# Analysis of Micromachined PZT Membranes for MEMS Power

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## ABSTRACT

The performance of a piezoelectric generator in terms of the quality factor Q, the electromechanical coupling coefficient $k^2$, and the efficiency were examined. The effect of design parameters such as membrane size, piezoelectric thickness, silicon thickness, and top electrode area are explored. The results show that both $k^2$ and Q are sensitive to PZT thickness and electrode size.

***Keywords***: pzt membrane, mems power, electromechanical coupling coefficient, quality factor, efficiency.

## 1 INTRODUCTION

The need for miniaturized power sources for MEMS and microelectronics devices is widely recognized. Micro-scale concepts to generate electrical power include devices which use the stored energy in fuels to those which harvest energy from the environment. Piezoelectric materials are increasingly employed in both types of devices to convert mechanical to electrical energy [1–5]. The use of piezoelectric materials yields significant advantages for micro power systems. Since piezoelectric materials convert mechanical energy into electrical energy via strain in the piezoelectric material, they lend themselves to devices that operate by bending or flexing which brings significant design advantages.

Recent work by our team at Washington State University has been directed at the design of a micro heat engine in which thermal power is converted to mechanical power through the use of a novel thermodynamic cycle. Mechanical power is then converted into electrical power through the use of a thin-film piezoelectric membrane generator [1].

In this paper we examine the performance of the piezoelectric generator in terms of the quality factor Q, the electromechanical coupling coefficient $k^2$, and the efficiency. The effect of design parameters such as membrane size, piezoelectric thickness, and silicon thickness are explored.

## 2 DEVICE FABRICATION

The structure of the thin-film piezoelectric membrane generator is a two-dimensional sandwich structure similar to that used for ultrasonic transducers [6]. Figure 1 shows a cross section of the membrane generator, which consists of a silicon membrane, a bottom platinum electrode, a thin-film of the piezoelectric ceramic PZT (Lead Zirconate Titanate) and a top gold electrode.

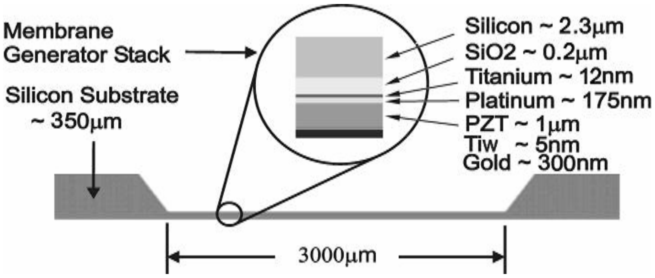

Figure 1: The structure of the PZT membrane generator.

The substrate for the PZT membrane generator is a (100) silicon wafer. Boron is doped into the one side of the silicon for an etch stop, and then an oxide layer is grown and patterned to provide a mask for anisotropic etching in ethylene diamine pyrochatechol (EDP). A 12nm layer of titanium and a 175nm thick layer of platinum are sputtered using DC magnetron sputtering. PZT is spun onto the platinum films in a sol-gel process [7]. A top electrode consisting of a 5nm TiW adhesion layer of gold and 300nm of gold is deposited by DC magnetron sputtering. Photolithography is then used to etch the top electrode and PZT around the top electrode. A completed membrane generator is shown in Fig. 2.

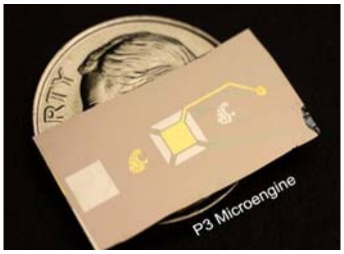

Figure 2: Piezoelectric membrane generator.

## 3 PIEZOELECTRIC MEMBRANE CHARACTERISTICS

A piezoelectric membrane generator produces power when it is strained in response to an applied pressure. In the micro heat engine that pressure is supplied by the periodic expansion and compression of a two-phase working fluid. The pressure pulse applied by the two-phase working fluid causes the piezoelectric membrane to flex out, straining the piezoelectric ceramic. This straining of the piezoelectric material causes the film to become thinner, due to Poisson's effect, and results in an electric potential across the electrodes. Since the pressure pulse is periodic, the membrane oscillates and produces an alternating current.

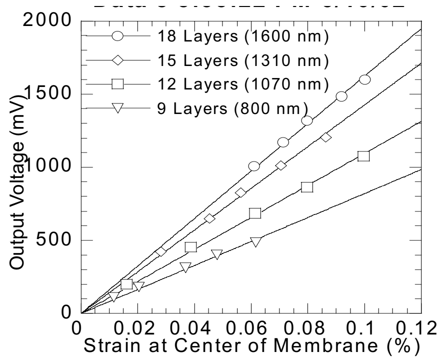

Figure 3: PZT output voltage vs. strain.

