

ULTRASONIC MICROHEATERS USING PIEZO-CERAMICS FOR CAUTERIZATION AND OTHER APPLICATIONS

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ABSTRACT

This paper presents the use of piezoelectric ultrasonic microheaters for cauterization of biological tissues for tumor ablation and hemostasis. Ultrasonic heaters using PZT-5A ceramic of 3.2 mm diameter and 191 μm thickness were used in the experiments. A finite element model was developed to predict the heat generated by these microheaters. The ultrasonic heaters attained maximum temperature and thermal efficiency at frequency corresponding to maximum conductance and maximum impedance respectively. The thermal efficiency at each resonance frequency (0.5-3 MHz) was proportional to effective coupling factor (0.25-0.5) at that mode. The thermal efficiency is 930°C/W for biological tissue. Stacked heaters provide about three times higher efficiency. Branding of porcine tissue using the proposed device is also discussed.

KEYWORDS

Ultrasonic heating, thermal elements, piezoelectric actuation, biological tissue

INTRODUCTION

Micro-heaters are ubiquitous in applications ranging from micro total analysis systems [1] to inertial sensing [2]. Resistive heating has long been taken for granted but frequently involves parasitic losses due to high currents. In recent years, there has been interest in using alternate materials (other than Au and poly-Si) in microheater fabrication such as TiN. In this paper, we discuss the feasibility of using lead zirconate titanate (PZT) for microheater applications.

Ultrasonic heating is a well known phenomenon at the macro scale, and has been used for applications such as cooking, welding, etc. [3-4]. Further, high intensity focused ultrasound has been used for treating cancer

(hyperthermia) and hemostasis [5-6].

Lead zirconate titanate (PZT) is a widely used material for generating ultrasonic waves. However, its application in MEMS has been mainly limited to its ability to convert electrical energy to mechanical energy and vice-versa. In this effort, we explore the possibility of circumventing the challenges posed by resistive heating by using ultrasonic micro-heaters. In particular, this paper explores ultrasonic heating by single-layer and stacked PZT microstructures, and evaluates temperature, efficiency, and electro-mechanical characteristics for these devices. The low thermal conductivity and high damping nature of biological tissue make ultrasonic heating attractive for medical applications (especially for cauterization of tissue for tumor ablation and hemostasis). These require a temperature of 60-100°C, that is well below the Curie temperature of PZT, $\approx 350^\circ\text{C}$ (Fig. 1) [7]. This technology is attractive for microsystems since bulk PZT is easily micromachined by a lithography-compatible ultrasonic technique as reported in [8].

The following sections present the analytical model for heat generation in PZT, fabrication, corresponding experimental characterization of PZT heaters and finally demonstrate the feasibility of proposed heaters for cauterization of biological tissues.

THEORY AND MODEL

The temperature of PZT tends to increase while converting the electrical energy to mechanical energy due to dielectric losses in PZT, and damping in both PZT and surrounding material. Off-resonance, the dielectric loss tends to be the major source of heat generation, while at resonance the damping tends to be the major contributor [9]. The high electrical impedance and low thermal conductivity of PZT (Table 1) reduce the losses due to parasitic resistance and conduction through connecting wires, thereby making this method highly power efficient. The product of density and specific heat capacity of PZT, which determines the thermal time constant, is almost same as other micro-heater materials (Table 1).

Table 1: Typical values for the properties of common material used as a microheater

Material	PZT-5A	Au	Si
Thermal conductivity, K (W/m.K)	1.1-1.5	315	150
Density, ρ (Kg/m ³)	7650	19300	2330
Specific heat capacity, c_p (J/Kg.K)	350	130	700
$\rho c_p \times 10^6$ (J/m ³ K)	2.67	2.5	1.6

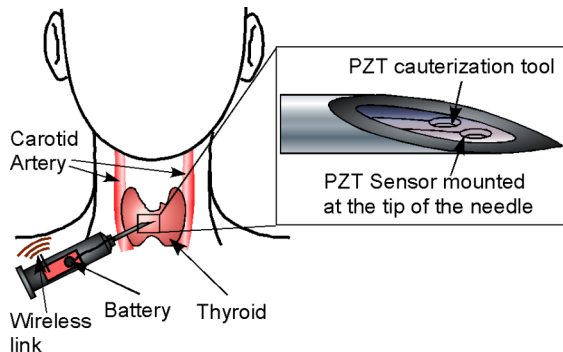


Fig.1: Concept diagram of portable ultrasonic cauterization device for tumor ablation and hemostasis.

