A Brief Overview of Power Generating Micro Electromechanical Systems

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***Abstract*— The interest and progress in the Micro Electromechanical Systems (MEMS) field is growing rapidly. Many applications are presenting themselves, e.g. for maintenance, medical purposes, space applications or security devices. Therefore a brief state of the art is presented in this paper. Designing these sensors and actuators takes special care because by scaling down the devices, one could encounter problems such as excessive friction losses, heat production, insufficient insulation or totally different physical phenomena. To get an idea about the properties of power generating MEMS, this paper derives the scaling laws for electrostatic, electromagnetic (with and without permanent magnets) and thermoelectric power generators. These three methods of generating electrical power will be compared.**

***Index Terms*— MEMS, micro generator, power, scaling laws**

I. INTRODUCTION

In the past few years, there has been a major progress in the Micro Electromechanical Systems (MEMS) domain. First of all, integrated circuit processing techniques are used to build up the MEMS device, which is not only an integrated circuit but also a sensor or an actuator. Thanks to this integration, MEMS inherit the advantages of modern integrated circuits: mass production, reproducibility and small size. This is directly related to lowering costs, good reproducibility in dimensions as well as in material properties and performance and it makes them applicable almost everywhere. On the other hand, new circuitry design techniques continuously decrease the power requirement which makes it theoretically possible for MEMS generators to provide enough power for a device, e.g. sensor, actuator or data transmission system. Recent projects have proven that MEMS can be fabricated and can operate properly. Some examples are the Seiko Kinetic watch, PicoRadio and μAMPS [1][2][3]. A brief state of the art will be stated in this paper. To design such small devices, one must know how certain systems behave when they are scaled down. To gain some insight in MEMS, the first step to take is to derive the scaling laws. Based upon the scaling laws, the most favorable method to generate power can be chosen. This will be discussed after the state of the art.

II. STATE OF THE ART

A. Fuel cells

Currently, fuel cells that are being developed for portable applications, are categorized in two types: DMFC (Direct Methanol Fuel Cells) and μ-PEFC (Micro Polymer Electrolyte Fuel Cells) [4]. Both types follow the same principle. The fuel is supplied to the anode of the fuel cell and decomposed into protons, electrons and some by-products under influence of a catalyst. The protons travel through an electrolyte to the cathode. At the cathode, the protons and electrons combine with oxygen and generate water with the support of a catalyst. The electrolyte, typically a perfluorosulfonate polymer, has the function of passing the protons and stopping the electrons from going through to the cathode. Therefore this membrane is called Proton Exchange Membrane (PEM). Connecting the anode through a load with the cathode, it is possible for the electron to travel to the cathode and reform with the proton and oxygen to water. Doing so, electric power is extracted from the cell. The difference between DMFC and PEFC is the fuel that is used. For DMFC this is methanol, for PEFC hydrogen. The protons in a DMFC carried through the electrolyte by hopping on water molecules, form H_3O^+. Therefore it is necessary to have water on the anode side. Because the structure of these molecules is almost the same as methanol, methanol tends to be dragged as well as water. Another system to carry methanol from anode to cathode is diffusion. This movement is called crossover which causes loss of fuel and decrease of electrical potential. The PEFC has no crossover problem so it generally generates higher power than DMFC. The crossover of DMFC can be reduced by using diluted methanol with water. At present 10wt% (weight

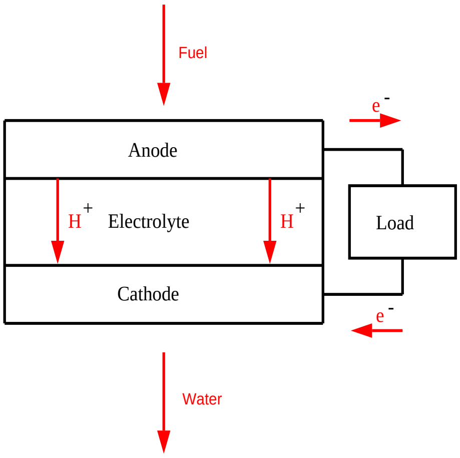

Fig. 1. Scheme of a fuel cell

percentage) of methanol is the maximum for DMFC fuel to generate electricity effectively.

