time before some sort of maintenance is needed. For this reason, techniques which can extract energy from their environment (energy scavenging) are highly attractive [1, 2]. Although the power levels such techniques can achieve tend to be low, many useful electronic devices have very low power consumption, and so energy scavenging has the potential to give such devices effectively unlimited maintenance-free lifetime.

The most developed form of energy scavenger is the solar cell, and this remains the ideal choice where high ambient light levels are reliably present. Where they are not, temperature differences, ambient man-made radiation and motion are potential sources. For motion in particular, a mechanical-to-electrical transduction mechanism is needed, and MEMS provides the ideal approach to achieving this at a small size scale, e.g. 1 cm^3 and below.

Devices that exploit motion achieve the highest power levels by using direct force, an example being the heel-strike generator [3]. However, this requires connection to (or interaction with) two structures moving relative to each other, which is often not practical and usually implies a relatively large device. More common are the inertial devices, in which a proof mass is suspended within a frame, and the frame mounted to a moving 'host' structure at a single point [4]. Power is extracted by damping the internal motion of the proof mass with an electromechanical transducer, and this transducer can be electrostatic, electromagnetic or piezoelectric [5]. All three mechanisms are realizable, and have been reported, in MEMS technology.

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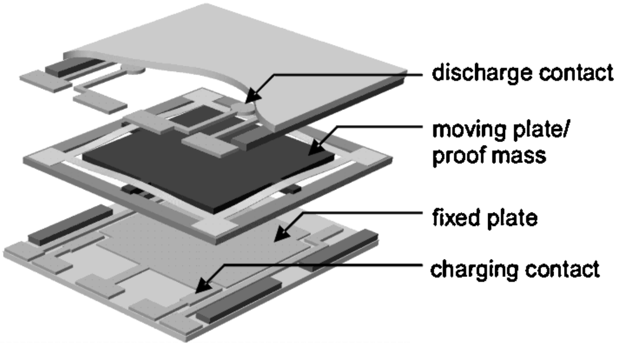

Figure 1. Electrostatic energy scavenger for low frequency applications.

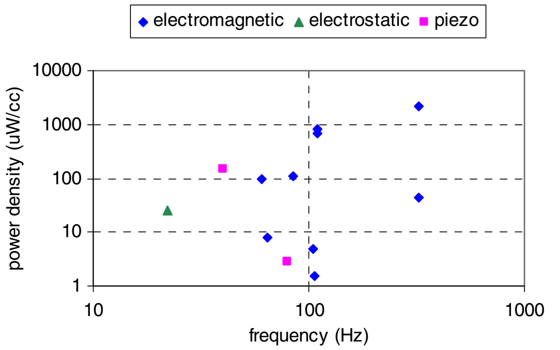

Figure 2. Power densities for reported inertial scavengers. (This figure is in colour only in the electronic version)

Which transduction method to use is a key design choice for inertial energy scavengers, and is dependent on two main application parameters: the acceptable device size and the frequency range of the source motion [6]. Electromagnetic (magnet and coil) transduction is well suited for relatively larger devices [7]. Permanent magnets can provide high magnetic flux, and flux gradients, over significant distances, allowing for a large internal travel range, and a larger volume (say 1 cc or more) allows the coils to have high numbers of turns without excessive series resistance.

Electrostatic devices, essentially variable capacitors with one plate attached to the proof mass, are better suited to smaller devices, say with internal travel below 1 mm, since high electric fields (and consequently strong damping forces) can be more easily achieved in small gaps. These devices are also well suited to monolithic integration, which is a more important concern at the lower size range, since they do not need to incorporate specialized (i.e. magnetic or piezoelectric) materials. They do require a priming voltage to be applied (unless an electret is employed); however, this does mean that the damping force has the potential for dynamic adjustment, a particularly valuable possibility for cases where the source motion varies significantly in amplitude.

In terms of source frequency, most applications so far examined fall into one of two categories. At the low frequency end are devices to be powered by body motion, mainly for body-worn or implanted sensors. Here the motion (including harmonics) is mostly in the 1s to low 10s of Hz, spectrally rich, and highly variable. We have developed a non-resonant electrostatic device particularly for such uses [8], which is illustrated in figure 1.