Important parameters to the output voltage produced by a piezoelectric membrane are the thickness of the PZT layer and the strain generated in the PZT layer during maximum membrane deflection. Fig. 3 illustrates these dependencies. In the figure, peak-to-peak open-circuit voltages are plotted against the tensile strain experienced by the PZT layer during maximum piezoelectric membrane deflection. Piezoelectric membrane output voltage increases linearly both with PZT layer thickness and with PZT maximum strain.

The chemistry of the PZT, specifically the ratio of Zr to Ti, can have a substantial impact on the specific output (V/%εμm PZT). A higher specific voltage translates to a higher voltage output from a membrane at a given strain.

The effects of PZT thickness and chemistry on power output from a 3mm membrane are shown in Fig. 4. All three piezoelectric membranes were driven with the same pressure and frequency. Power is greatest from the 30 layer, 40:60 PZT membrane at a load resistance of 15 kΩ.

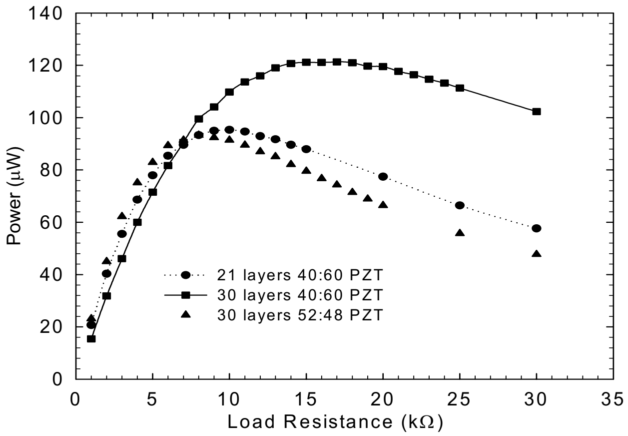

Figure 4: PZT output power vs. load resistance.

## 3.1 Mechanical behavior

The mechanical resonance frequency of the membrane generator is very important for power generation and efficiency. The frequency response of an electrically excited piezoelectric membrane generator is shown in Fig. 5. Deflection measurements are acquired using an optical lever consisting of a laser beam and detector. The detector voltage is directly proportional to the generator deflection in both time and space. These measurements are acquired in air with the membrane suspended in a clamping jig.

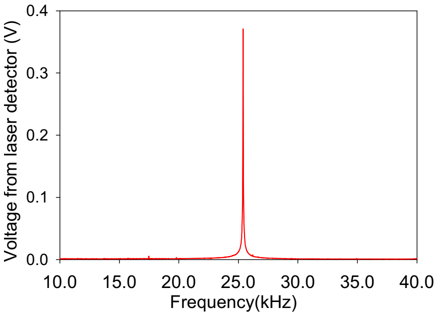

Figure 5: Membrane generator's frequency response.

The resonance frequency of membrane is function of membrane size, stiffness and mass [8]. Table 1 shows the variation of resonance frequency with changes in membrane size, piezoelectric thickness and silicon thickness. As membrane size is increased from 3 to 6 mm, the resonance frequency decreases from 28.4 kHz to 14.8 kHz.

## 3.2 Electrical behavior

The PZT oscillator can be modeled with an equivalent circuit as shown in Fig. 6. It consists of the resistances of top and bottom electrode, shunt capacitance $C_o$, and mechanical components, $C_m$, $R_m$ and $L_m$. The shunt capacitance $C_o$ is a function of the electrode size and separation, $C_m$ is inversely proportional to the stiffness of the membrane, $L_m$ is proportional to the effective mass, and

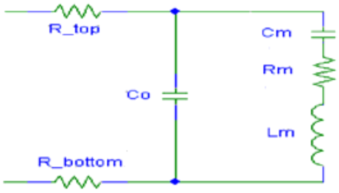

Figure 6: Equivalent electrical circuit of generator.

$R_m$ is dependent upon the damping characteristics of the structure.

Impedance and phase data were acquired for each of the membranes using an impedance analyzer. The PZT membranes were poled by applying 120 kV/cm parallel to the direction of measurement for 10 minutes. The membranes were not tested until a minimum of 24 hours had elapsed after poling. With the impedance data, the equivalent circuit of each membrane was found by impedance data matching as shown in Fig 7.

