Voltage generation of piezoelectric cantilevers by laser heating

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Converting ambient thermal energy into electricity is of great interest in harvesting energy from the environment. Piezoelectric cantilevers have previously been shown to be an effective biosensor and a tool for elasticity mapping. Here we show that a single piezoelectric (lead-zirconate titanate (PZT)) layer cantilever can be used to convert heat to electricity through pyroelectric effect. Furthermore, piezoelectric-metal (PZT-Ti) bi-layer cantilever showed an enhanced induced voltage over the single PZT layer alone due to the additional piezoelectric effect. This type of device can be a way for converting heat energy into electricity. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4766412>]

I. INTRODUCTION

Harvesting ambient energy from environment is an important step in preserving the earth's resources. Piezoelectric materials have been a candidate material for harvesting energy because they can generate voltage when deformed. Energy harvesting from ambient mechanical vibration using piezoelectric materials is an active topic of research in recent years.^{1–3} Converting ambient thermal energy into electricity is another attractive approach. Pyroelectric effect has been demonstrated to convert thermal energy into electricity.⁴ A single layer of pyroelectric material can convert heat into electricity through the pyroelectric effect. However, pyroelectric effect cannot be utilized at any temperature and is only effective near the Curie temperature of the pyroelectric materials. Meanwhile, a bi-layer structure can be very sensitive to small temperature change. The photo-thermal spectroscopy utilizing such effect has been demonstrated to have femto-joule sensitivity.⁵ More recently, the photo-thermal effect of cantilevers was exploited for the detection of explosives.⁶ Furthermore, when piezoelectric materials are part of the bi-layer cantilevers, the photo-thermal effect can generate electricity. As a result, it is possible to convert thermal energy into electricity using the piezoelectric effect of a bi-layer structure. Theoretical analysis of functionally gradient piezoelectric materials subjected to a thermal load has recently been performed.⁷ However, no direct demonstration of voltage generation from heat using piezoelectric materials has been presented.

Recently we have developed a piezoelectric-nonpiezoelectric bi-layer unimorph cantilever that can be used as a sensor⁸ for small molecules and cells^{9–11} as well as a finger to probe elastic properties of soft tissues.^{12–14} The same structure can also generate voltage when it is deformed by a mechanical force.¹⁵

The piezoelectric-nonpiezoelectric bi-layer cantilever is a versatile device for converting heat into electricity. It can convert heat to electricity through the pyroelectric effect. In addition, it can convert heat into electricity through the piezo-

electric effect involving bending and elongation of the bi-layer cantilever. As a result, it is possible to convert thermal energy into electricity more effectively by combining pyroelectric and piezoelectric effect through the bi-layer structure.

In this paper, we study the generation of voltage by applying a laser beam to the piezoelectric cantilevers. It is shown that voltage can be generated by shining a laser beam on a piezoelectric layer with electrodes. By combining the pyroelectric and piezoelectric features of ferroelectric material, the voltage generated by laser heating can be enhanced when a metal layer is bonded to the piezoelectric layer in the form of a bi-layer cantilever. This type of device has great potential in converting heat into electricity.

II. EXPERIMENTAL

Piezoelectric unimorph cantilevers of width of 2–5 mm and length of 15–25 mm were fabricated by bonding a lead zirconate titanate (PZT) layer of 127 μm thickness (T105-A4E-602, Piezo Systems, Boston, MA) to a 50 μm thick titanium sheet using a conductive glue (GC Electronics, Rockford, IL). After gluing, cantilevers were placed in an 80 °C oven overnight. The edges were sanded to make sure that the top and bottom electrodes of PZT were well separated. The PZT layer comes with Ni electrode of thickness 200 nm (information provided by the manufacturer) on both sides. Similar experiments were performed on PZT layer without the Ti layer for comparison. The displacements of the cantilever were measured using a laser displacement meter (LK-G35, Keyence Corporation, Osaka, Japan) with a resolution of 0.05 μm . The induced voltage was acquired by the digital storage oscilloscope (TDS2022B, Tektronix). The measurements were conducted on a Newport optical table to minimize low-frequency background vibrations. A laser (wavelength 1064 nm) was used to focus on the PZT layer in order to generate the induced voltage and the displacement. The laser displacement meter and the digital oscilloscope were connected to a personal computer (PC). All measurement and data acquisition were controlled from the PC.