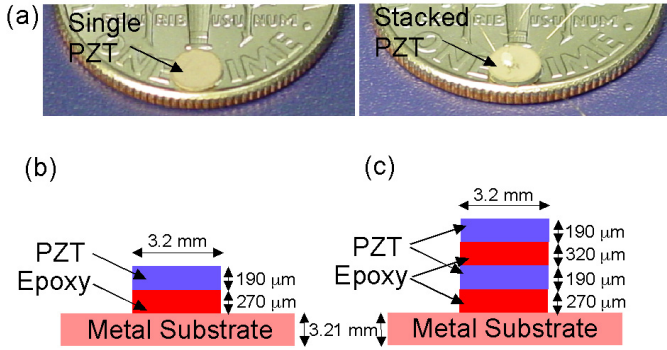


Fig 2: (a) Photograph of the single and stacked device used in the experiments. Schematic of the (b) non-stacked PZT structure and (c) stacked PZT structure.

A finite element model has been developed to predict the temperature rise under various operating conditions [10]. The simulation consists of three steps. First, the complex electromechanical admittance of the PZT-embedded structure is calculated. A suitable damping model is necessary in order to model the dissipation of energy in the structure. In this case, a linear viscous damping model is assumed. Next, the internal heat generation rate per unit volume (Q_p) of the PZT structure is computed using the following correlations:

$$P = \frac{I_m V_m}{2} \cos \phi = \frac{V_m^2}{2} \text{Re}(A) \quad (1)$$

$$Q_p = \frac{P}{\text{volume(PZT)}} \quad (2)$$

where V_m and I_m are the magnitude of the actuation voltage and current, ϕ is the phase difference between the voltage and current, A is the complex admittance calculated from the FEM model. Finally this internal heat generation rate is provided as input to a steady state heat conduction thermal model to compute the temperature rise. The convection heat transfer boundary condition is applied at all external boundaries. This process is repeated for all actuation frequencies. The material properties of PZT-5A provided in [11] are used for the simulations discussed here.

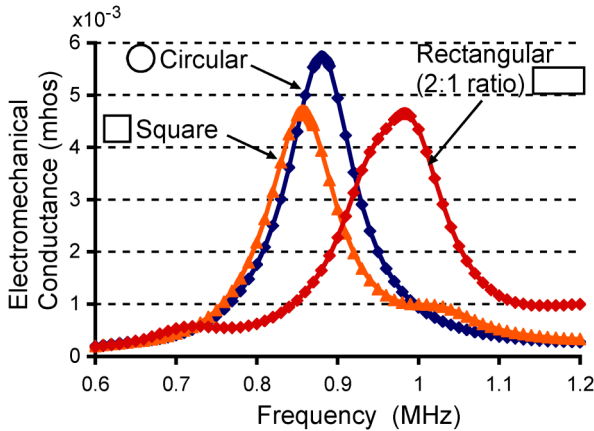


Fig. 3: Comparison of the simulated conductance of the PZT bonded to a brass substrate. Different cross-sectional shapes were used, with the same volume and cross sectional area. The circular shape provides the most favorable response.

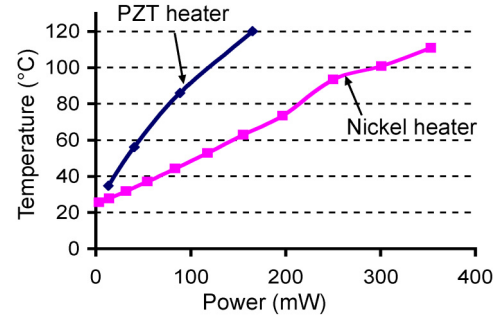


Fig. 4: Comparison of temperature attained for various power input by Ni and PZT heater on biological tissue. The PZT heater was 2x times more power efficient than the Ni heater

Shape selection

The simulation model described in the previous section is used to determine the shape (for a given volume and surface area) for generating maximum temperature at an applied voltage. Equations 1 and 2 suggest that for an applied voltage and frequency of operation, the internal heat generation rate is proportional to the conductance (*i.e.* the real part of the admittance). Figure 3 shows the comparison of the conductance of PZT heater for different shapes. The simulations suggest that the circular shape is the most suitable.

FABRICATION

The circular ultrasonic heaters (3.2 mm diameter and 191 μm thick) can be fabricated using the bulk micromachining process described in [8]. The ultrasonic machining tool is fabricated from a 0.5 mm thick steel sheet using the micro electrodischarge machining process. The pattern on this tool is transferred to the PZT using ultrasonic machining with the help of tungsten carbide powder. Finally the PZT is flipped and lapped from behind to release the pattern. Metal is sputtered on both sides to form the electrodes. The stacked PZT heaters (Fig. 2c) are fabricated by bonding two of the above described PZT heaters one above the other.