B. Thermoelectric

The thermoelectric effects can be used for the direct conversion of thermal into electrical energy. They are applied for small scale alternative energy generation, preferably as a component in complex systems which contain an internal heat flow crossing a large temperature difference. A thermoelectric generator consists of a p-type and a n-type bar which are exposed to a temperature difference. The p-type and n-type bars are connected in series while for temperature they are connected in parallel (see figure 2). Because of the Seebeck effect a voltage will appear across the bars, opposite in sign because of the p- en n-type material. If a load is connected in series with this system, electrical power can be extracted. Although energy conversion efficiencies are low (in the range of 2-10%), it can be used as an energy source if it is combined with a fuel combustor since the energy density of this fuel is very high [5][6][7]. The total energy density of the system can in that case be higher than that of a battery. Stordeur and Stark have developed a thermoelectric generator targeted specifically at microsystems. The device combines 2.250 thermocouples in an area of $67\ mm^2$ and produces $20\ \mu W$ at a temperature difference of $20\ K$. The device offers relatively high output voltages of $100\ mVK^{-1}$ [8].

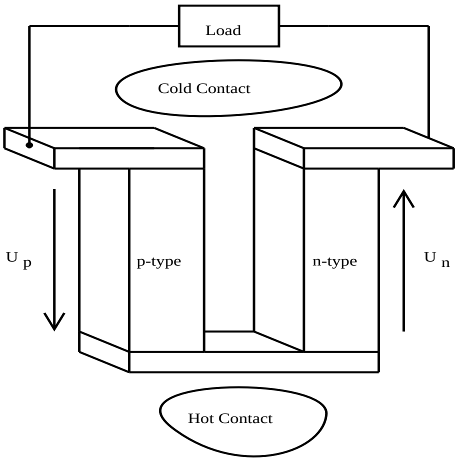

Fig. 2. Scheme of a thermoelectric cell

C. Piezoelectric

The piezoelectric effects can be used for the direct conversion of mechanical into electrical energy. There are few reported studies on the possibility of piezoelectric materials for power generation but the national university of Singapore has performed an analysis of a thick-film piezoelectric material placed on both sides of a cantilever beam along with a seismic mass [9]. The conclusion of this analysis was that the higher the frequency the higher the output power was but the less the efficiency. Another example that has been reported, consists of a steel ball that strikes a piezoelectric membrane. This device produces enough energy to power a digital watch by shaking up and down your hand or a door alarm by vibrations caused by the burglar [10].

D. Electromagnetic

Most of the electromagnetic power MEMS are based on a magnet mounted on a spring. The magnet follows a path through a coil when excited by ambient vibration. This movement will induce a voltage over the coil and when a load is connected, electric power can be extracted. A schematic overview, represented in theory by a mass-spring-damper-system, is shown in figure 3. Some examples of devices that are fabricated are a microphone or a device that works by a human walking motion [11] [12]. The first one can generate up to $20\ \mu W$, the latter $400\ \mu W$. The last one has a sophisticated low-power signal-processing system connected to the generator. It can perform 11.000 cycles of operation from one excitation. Another system that uses the human walk for power generation is that of the Yamaguchi University [13]. The system is tuned to the frequency of the human walking motion. The average generated power was $18,7\ mW$. Other examples are the AGS (automatic power-generator) for wristwatches and the micro power generator of the university of Hong Kong. The watch converts mechanical movements (changes in postures) via electromagnetism into electric power, the micro power generator is a resonator packaged in an AA-battery. A $100\ k\Omega$ resistor was attached to the capacitor of the power management circuit and the potential difference across the resistor was measured. The transducer produced a voltage output of $1{,}34\ Vpp$ at $85\ Hz$ (first mode) and $1{,}44\ Vpp$ at $111\ Hz$ (third mode). This corresponds to $\sim 24\mu W$ and $\sim 27\mu W$. This experiment was made with only one transducer. The packaging can contain two transducers [14].