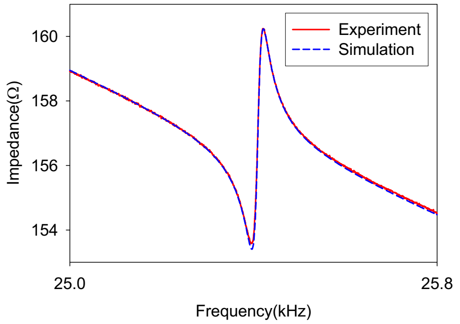

Figure 7: The impedance curves of experiment and simulation of membrane generator.

## 4 EXPRESSION FOR THE GENERATOR EFFICIENCY WITH K$^2$ AND Q

Although researchers conducting fundamental studies [9] have noted that high efficiency for piezoelectric conversion devices requires large quality and electromechanical coupling factors, they provide no discussion of the impact of Q and $k^2$ on efficiency η or guidelines for device development.

An exact expression for efficiency of a piezoelectric element may be derived from first principles [10]. The device is modeled as a rigid mass (m) coupled to a stationary surface through a spring (s), with a damper (b), and a piezoelectric element poled in the thickness direction. An applied force excites the system and energy is extracted by connecting an electric circuit to the electrodes on the piezoelectric element. Details of the derivation are provided in [10].

As shown in equation (1), the expression for the generator efficiency η depends only on the quality factor Q and the electromechanical coupling coefficient $k^2$. This relationship is shown graphically in Fig. 8.

$$\eta = \frac{\frac{1}{2}\frac{k^2}{1-k^2}}{\frac{1}{Q}+\frac{1}{2}\frac{k^2}{1-k^2}} \qquad (1)$$

This expression can be used to gain further insight into the design of micro power generators using piezoelectric oscillators. For example, if a device efficiency of 85% is desired there are several combinations of $k^2$ and Q that will work: 1) $k^2 = 0.01$ and Q = 1000, 2) $k^2 = 0.05$ and Q = 200, and 3) $k^2 = 0.1$ and Q = 100. This gives the designer some flexibility in choosing the piezoelectric material, configuration and structure for the device.

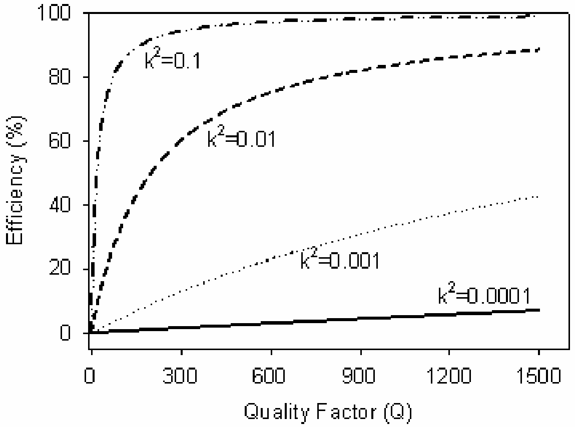

Figure 8: The relationship among η, Q and $k^2$.

The quality factor, $Q=(ms)^{1/2}/b$, depends on the effective mass, stiffness, and damping of the structure. In terms of the circuit analog $Q = 1/R_m(L_m/C_m)^{1/2}$. The electromechanically coupling coefficient, $k^2=C_m/(C_o+C_m)$, is a function of the material properties and electrode configuration through $C_o$. The parameter $C_m$ is inversely

| | PZT thickness (μm) | Membrane size (mm$^2$) | Si thickness (μm) | Top electro size (mm$^2$) | %change in $C_o$ | %change in $C_m$ | %change in $L_m$ | %change in $R_m$ | Resonance frequency [kHz] |
|---|---|---|---|---|---|---|---|---|---|
| Ref. | 1 | 3x3 | 2 | 2x2 | - | - | - | - | 25.4 |
| Case 1 | 2 | 3x3 | 1 | 2x2 | - 50 | - 44 | 47 | 214 | 28.4 |
| Case 2 | 1 | 3x3 | 1 | 2x2 | 0 | - 33 | 39 | - 66 | 26.3 |
| Case 3 | 1.8 | 3x3 | 2 | 2x2 | - 45 | - 8 | - 8 | - 69 | 27.7 |
| Case 4 | 3 | 3x3 | 2 | 1.6x1.6 | - 79 | - 7 | 103 | 35 | 18.5 |
| Case 5 | 1 | 6x6 | 2 | 2x2 | 0 | - 69 | 826 | 100 | 14.8 |

Table 1: Membrane generator property according to design parameters.

proportional to the structural stiffness of the device. Thus the equivalent circuit model may be used to explore the effect of mechanical design changes to the electromechanical performance of the piezoelectric generator.