The experimental setup is shown in Fig. 1. Using different laser intensity, we observed different induced voltage and bending displacement from the samples. With a particular laser power, we measured the displacement of the cantilever as well as the induced voltage at the same time. The laser power was varied from 0 to 300 mW. The laser beam was focused on the tip of the cantilever away from the clamping position. A typical set of data of displacement and induced voltage of the PZT-Ti cantilever at the power of 195.6 mW is shown in Fig. 2. As can be seen, when the cantilever was deformed by the different thermal expansion coefficient between PZT and Ti (thermal expansion coefficient of Ti, Ni, and PZT is 8.6, 13.4, and $4 \times 10^{-6} \cdot \text{K}^{-1}$, respectively, at 25°C),¹⁶ induced voltage was observed. There was a direct correlation between the displacement and the induced voltage: As the cantilever was deformed, an induced voltage was produced.

As we turned the laser on, shining on the PZT side, we observed the displacement of the bi-layer toward the PZT layer side due to the larger thermal expansion of Ti than that

FIG. 1. The experimental set-up. When the laser shines on the PZT side, the cantilever bent toward the PZT layer side with a finite displacement. When the laser is turned off, the cantilever bent toward the Ti side and returned to the zero-displacement position.

FIG. 2. The induced voltage and displacement of the PZT-Ti bi-layer cantilever as a function of time. Note the different behavior between when the laser was turned on and when the laser was turned off.

of PZT. When the laser was turned off, the cantilever bent toward the Ti side and returned to the zero-displacement position. The detailed geometry of the position of laser and the way the bi-layer bend are shown in Fig. 1. When the laser was turned off, the induced voltage was opposite to the induced voltage obtained when the laser was turned on. Since the induced voltage depends on whether the laser is turned on or off, we will denote the voltage induced when laser is turned on, the turn-on induced voltage, labeled as $V_{\text{ind,on}}$, and the voltage induced when laser is turned off, the turn-off induced voltage, $V_{\text{ind,off}}$.

III. RESULTS AND DISCUSSION

The induced voltage changed with time as shown in Fig. 2. We plot the maximum induced voltage as a function of laser power in Fig. 3(a). Similarly we can plot the displacement as a function of laser power as shown in Fig. 3(b). It was found that increasing the laser power increased the displacement. The data in Fig. 3(b) are found to be roughly linear with a slope of $0.37 \mu\text{m}/\text{mW}$. However, the laser power cannot be increased indefinitely. When the laser power reached 280 mW, the PZT layer was burnt, and no displacement was observed at this high power.

Combining the results of Figs. 3(a) and 3(b), we obtain the relationship between the induced voltage and the displacement, as shown in Fig. 4. Even though the relationship is not exactly linear, we use a linear fit to obtain an overall trend. The slope of a linear fit of turn-off induced voltage versus displacement is $2.7 \text{ mV}/\mu\text{m}$. On the other hand, the slope of a linear fit of turn-on induced voltage versus displacement is $1.08 \text{ mV}/\mu\text{m}$. Clearly, turning off the laser generated more induced voltage than turning on the laser.

A. Pyroelectric contribution vs. piezoelectric contribution

The observed induced voltage due to laser heating most likely comes from the thermal expansion mismatch of the

FIG. 3. (a) The induced voltage versus laser power of PZT-Ti bi-layer cantilever and PZT layer as the laser is turned on or turned off. Note that the turned-off induced voltage is larger than turned-on induced voltage. (b) The displacement of PZT layer and PZT-Ti bi-layer cantilevers as a function of laser power.

PZT and Ti layers. The resulting bending gives rise to the induced voltage due to the piezoelectric effect. To understand the behavior of the PZT-Ti better, we performed similar experiments on PZT layer alone without the Ti layer. The displacement results of the PZT layer as a function laser power is also shown in Fig. 3(b). There was minimal displacement observed when laser beam was either turned on or turned off at the PZT layer. Similarly, Fig. 3(a) shows the induced voltage of PZT layer as a function of laser power is smaller than that of PZT-Ti bi-layer. Even though there are Ni electrode layers on both sides of PZT, there is no bending produced due to the symmetric thermal expansion mismatch of top and bottom Ni electrodes with PZT that cancels each other out. On the other hand, the addition of a Ti layer creates an asymmetric thermal expansion mismatch resulting in significant bending which enhances the induced voltage of PZT.