EXPERIMENTAL RESULTS

Test set-up

The schematic and a sample photograph of the PZT

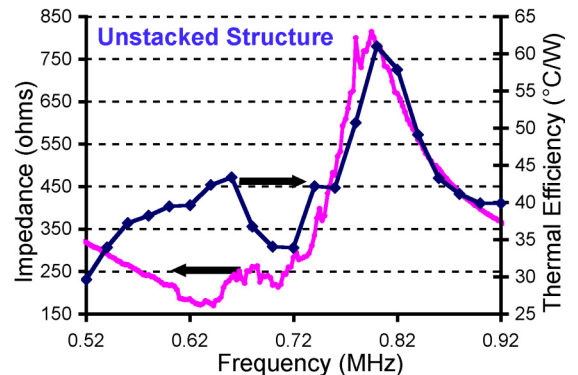


Fig. 5: Thermal efficiency and impedance of the PZT heater as a function of frequency at mode 2 on brass.

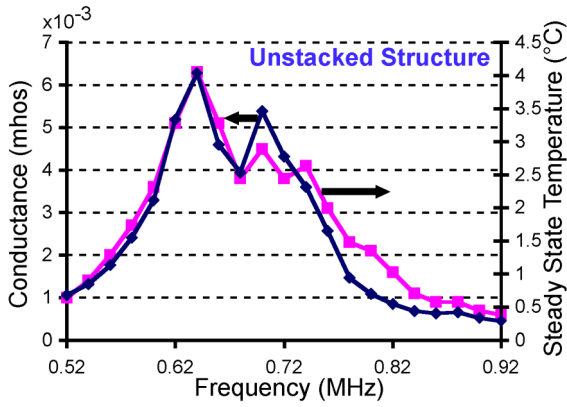


Fig. 6: Temperature attained by PZT and conductance as a function of frequency of excitation at mode 2 on brass.

heaters used in the experiments are shown in Fig. 2. The PZT heaters are actuated using an Agilent 33250A function generator. The voltage applied across the PZT and the current flowing through it are measured using an oscilloscope and Tektronix CT1 (1 GHz) current probe, respectively. A K-type thermocouple read using a HH506A multilogger thermometer is bonded to the top of the PZT using non-conductive epoxy to measure the temperature.

Comparison with resistive heater

The proposed PZT heater is first compared with bulk micromachined Ni heaters under similar conditions. The ‘V’ shaped Ni heaters ($4 \times 1.3 \times 0.05 \text{ mm}^3$, $R=2\Omega$) are fabricated from metal foil by photochemical machining [12]. The PZT heater is actuated at its resonance frequency (650 kHz). Figure 4 suggests that the PZT heater is 2x times more power efficient than the resistive heater.

Operating frequency optimization

The PZT heaters are characterized to determine the operating frequency that provides maximum thermal efficiency. Figure 5 shows the variation of thermal efficiency and impedance of the PZT with frequency. It suggests that the PZT heater attains maximum efficiency at its anti-resonance (maximum impedance) frequency. This is believed to be due to minimum parasitic losses, as the

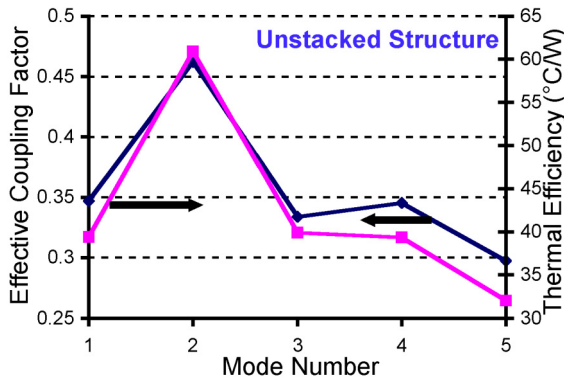


Fig. 7: Thermal efficiency and coupling factor for various mode shapes observed in non-stacked PZT heater bonded to brass.