Here a silicon micro-machined proof mass forms the moving plate of a variable capacitor which is charged to a priming voltage at its minimum separation. The plates are then forced apart by the external motion, so that the capacitance drops while the charge remains constant. This causes the voltage (and energy) to rise, and the energy is discharged into an output circuit at the extent of its travel. The measured power was 2.6 μW at 26 Hz.

The second application area uses machine motion, where the frequencies may be in the 100s or 1000s of Hz, and typically the source motion amplitudes are less than the internal travel range of the energy scavengers. In these applications optimal power output requires resonant enhancement of the internal motion, with modest damping forces, and parasitic damping forces (such as air resistance) are generally the limiting factor. Piezo-electric devices are well suited to such applications [9]. At high frequencies their internal leakage currents are not a major concern, and they can produce significant voltages even for low damping forces, which is an advantage for power processing circuitry (particularly rectification).

It can be shown that the maximum power available from inertial scavengers scales with the cube of frequency [5]. However, analysis of reported working devices (figure 2) illustrates the increasing difficulty in reaching the theoretic limit as frequency increases. A proportionality of f^2 fits the data more closely.

Energy scavenging power supplies are not the only ones where miniaturized electromechanical transducers are required. Rotating micro-generators, driven by turbines, have seen major research efforts for a number of years. Of these, the most ambitious are those proposing to use gas turbines as the motion source [10], and although such devices have not been fully realized, major advances have been made on the constituent sub-systems, including high speed (10^6 rpm) rotating turbines, combustor systems and the associated high temperature materials. Meanwhile, MEMS rotating generators using airflow driven turbines have been fully realized, and demonstrate mW power levels [11].

Power supplies without moving parts also benefit from the micromachining techniques of MEMS. Highly miniaturized fuel cells are being developed by many groups, and micromachining offers advantages such as the use of microfluidic channels in the separator plates [12]. MEMS technology has also been applied to batteries. For example, in [13], silicon micromachining is used to fabricate three-dimensional inter-digitated electrode arrays in nickel–zinc microbatteries.

3. Circuit protection

MEMS has been widely explored for fabricating micro-mechanical electrical switches. Many of these have been for switching radio frequency signals, where low insertion loss and power consumption, and high linearity, provide benefits over established solid-state solutions. However, circuit protection provides another interesting application of such devices. For

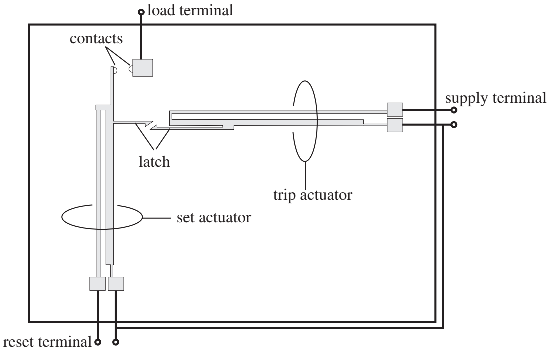

Figure 3. Schematic of MEMS circuit breaker.

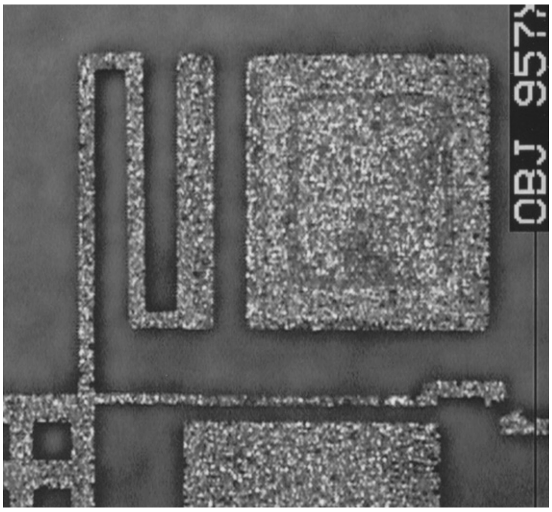

Figure 4. Optical micrograph of circuit breaker latch area and contact in open state.