The induced voltage of PZT layer alone is likely due to either the lateral deformation or the pyroelectric effect of the PZT layer. To gain further insight, we glued the PZT layer to a substrate to prevent lateral deformation of the PZT and performed the laser heating experiment again. The substrate is a glass slide of 5 cm long, 2.5 cm wide, and 1 mm thick. The PZT dimension is much smaller than the substrate; therefore

the impact of the laser on the substrate is negligible. It was found that the induced voltage values were similar to the results shown in Fig. 3(a) for the PZT layer alone. The only difference is that the relaxation time for the PZT sample glued to a substrate is somewhat shorter (~ 5 s) than the PZT layer cantilever sample (~ 25 s). The relaxation time was taken at the time when the induced voltage was decreased to $1/e$ of the initial induced voltage. We speculate the relaxation time is related to domain switching. The substrate likely pins the domains and limits domain switching and thus reduces relaxation time. Therefore, the induced voltage of PZT single-layer cantilever is attributed to the pyroelectric effect.

On the other hand, the addition of a Ti layer creates an asymmetric thermal mismatch resulting in significant bending. Since there is no significant bending on PZT layer, the induced voltage of PZT layer alone is mostly due to the pyroelectric effect of the PZT layer. In contrast, with significant bending, the PZT-Ti bi-layer shows larger induced voltage due to the combined contributions of pyroelectric and piezoelectric effect.

To differentiate the pyroelectric effect from the piezoelectric effect, we considered the induced voltage of PZT layer alone as the contribution from pyroelectricity, and the remaining contribution as the piezoelectric effect. The results of such analysis are shown in Fig. 5. The pyroelectric contribution is calculated as a ratio of pyroelectric effect to the sum of pyroelectric and piezoelectric effects for PZT-Ti bi-layer and is plotted as a function of laser power in Fig. 5(a). It can be seen that for PZT-Ti bi-layer, the contribution of pyroelectric effect decreased with increasing laser power indicating the contribution of piezoelectric effect increased with increasing laser power. At low laser power, the pyroelectric effect dominates the voltage generation behavior while at higher laser power the contribution from piezoelectric effect becomes important. This result is consistent with the displacement as a function of laser power for PZT-Ti shown in Fig. 3(b).

It was found that the $V_{\text{ind,off}}$ is always higher than the $V_{\text{ind,on}}$. This can be more clearly seen in Fig. 5(b) where the ratio of $V_{\text{off}}/V_{\text{on}}$ is plotted. The behavior is more pronounced in the case of PZT-Ti bi-layer cantilevers. The reason for this difference is related to the fact that the surrounding environment favors the turn-off process (cooling to the temperature

FIG. 4. The induced voltage versus displacements of PZT-Ti bi-layer cantilever when the voltage is turned on and turned off, respectively.

FIG. 5. (a) The pyroelectric contribution to total induced voltage at different power. The contribution of pyroelectric effect decreased with increasing laser power. (b) The $V_{\text{off}}/V_{\text{on}}$ ratio for PZT-Ti and PZT cantilever as a function of laser power. The ratio is always larger 1 indicating that the heating rate is slower than cooling rate.

of the surrounding) over the turn-on process (heating to a higher temperature against the surrounding). As a result, the heating rate during turn-on is lower than the cooling rate during turn-off. From the fact that the pyroelectric response is proportional to the rate of changing temperature, we can expect the ratio of $V_{\text{off}}/V_{\text{on}}$ to be larger than 1, as seen in Fig. 5(b). Moreover, for PZT-Ti bi-layer cantilever with the additional piezoelectric effect, it is expected that a faster rate of change can result in higher induced voltage since a constant load does not maintain the induced voltage. Consequently, during the turn-on process, the rate of deformation is slower and results in a smaller V_{on} . On the other hand, during the turn-off process, the rate of deformation is faster and results in a larger V_{off} .