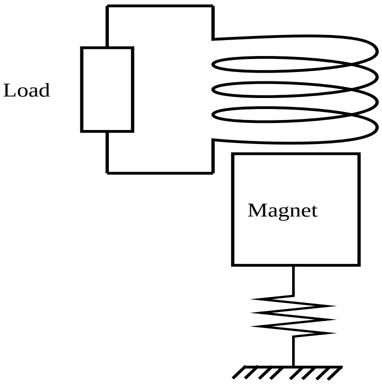

Fig. 3. Scheme of a electromagnetic system

E. Electrostatic

Systems that relay on electrostatic power generation, consist of variable capacitors. Mostly they use inertial forces to do work against the electric field of the capacitor. Doing so, they convert mechanical energy into electrical energy. Some examples of electrostatic power generators are the ones of Imperial College (London) and the one that is currently being developed at the Katholieke Universiteit van Leuven (Belgium) [15][16]. The first uses a capacitor that first needs to be charged by an external voltage source of 26 V. This device is capable of producing 24 μW at 10 Hz. The latter uses an electret to polarize the two capacitors. Using a electret eliminates the need of a battery to charge the capacitors. Then by varying one capacitor, charges are transported through the load. This device should deliver 100 μW of electrical power at 1200 Hz with a displacement of 20 μm.

F. Photovoltaic

These devices, powered by light, are well established. Self supported systems, such as calculators and watches, are available on the market. Lee et al. developed a thin film solar cell to produce the open circuit voltage (1,8 $\sim$ 2,3 V) and short circuit current density (2,8 mA/cm^2) required to supply MEMS electrostatic actuators. They connected 100 single solar cells in series, occupying a total of 1 cm^2. To prove the usefulness, they packaged it with a movable micromachined silicon mirror. By controlling the incident light intensity, the deflection of the Si mirror was controlled [17]. Ross fabricated a system were optical power ($GaAlAs$-laser with wavelength of 800 nm) is brought to the remote system. The light is than converted to electrical power by a photovoltaic cell and voltage converters are than used to produce an useful voltage. Injecting 4 mW of light, $0,5$ mW of electrical power was available for sensing [18]. The piezoelectric material PLZT(3/52/48) (correct formula is $Pb_{1-x}La_x(Zr_yTi_z)_{1-x/4}$ with shortened notation PLZT(100.x/100.y/100.z) has in bulk condition an output voltage that is over a kV/cm [19]. The current on the other hand is very small (nA). If the PLZT material is in a thin film structure (thickness 4 μm) it produces a voltage in the order of one but the current is higher (μA) both with 150 mW/cm^2 of incident light energy.

G. Thermophotovoltaic

Thermophotovoltaic systems (TPV) consists of four elements: the heat source, a micro flame tube combustor (emitter), the filter and the low band-gap photovoltaic array [20]. A fuel is combusted in a micro combustor. When the emitter is heated to a sufficiently high temperature, it emits photons. When the photons with greater energy than the band-gap of the PV cells, impinge, they evoke free electrons and produce electrical power output. Possible heat sources for the system include concentrated solar energy, the combustion of various fuels, and nuclear decay. The emittor can be made from broadband materials such as SiC, or selective emitting materials such as $Er_3Al_5O_{12}$, $Co-$ doped MgO, Yb_2O_3 or surface microstructures by means of micromachining [21]. A broadband emitter passes also photons with energies not sufficient enough to generate charge carriers in the PV cells. If these photons aren't stopped, they will be absorbed by the PV cells and result in destructive heat load on the generator components, which lower the conversion efficiency of the system. To improve the system, these photons should be send back to the emitter. For this a filter is used that reflects all photons with too low energy and transmits all convertible to the PV system. The advantage of TPV is the lack of moving parts. The university of Singapore has constructed a TPV system that consists of a SiC emitter, a 9 layer dielectric filter and a $GaSb$ PV cell array. They are capable of producing 0,92 W of electrical power with open-circuit voltage 2,32 V and short-circuit current 0,52 A. The combustor has a volume of 0,113 cm^3 and uses hydrogen at a rate of 4,2 g/hr with $H_2/air\ ratio$ equal to 0,9.