over-current protection, conventional fuses are becoming increasingly unacceptable in electronics applications, where an ability to recover without part replacement is demanded. The common alternative is the PTC (positive temperature coefficient) device, which undergoes a phase transition to a highly insulating state when over-heated by an over-current event, but gradually recovers when the condition disappears. While effective and cheap, these devices have a number of disadvantages, such as long and variable trip times, high ambient temperature dependence and lack of external controllability. Electrically resettable circuit breaking relays can overcome all these problems, and MEMS provides an approach to making them sufficiently small and, potentially, low cost, for electronics applications.

We developed such a MEMS circuit breaker, in which the load current is passed through a thermal actuator which provides the tripping function [14]. This device is illustrated in figures 3 and 4.

Both the trip and set actuators are thermal shape bimorphs, with actuation in-plane. This keeps most of the mechanical complexity in one processing plane, where it can be provided by photomask design rather than multiple deposition steps and vertical shaping. Trip currents were about 350 mA, temperature sensitivity 0.15% °C^{-1}, and trip times in the range 1–100 ms depending on over-current levels. Because resetting is under programmable control, such devices can potentially form part of smart power modules.

The relatively low contact area achieved in this device, as in lateral motion MEMS switches in general, is an important factor limiting the rated current. In [15] a switch is described with vertical motion, using magnetic actuation, with a proposed application in circuit breaking, although only preliminary experimental results were provided.

Besides size, the rapid switching speed achieved in a MEMS device can be a key advantage over conventional circuit breakers. For this reason, high current applications of MEMS in circuit protection have been investigated by several groups [16, 17]. In these cases, current and voltage handling limits are overcome by combining arrays of switches in parallel and series.

4. Power conditioning

In addition to generating and switching electrical power, power conditioning is another possible application of MEMS structures. Conditioning requirements can include rectification, regulation and dc level conversion. These functions are required when systems are powered by batteries or mains supplies, and may be even more challenging when energy scavenging supplies are used [18].

Conversion and regulation, in particular, require devices that can temporarily store power, and usually capacitors and inductors perform this function. However, MEMS devices can provide coupling of electrical signals into the mechanical domain, where energy storage in moving masses and strained springs is possible. This was the basis of a proposal by Noworolski and Sanders [19] for a dc–dc converter based on a resonant MEMS structure. Typically, integrated dc–dc converters use switched oscillating circuits, with resonant LC tanks providing the energy transfer. However, integrating the magnetic materials required is not straightforward, and the inductive components cause significant losses, particularly at the high switching frequencies needed for high power densities. A mechanically resonant MEMS structure provides a possible approach to eliminating the magnetic components, while maintaining compatibility with monolithic integration.

The operating principle of the device of [19] is shown in figure 5. The upper schematic represents two variable capacitors, electrically isolated but mechanically coupled. These are connected to the input and output sides respectively, and are driven at their mechanical resonant frequency. The lower diagram illustrates the mechanical construction. The lower rectangles represent the anchored lower plates of the capacitors, while the upper plates are connected to their anchors via springs. An insulating mechanical link couples the two sides.

High power densities are an important factor in integrated power conversion, and in this case, using a 1 MHz resonant frequency, a density of 0.8 W cm^{-2} of device area was attained. In fact, strained silicon mechanisms provide a quite high energy storage density. Assuming a Young's modulus $E \approx 200$ GPa, a modest strain of $\varepsilon = 10^{-4}$ gives an energy density $^1/_2 E\varepsilon^2 = 1$ mJ cm^{-3}. By comparison, a capacitor with a dielectric of relative permittivity $\varepsilon_r = 4$ and an electric field $\mathrm{E} = 10^6$ V m^{-1} stores $^1/_2 \varepsilon_r \varepsilon_o \mathrm{E}^2 = 0.02$ mJ cm^{-3}.