## 5 EFFECT OF PARAMETER CHANGE ON Q AND $K^2$

The design parameters of six piezoelectric membranes are provided in Table 1. PZT thickness, Si thickness, membrane size, and top electrode area were varied. The effect of these changes on the circuit parameters, $C_o$, $C_m$, $L_m$, and $R_m$ are shown in the table. Fig. 9 shows the relative effect of these design changes on $k^2$ and Q. Decreasing the Si thickness while maintaining the PZT thickness results in the largest improvement in Q with a smaller decrease in $k^2$. Increasing the PZT thickness while maintaining the Si thickness resulted in increase in Q and $k^2$. Increasing the PZT thickness and decreasing the top electrode area resulted in an increase in Q and a remarkable increase in $k^2$. Increasing the PZT thickness and decreasing Si thickness resulted in a decrease in Q and a slight increase in $k^2$, and high resonance frequency because of high residual stress from the thin Si layer. Increasing the membrane size leads to a substantial increase in Q with a correspondingly substantial decrease in $k^2$.

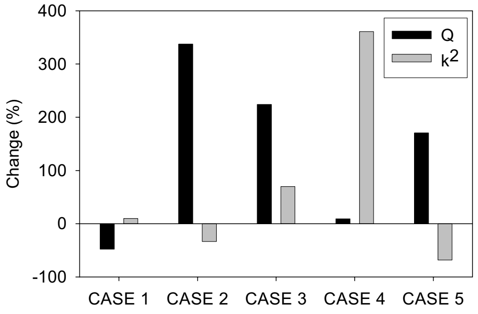

Figure 9: The effect of parameter change on Q and $k^2$.

## 6 SUMMARY

The effect of design parameters such as membrane size, piezoelectric thickness, silicon thickness, and top electrode area of a piezoelectric membrane generator were explored. The efficiency of a piezoelectric generator may be expressed in terms of the coupling coefficient, $k^2$ and the quality factor, Q. Thus the effect of design parameters on the electromechanical coupling coefficient and quality factor were evaluated. The results show that both $k^2$ and Q are sensitive to PZT thickness and electrode size.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] S. Whalen, M. Thompson, D. Bahr, C. Richards and R. Richards, "Design, fabrication and testing of the $P^3$ micro heat engine, Sensors and Actuators, A: Physical, Vol. 104, No. 3, pp. 290-298, 2003.

[2] N.M. White, P.Glynne-Jones, and S.P. Beeby, "A novel thick-film piezoelectric micro-generator," Smart Materials and Structures, Vol 10, No. 4, pp 850-852, 2001.

[3] R. Sharaf, W. Badawy, W. Mausa, "Piezoelectrically m-generator for implantable bio-devices," Photonics West MEMS/MOEMS Conference, Proceedings of SPIE Vol. 5344, January 2004, San Jose, CA.

[4] H. Li, A. Lal, J. Blanchard, D. Henderson, "Self-reciprocating radioisotope-powered cantilever," Journal of Applied Physics, Vol. 92, No. 2, pp. 1122–1127, 2002.

[5] N.W. Hagood, et al. "Micro-hydraulic transducer technology for actuation and power generation", Proceedings of SPIE - The International Society for Optical Engineering, Vol. 3985, pp. 680-688, 2000.

[6] J.Baborowski, N. Ledermann, P. Muralt, "Piezoelectric Micromachined Ultrasonic Transducers based on PZT Films, in Materials," Research Society Symposium Proceedings, Nano- and Microelectromechanical Systems (NEMS and MEMS) and Molecular Machines eds. D. A. LaVan, A. A. Ayon, T. E. Buchheit, M. J. Madou, 741 J12.4.1-6, 2003.

[7] L.M.R. Eakins, B.W.Olson, C.D. Richards, R.F.Richards and D.F. Bahr, "Influence of structure and chemistry on piezoelectric properties of lead zirconate titanate in a microelectromechanical system power generation application," JMR, Vol.18, pp. 2079-2086, 2003

[8] Richard Haberman, "Applied partial differential equations," Prentice Hall, 4th, pp. 142-147, 2004

[9] M. Umeda, K. Nakamura, S. Ueha., "Analysis of the transformation of mechanical impact energy to electric energy using piezoelectric vibrator," Japanese Journal of Applied Physics, Part 1: Regular Paper & Short Notes & Review Papers, Vol. 35, No. 5B, pp. 3267-3273, 1996.

[10] C. D. Richards, M. J. Anderson, D. F. Bahr, and R.F. Richards, "Efficiency of Energy Conversion for Devices containing a Piezoelectric Component," submitted to J. Micromechanics and Microengineering.