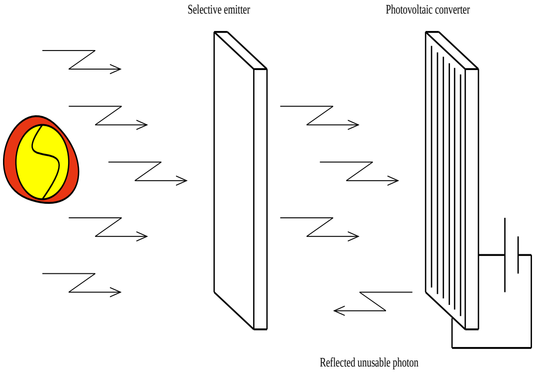

Fig. 4. Scheme of a thermophotovoltaic system

H. Turbine-generator couple

The concept of a turbine-generator couple is totally different from the previous ones. The previous conversion processes use external energy sources, e.g. sun, vibration and heat. The turbine can be driven with pressurized gas that is available or with combustion of fuel. The first method of power generation belongs to the external energy sources but the second one needs an internal energy source. A Realization of the first one is done by Imperial College in London. They use an axial flow turbine for low pressure ratios (1,05) at 30.000 rpm. Inserted in the rotor there are permanent magnets (NdBFe) which provide the flux through the planar coils on the stator. A power of 1 mW can be produced (serious losses in the generator) [22]. An example of the second method is the turbine-generator couple of MIT (Massachusetts Institute of Technology). The combustion chamber of only 191 mm^3 can produce 1100 MW/m^3 when using premixed hydrogen-air and exit temperatures greater than 1600 K, efficiencies over 90 %. For hydrocarbon fuels, efficiencies of 60 % and power densities of 500 MW/m^3 were achieved [23]. For motor and generator, they used an electrostatic induction machine [24]. The output power should be around 10 W with a 4 mm diameter and 3 μm air gap. The Katholieke Universiteit van Leuven (K.U.Leuven) is currently developing a micro turbine-generator couple.

III. SCALE ANALYSIS

In the following section, the scaling laws for electrostatic, electromagnetic and thermoelectric power generators are derived. Since these devices are reciprocal concepts, the scaling laws are also applicable to actuators. To derive the scaling laws, the Buckingham π theorem is used. It is stated as follows: If an equation involving k variables is dimensionally homogeneous, it can be reduced to a relationship among k - r independent dimensionless products, where r is the minimum number of reference dimensions required to describe the variables. For the following generators this theorem tells to take 5 independent parameters to form the five independent dimensions, being kg, m, s, A and K. With these five independent parameters all the other (dependent) parameters can be formed if dealing with homogeneous equation. The parameters that are used in this article are depicted in Table I.

A. Electrostatic generators

Starting from the Buckingham π theorem, the five independent variables which quantify the electrostatic forces between two parallel plates are chosen to be E, d, ϵ, f and T. These are the electric field between the plates of the generator (capacitor), a characteristic length, the permittivity of the medium between the plates, the frequency and the temperature. Using the Buckingham π theorem, the force coefficient C_F can be written as:

$$C_F = \frac{F}{\epsilon E^2 d^2} \tag{1}$$

Further on in the paper, this coefficient will be replaced by a proportion sign. Equation (1) shows that the force scales with $length^2$ if the electric field is assumed to be constant. However for small scales ($d < 10\ \mu m$), there is an increase possible in the electric field strength according to Paschen's law and so compensating the decrease of the distance. This advantage does not last, recent studies showed that after ($d < 4\ \mu m$) Paschen's law isn't applicable anymore and the electric field decreases dramatically [25]. The Buckingham π theorem is vague about the real dimensions combined in the characteristic parameter d. To retrieve the origin of d, the electrostatic generator can be written as a capacitor. The capacitance, by using the π theorem, is written as follows:

$$C \sim \epsilon d \tag{2}$$

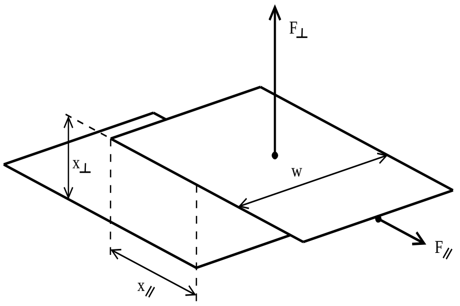

Fig. 5. An electrostatic system

d consists of $\frac{wx_{//}}{x_\perp}$ using the theory of parallel plates for capacitors, see figure 5. The next quantity that is needed, is the voltage V. With the help of the π theorem:

$$U \sim Ed \tag{3}$$

herein d equals $x_\perp$. From this point on, every quantity can be derived and every d can be specified. Doing so, the total energy is found as:

$$W \sim QU \tag{4}$$

with $Q \sim UC$ and thus $Q \sim \epsilon E w x_{//}$. Now that the energy is known, there are two different ways to produce force on these plates, with perpendicular or parallel motion. Beginning with the perpendicular motion, the theorem of virtual work is used to derive $x_\perp$. The force acting perpendicular to the plate is calculated as follows:

$$\begin{aligned} F_\perp &= \frac{dW}{dx_\perp} \sim \epsilon E^2 d^2 && (5) \\ &\sim \epsilon E^2 w x_{//} && (6) \end{aligned}$$

This force is used to calculate the power that can be extracted:

$$P_\perp = F_\perp v_\perp \sim \epsilon E^2 d^3 f \tag{7}$$

or

$$P_\perp \sim \epsilon E^2 w x_{//} v_\perp \tag{8}$$

For the parallel movement the same derivation is valid :

$$\begin{aligned} F_{//} &= \frac{dW}{dx_{//}} \sim \epsilon E^2 w x_\perp && (9) \\ P_{//} &= F_{//} v_{//} && (10) \\ &\sim \epsilon E^2 d^3 f && (11) \end{aligned}$$

or

$$P_{//} \sim \epsilon E^2 w x_\perp v_{//} \tag{12}$$

If the charge is the characterizing parameter, than E in the equations above must be replaced by $\frac{Q}{\epsilon d^2}$ or $\frac{Q}{\epsilon w x_{//}}$. This gives for the force and power the following equations:

$$\begin{aligned} F_\perp &\sim \frac{Q^2}{\epsilon d^2} \sim \frac{Q^2}{\epsilon w x_{//}} && (13) \\ P_\perp &\sim \frac{Q^2}{\epsilon d f} \sim \frac{Q^2 v_\perp}{\epsilon w x_{//}} && (14) \\ F_{//} &\sim \frac{Q^2}{\epsilon d^2} \sim \frac{Q^2 x_\perp}{\epsilon w x_{//}^2} && (15) \\ P_{//} &\sim \frac{Q^2}{\epsilon d f} \sim \frac{Q^2 x_\perp v_{//}}{\epsilon w x_{//}^2} && (16) \end{aligned}$$

In the same way, the equations can be derived for U as a characterizing parameter, just replace E by $\frac{U}{d}$ or $\frac{U}{x_\perp}$.