Also it was observed that the signals of turn-off induced voltages are more stable than those of turn-on induced voltage. We believe that the reason for the unstable signal when the laser was turned on is due to the instability of the power supply for the laser. The decay time of the $V_{\text{ind,on}}$ was about 6–15 s and 8–12 s for $V_{\text{ind,off}}$. This order of relaxation time is much slower than the decay time of induced voltage generated by applying a mechanical force to cause the bending of the bi-layer.¹⁷ The relaxation time due to mechanical bending is typically 20–40 ms. Therefore the process of induced voltage due to thermal conversion is much slower than mechanical conversion. Using a linear fit to the data in Fig. 3(a), the slope of $V_{\text{ind,off}}$ versus laser power is about 1 mV/mW whereas that of the $V_{\text{ind,on}}$ is only about 0.4 mV/mW.

B. Sign of charge generation

The sign of the charge generation has been shown in Fig. 1. As the laser was turn on and shone on the PZT side, the cantilever bent toward the laser with negative charges generated on the surface facing the laser. To understand why the generated charge was negative facing the laser, we created the illustrations in Fig. 6 to show the effects involved. In the piezoelectric effect, there are two contributions. One is the elongation of the PZT as shown in Fig. 6(a). The PZT is elongated because it is bonded to Ti which extends more than the PZT during heating because of a larger thermal

expansion coefficient. When a piezoelectric material is elongated, charge generation occurs. For the specific example in Fig. 6(a) with a polarization pointing to the right, an elongation in the vertical direction will generate negative charge on the right-hand side surface which tries to create an electric field that will return the piece to its original length.¹⁸ Another effect is bending, again due to the thermal expansion mismatch of the PZT and Ti. The bending also causes charge generation as shown in Fig. 6(b).¹⁸ Finally the pyroelectric effect generates charge as shown in Fig. 6(c) on heating. As shown in Fig. 6, the pyroelectric and the elongation effect have the same sign of charge generation while the bending effect shows opposite sign. In the case of PZT-Ti bi-layer cantilever that we studied here, the observed induced voltage indicated the contributions of pyroelectric and elongation

FIG. 6. Illustrations of (a) elongation, (b) bending, and (c) pyroelectric effects of piezoelectric-nonpiezoelectric bi-layer cantilever.

FIG. 7. Schematic of a piezoelectric (p) and metal (np) bi-layers where t_p and t_{np} are the thickness of the piezoelectric layer and that of the metal layer, respectively. The boundary between the piezoelectric and metal layers is chosen as the origin, and t_n denotes the position of the neutral plane.

effects win over that from the bending effect. Furthermore, due to the smaller contribution of pyroelectric effect compared to the piezoelectric effect shown in Fig. 5(a), we concluded that the elongation effect is the dominant effect in the enhancement of induced voltage over that of the pyroelectric effect of the single-layer PZT.

C. Voltage generation of a piezoelectric/nonpiezoelectric bi-layer cantilever

An earlier study has theoretically examined the piezoelectric voltage generation across the piezoelectric layer of a piezoelectric–nonpiezoelectric bi-layer transducer due to an applied electric field applied to the piezoelectric layer and/or the thermal expansion mismatch of the two layers.¹⁹ In the present case, the piezoelectric voltage in the PZT resulted solely from thermal expansion mismatch. Following Ref. 19, a schematic of the coordinates of a piezoelectric bi-layer cantilever undergoing thermal expansion is given in Fig. 7. Given that the thickness of the transducer is much smaller than the radius of curvature of the transducer, the total in-plane lateral strain, ε , in the θ -direction at an axial position z within the bi-layer can be written as the sum of the bending strain due to the thermal expansion mismatch between the piezoelectric layer and the nonpiezoelectric layer and the uniform constraint in-plane strain within the bi-layer due to the thermal expansion as

$$\varepsilon = \left(\frac{z - t_n}{r} \right) + c, \quad (1)$$

where the first term of Eq. (1) is the bending strain with t_n being the axial position of the bending-strain neutral plane, r the radius of bending curvature of the inner surface of the transducer and the second term, c , being the constrained in-plane strain due to the uniform thermal expansion of the bi-layer. The axial position of the bending-strain neutral plane, t_n , the radius of curvature, r , and the constraint strain, c , can be expressed as¹⁹

$$t_n = \frac{E_p t_p^2 - E_{np} t_{np}^2}{2(E_p t_p + E_{np} t_{np})}, \quad (2)$$

$$C = \frac{(E_p t_p \alpha_p + E_{np} t_{np} \alpha_{np}) \Delta T}{(E_p t_p + E_{np} t_{np})}, \quad (3)$$