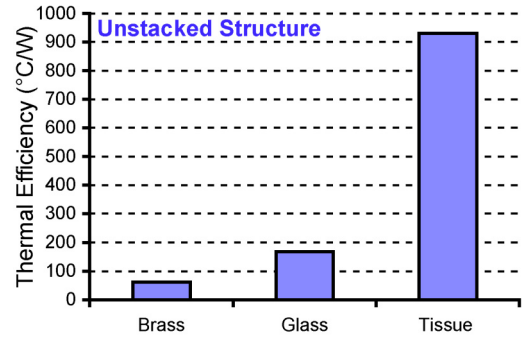


Fig. 8: Thermal efficiency of PZT microheater on different substrates. The efficiency of the heater was higher for highly damping substrates like biological tissue (elytra of beetle). current flowing through the system is minimum for a given voltage.

The variation of steady state temperature is also studied. Figure 6 suggests that the change in temperature is maximum at the frequency of maximum conductance (minimum impedance). Hence, when selecting the frequency, there is a trade-off between maximum temperature and maximum efficiency, depending on the application.

The thermal efficiencies of various resonance modes are also studied. It is observed that the thermal efficiency is proportional to the effective coupling factor (k_{eff}) of each mode (Fig. 7). The effective coupling factor is defined as

$$k_{eff} = \left(\frac{f_{ar}^2 - f_r^2}{f_{ar}^2} \right)^{0.5} \quad (3)$$

For the present case with PZT bonded to brass plate, mode 2 is observed to be the most suitable.

Effect of substrate

The PZT heaters are bonded to three different substrates namely, brass, glass, and biological tissue (*i.e.*, the elytra of the beetles). Figure 8 suggests that the thermal efficiency increases in substrates with high damping coefficient and low thermal conductivity. The PZT heater is found to attain a maximum thermal efficiency of 930°C/W when bonded to the elytra of beetle.

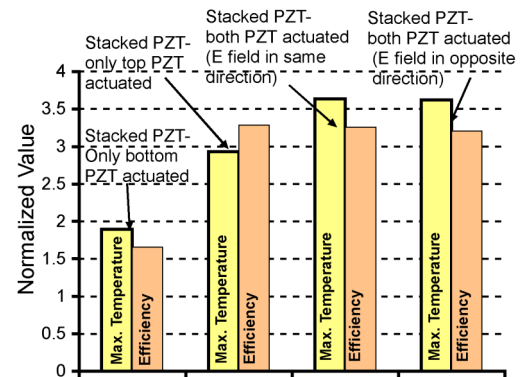


Fig. 9: Normalized maximum temperature ($T_{max}/T_{max-unstacked}$) & efficiency ($eff_{unstacked}$) attained by stacked PZT heater.

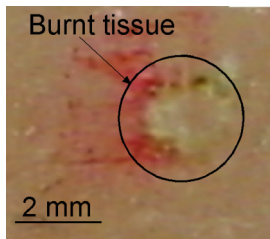


Fig. 10: Cauterization of porcine tissue using PZT heater probe

Stacked structure

Stacked structures are designed to improve the efficiency and maximum temperature rise of micro-heaters. The stacked heaters are fabricated by bonding two circular PZT heaters (diameter = 3.2 mm, thickness = 191 μm) using 320 μm thick non-conductive epoxy (Fig. 2). The stacked heaters are tested in four modes – actuation of bottom PZT alone, actuation of top PZT alone, and actuation of both PZTs with the electric field in the same and opposite directions. The stacked heaters generate 3.5x the temperature rise and are 3.25x more efficient than unstacked structures (Fig. 9). It is conjectured that the presence of a lower layer of PZT (with low thermal conductance) reduces the heat loss to the substrate from top PZT, resulting in higher efficiency. The direction of electric field does not have significant effect on the temperature rise and efficiency of the heaters.

Cauterization experiment

A porcine tissue sample is used for cauterization experiments. The experiment setup is same as the one used for heater characterization. The unstacked PZT heater probe branded the porcine tissue at a sinusoidal voltage of 10 V_{RMS} and an interface temperature of 150°C (Fig. 10). The whole cauterization process requires about 3 seconds.

CONCLUSIONS

The feasibility of using PZT based ultrasonic heaters for MEMS application was discussed. The PZT heaters were found to attain maximum thermal efficiency around the resonance frequency. In selecting the drive frequency, there was a compromise between the maximum temperature, which was achieved at frequency of minimum impedance, and maximum efficiency, which was achieved at frequency of maximum impedance. The thermal efficiency was tripled when a stacked structure was used. A FEM model was also developed in order to predict the heat generated in these heaters. Finally, the capability of the proposed device to cauterize biological tissue was demonstrated. Ultrasonic PZT micro-heaters hold significant promise for precise, high-resolution biomedical applications such as cauterization accompanying microsurgery and needle biopsy.

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