B. Electromagnetic generators

The parameters that are chosen, are J, d, μ, f and K. These are respectively the current density, the characterizing distance, the magnetic permeability, the frequency and the temperature. To derive the scaling laws for electromagnetism, consider two parallel wires with length l, positioned at a distance w of each other and diameters r_1 and r_2. The field intensity H (created

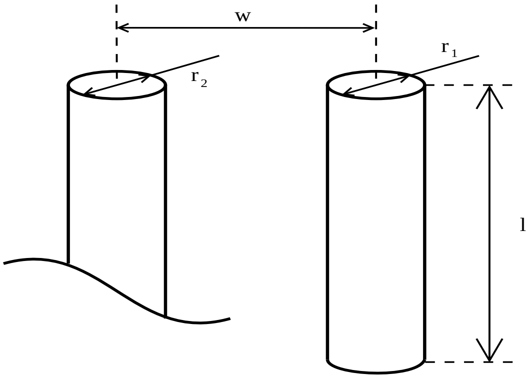

Fig. 6. An electromagnetic system

by wire 1) can be written as (using the π-theorem):

$$H \sim Jd \quad (17)$$

herein d consists of $\frac{r_1^2}{w}$, this follows from Ampère's law. The next step is to calculate B_1 with the help of μ:

$$B \sim \mu J d \quad (18)$$
$$B_1 \sim \frac{\mu J_1 r_1^2}{w} \quad (19)$$

The force can now be calculated using the π-theorem, which corresponds to the Bli-rule:

$$F \sim \mu J^2 d^4 \quad (20)$$
$$\sim \frac{\mu J_1 J_2 r_1^2 r_2^2 l}{w} \quad (21)$$

The power that can be generated by a device than follows the following law:

$$P \sim \mu J^2 d^5 f \quad (22)$$
$$\sim \mu J^2 d^5 \omega \quad (23)$$
$$\sim \frac{\mu J_1 J_2 r_1^2 r_2^2 l v}{w} \quad (24)$$

If the system is scaled down, the power scales with d^5 thus if the media and the current density are kept constant, than the number of revolutions has to increase dramatically if the power is kept constant.

For generators that use permanent magnets (PM), the formulas can be rewritten. The characteristic parameters are B, J, d, f (or ω for circumferential movements) and T. The force acting on the wire or on the PM is written as:

$$F \sim BJd^3 \quad (25)$$

The force scales with the third power of the characterizing length, instead of the fourth power as in equation (20). The power that can be generated with a PM generator scales with the following law:

$$P \sim BJd^4\omega \quad (26)$$

So with PM power scales with the fourth power of the characteristic length, instead of the fifth. To determine the heat losses, the characterizing parameters ρ_e, J, d, f and K are chosen, where ρ_e is the specific resistivity. Applying the Buckingham π theorem:

$$P_{heat} \sim \rho_e J^2 d^3 \quad (27)$$

From the point of view of heat dissipation, electromagnetic systems are not so favorable because of the J^2 term and the third power of the distance, with and without PM. The only difference between with or without PM is that the wiring in PM generators is half of that without.

C. Thermoelectric generators

For thermoelectric generator, the characteristic parameters are chosen to be ρ_e, d, T and S. These are respectively the specific electric resistivity, a characteristic distance, the temperature and the Seebeck-constant. This gives for the current density:

$$J \sim \frac{TS}{\rho_e d} \quad (28)$$

For the voltage this gives:

$$U \sim TS \quad (29)$$

The power that can be extracted out of the system is:

$$P \sim \frac{T^2 d S^2}{\rho_e} \quad (30)$$

In the exact theory Z is the figure of merit, consisting of material parameters and written as $Z \sim \frac{S^2 d}{\rho_e K}$, with K the total thermal conductivity. So filling in this result in equation (30) gives $P \sim ZKT^2$. In this formula it is clear that the bigger the temperature difference (here represented as T), the more power can be extracted, the same goes for the figure of merit.