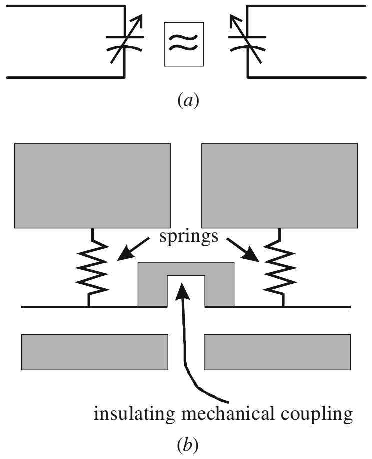

Figure 5. Schematic of a MEMS dc–dc converter (after [19]).

Other applications of MEMS in power conversion have also been described. In [20] a dc–dc converter is proposed and modelled which uses a MEMS variable capacitor operated by an actuator, in a charge pump configuration.

Even in conventional dc–dc converter circuits, micromachining has an important role to play, in the fabrication of inductors. A key challenge in achieving integrated switching dc–dc converters is to realize on-chip inductors of sufficient quality factor (Q). While this is in general not possible by conventional CMOS processing, MEMS-style fabrication offers major advantages [21, 22]. Firstly, while only planar coils are possible in conventional CMOS, the greater three-dimensionality of MEMS structures allows solenoids to be fabricated. These provide higher inductance for a given conductor length, because of improved flux coupling, and so achieve higher Q. Typically the solenoid is fabricated with its axis parallel to the wafer surface, with rectangular windings built up as three levels of metallization. Another advantage of MEMS processing is the possibility of introducing additional functional materials. For highly compact switched power supplies, high switching frequencies are required, for which conventional metal inductor cores are excessively lossy. This problem has been overcome in MEMS inductors by the integration of ferrite cores.

5. Discussion and conclusions

It can be seen that MEMS technology provides a wide range of uses in integrated power systems. Although there has been no large-scale commercial deployment of these yet, the potential is considerable. Two further developments are probably needed before this potential can be realized. Firstly, true integration of these MEMS devices with the associated circuitry will make exploitation more practicable. MEMS energy scavenging, for example, creates considerable challenges for power conversion circuitry, and these issues are beginning to be addressed [23].

A second driver to realize the potential of MEMS in power supplies is that the cost/benefit ratio of adding MEMS processing will be significantly improved when a number of related MEMS functions are co-integrated within single modules. These functions may include sensing, as well as the power functions themselves. In fact, sensing functions may add requirements for enhanced circuit protection, particularly as sensors often need to interface to the local environment to access the measurand, and this may increase the risk of electrical interference. This is illustrated in [24], where a system-on-chip MEMS-based gas sensor is reported in which electrostatic discharge protection is integrated in the package (although this function is not provided by MEMS). In [25], general considerations for integrating power generation and storage with MEMS devices were presented, including useful comparison tables of storage densities and actuator power requirements.

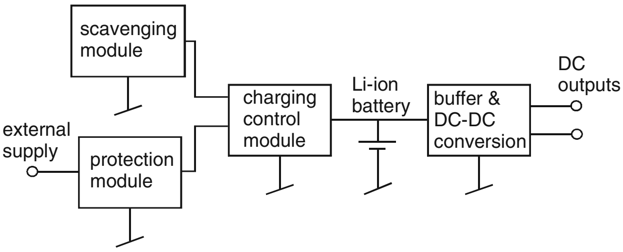

Figure 6. Possible interconnection of MEMS and other modules in a power supply for portable electronics.

Smart power supply modules are an attractive platform for achieving some of the advantages of integration described above. Such modules could incorporate, in addition to power supply, regulation and protection, such features as intelligent fault monitoring and restoration, thermal management and temperature compensation, variable supply rail voltages, and hibernation cycles. One possible architecture is illustrated in figure 6. A MEMS scavenging module is used to top up a rechargeable battery between external charging cycles. A protection module, which could include MEMS over-current protection, is provided between the charging point and the internal circuits and battery. A control module regulates charging from either the scavenger or the external connection. Finally, an output module provides conversion of the battery voltage to other dc levels, and again this could include MEMS components. Monolithic integration of the various MEMS functions in this system should provide a more cost effective solution than using several discrete devices.

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