D. Electrostatic versus electromagnetic

Which one is the most promising with regard to power generation on micro scale? To give an idea, it is appropriate to compare the energy densities of two conversion methods. For electrostatic devices the maximum energy between the plates is $w_{stat} \sim \epsilon E_{max}^2$ with E_{max} the breakdown field. The electromagnetic energy density between the poles is $w_{magn} \sim \frac{B_{max}^2}{\mu}$ with B_{max} the magnetic field density when the material is saturated. With ϵ the permittivity of air, E_{max} in the order of $10^6\ V/m$, μ the permeability of air and B_{max} in the order of $1\ T$. With these values the energy densities are $w_{stat} \sim 10\ J/m^3$ and $w_{magn} \sim 10^6\ J/m^3$. So the energy density of a electromagnetic system is 10^5 more than for an electrostatic system. But for very small distances in an electrostatic system, there is an increase in the field, and the energy densities between electrostatic and electromagnetic become comparable but since the distance is very small (submicron scale) it is not favorable for moving parts.

IV. CONCLUSION

One could summarize the above analysis as follows: Electrostatic power generation scales with the third power of distance where as electromagnetic power generation scales with the fourth as a result if the system is scaled down, electrostatic power generation scales more favorable than electromagnetic power generation. Electromagnetic power generation has the side effect of heat losses because of the current. These heat losses scale with the power two of the current density and with the power three of the distance. This means that, when scaling down, the heat losses gain relatively with respect to the power generation. On the other hand, electromagnetism has the highest power density, in the order of 10^5 higher than electrostatic.

TABLE I

DIMENSION TABLE

	kg	m	s	A	K
Mechanic					
d		$+1$			
$f\ or\ \omega$			-1		
V		$+1$	-1		
Electric					
I				$+1$	
J		-2		$+1$	
U	$+1$	$+2$	-3	-1	
Q			$+1$	$+1$	
ρ_e	$+1$	$+3$	-3	-2	
ϕ	$+1$	$+2$	-2	-1	
B	$+1$		-2	-1	
H		-1		$+1$	
μ	$+1$	$+1$	-2	-2	
E	$+1$	$+1$	-3	-1	
ϵ	-1	-3	$+4$	$+2$	
C	-1	-2	$+3$	$+2$	
Thermal					
T					$+1$
K	$+1$	$+2$	-3		-1
S	$+1$	$+2$	-3	-1	-1
Z					-1
General					
F	$+1$	$+1$	-2		
T	$+1$	$+2$	-2		
A	$+1$	$+2$	-2		
P	$+1$	$+2$	-3		

REFERENCES

[1] J. Okazaki, Y. Osaki, H. Hosaka, K. Sasaki, H. Yamakawa, and K. Itao, "Dynamic analysis and impedance control of automatic power generators using mechanical vibration," *PowerMEMS 2002, International Workshop*, November 2002.

[2] J. Rabaey, M. Ammer, D. Patel, and S. Roundy, "Picoradio supports ad hoc ultra-low power wireless networking," *Computer Magazine*, July 2000.

[3] D. D. Wentzloff, B. Calhoun, R. Min, A. Wang, N. Ickes, and A. Chandrakasan, "Design consideration for next generation wireless power-aware microsensor nodes," *Proc. 17th Int. Conf. on VLSI Design*, 2004.

[4] E. Sakaue, "Small fuel cell systems for mobile information tools," *PowerMEMS 2003, International Workshop*, pp. 7–10, December 2003.

[5] J. Li, A. Moriya, S. Sugimoto, S. Tanaka, M. Esashi, H. Okamura, and R. Watanabe, "Development of thermoelectric micro-modules by silicon molding process," *PowerMEMS 2002, International Workshop*, November 2002.

[6] K. Yoshida, K. Kobayashi, T. Nakajima, D. Satoh, S. Tanaka, and M. Esashi, "Micro-thermoelectric generator using catalytic combustor," *PowerMEMS 2002, International Workshop*, November 2002.

[7] S. Sugiyama and T. Toriyama, "Surfacemicromachined polysilicon-metal thermopile for power generation," *PowerMEMS 2002, International Workshop*, November 2002.

[8] M. Stordeur and L. Stark, "Low power thermoelectric generator - self-sufficient energy supply for micro systems," 16^{th}*International Conference on Thermoelectrics*, pp. 575–577, 1997.

[9] F. Lu, H. Lee, and S. Lim, "Modeling and analysis of micro piezoelectric power generators for micro-electromechanical systems application," *Smart Materials and Structures*, pp. 57–63, November 2003.

[10] M. Umeda, K. Nakamura, and S. Ueha, "Energy storage characteristics of a piezo-generator using impact induced vibration," *Japanese Journal of Applied Physics*, vol. 36, pp. 3146–3151, 1997.

[11] C. Shearwood and R. Yates, "Development of a resonant electromagnetic micro-generator," *Electronic Letters*, vol. 33, no. 22, pp. 1883–1884, 1997.

[12] R. Amirtharajah and A. Chandrakasan, "Self-powered signal processing using vibration-based power generation," *IEEE Journal of Solid-State Circuits*, vol. 33, pp. 687–695, May 1998.

[13] K. Nakano, T. Saito, A. Nakayama, and T. Kurose, "A portable generator using vibration due to human walking," *PowerMEMS 2002, International Workshop*, November 2002.

[14] J. Lee, S. Yuen, M. Luk, G. Chan, K. Lei, W. Li, P. Leong, and Y. Yam, "Vibration-to-electrical power conversion using high-aspect-ratio mems resonators," *PowerMEMS 2003, International Workshop*, pp. 81–85, December 2003.

[15] P. Miao, A. Holmes, E. Yeatman, and T. Green, "Micro-machined variable capacitors for power generation." Modular Hybrid Artefacts With Adaptive Functionality: Oresteia, 2002.

[16] T. Sterken, K. Baert, B. Puers, and S.Borghs, "Power extraction from ambient vibration," *SeSens*, 2002.

[17] J. Lee, Z. Chen, M. Allen, and R. Arya, "A miniaturized high-voltage solar cell array as an electrostatic mems power supply," *Journal of Microelectromechanical Systems*, vol. 4, pp. 102–108, September 1995.

[18] J. Ross, "Optical power for sensor interfaces," *Measurement Science and Technology*, vol. 3, pp. 651–655, 1992.

[19] M. Ichiki, Y. Morikawa, K. Nonaka, and R. Maeda, "Photovoltaic effect of piezoelectrics and its application," *PowerMEMS 2003, International Workshop*, pp. 167–169, December 2003.

[20] W. Yang, S. Chou, C. Shu, H. Xue, Z. Li, and S. Lim, "A prototype microthermophotovoltaic system," *PowerMEMS 2003, International Workshop*, pp. 94–97, December 2003.

[21] H. Sai, Y. Kanamori, and H. Yugami, "Selective emitters for thermophotovoltaic generation by means of metallic surface microstructures," *PowerMEMS 2003, International Workshop*, pp. 118–121, December 2003.

[22] A. Holmes, G. Hong, K. Pullen, and K. Buffard, "Axial-flow microturbine with electromagnetic generator: Design, cfd simulation and prototype demonstration," *MEMS 2004, Technical Digest*, pp. 568–571, January 2004.

[23] C. Spadaccini, A. Mehra, J. Lee, X. Zhang, S. Lukachko, and I. Waitz, "High power density siliconq combustion systems for micro gas turbine engines," *ASME Journal of Engineering for Gas Turbine and Power*, pp. 709–719, July 2003.

[24] A. H. Epstein, S. A. Jacobson, J. Protz, and L. Frechette, "Shirtbutton-sized gas turbines: The engineering challenges of micro high speed rotating machinery," *Proc. of 8th Int. Symp. on Transport Phenomena and Dynamics of Rotating Machinery*, January 2000.

[25] J.-M. Torres and R. Dhariwal, "Electric field breakdown at micrometre separations in air and nitrogen at atmospheric pressure," *IEE Proceedings of Science and Measurement Technology*, vol. 147, pp. 261–265, September 2000.

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