and

$$\frac{1}{r} = \frac{6E_p E_{np} t_p t_{np} (t_p + t_{np}) (\alpha_p - \alpha_{np}) \Delta T}{E_{np}^2 t_{np}^4 + E_p^2 t_p^4 + 2E_{np} E_p t_p t_{np} (2t_p^2 + 2t_{np}^2 + 3t_p t_{np})}, \quad (4)$$

where E_p , α_p , and t_p are, respectively, the Young's modulus, thermal expansion coefficient, and thickness of the piezoelectric layer and E_{np} , α_{np} , and t_{np} are, respectively, the Young's modulus, thermal expansion coefficient, and thickness of the nonpiezoelectric layer, and ΔT the temperature change.

The piezoelectric electric field at any axial position, z , $E(z)$ can be obtained by multiplying the in-plane stress σ by the g_{31} piezoelectric stress constant.¹⁷ Using the relationship that $\sigma = \varepsilon E_p$, $E(z)$ can be expressed as

$$\begin{aligned} E(z) &= g_{31} \sigma = g_{31} \varepsilon E_p = g_{31} E_p \left(\frac{z - t_n}{r} + C \right) \\ &= E_{bending} + E_{elongation}. \end{aligned} \quad (5)$$

Substituting Eqs. (2)–(4) into $E(z)$ and integrating $E(z)$ over z , the induced voltage V_{in} across the thickness of the piezoelectric layer was then

$$\begin{aligned} V_{in} &= \int_0^{t_p} E dz = g_{31} E_p \left\{ \frac{1}{r} \left(\frac{1}{2} t_p^2 - t_n t_p \right) + C t_p \right\} \Delta T \\ &= V_{bending} + V_{elongation}, \end{aligned}$$

where

$$V_{bending} = g_{31} E_p \frac{1}{r} \left(\frac{1}{2} t_p^2 - t_n t_p \right) \Delta T, \quad (6)$$

and

$$V_{elongation} = g_{31} E_p C t_p \Delta T. \quad (7)$$

TABLE I. Physical parameters of the PZT (p) and metal (np) bi-layers. Stainless steel (SS) and Ti are examples of metals.

	E_p (Pa)	t_p (m)	E_{np} (Pa)	t_{np} (m)	t_n (m)
PZT/Ti	6.6×10^{10}	1.27×10^{-4}	1.1×10^{11}	5×10^{-5}	2.84×10^{-5}
PZT/SS	6.6×10^{10}	1.27×10^{-4}	2×10^{11}	5×10^{-5}	1.54×10^{-5}
	$g_{31}(\text{PZT})$ (V m/N)	α_p (1/K)	α_{np} (1/K)	$C/\Delta T$ (1/K)	$1/r\Delta T$ (1/m K)
PZT/Ti	-1.16×10^{-2}	4×10^{-6}	8.6×10^{-6}	5.82×10^{-6}	-3.52×10^{-2}
PZT/SS	-1.16×10^{-2}	4×10^{-6}	1.73×10^{-5}	1.12×10^{-5}	-1.09×10^{-1}

TABLE II. Induced voltage normalized by temperature change ΔT for PZT/Ti and PZT/SS bi-layer cantilevers.

	$V_{\text{bending}}/\Delta T$ (V/K)	$V_{\text{elongation}}/\Delta T$ (V/K)	$V_{\text{total}}/\Delta T$ (V/K)
PZT/Ti	1.20×10^{-1}	-5.66×10^{-1}	-4.46×10^{-1}
PZT/SS	5.12×10^{-1}	-1.09	-5.80×10^{-1}

Substituting the corresponding values of Table I into Eqs. (6) and (7), we found that the sign of V_{bending} is opposite to that of $V_{\text{elongation}}$ and the magnitude of $V_{\text{elongation}}$ is larger than that of V_{bending} as shown in Table II. The results in Table II are consistent with the observed results schematically illustrated in Fig. 6. Moreover, we can compare two kinds of bi-layer cantilevers composed of different metals, such as titanium and stainless steel, respectively. Based on calculation, the scaling analysis shows that the cantilever made by a harder metal, e.g., stainless steel, with higher Young's modulus and higher thermal expansion coefficient, can generate larger induced voltage, as shown in Table II.

IV. CONCLUSIONS

In summary, it is shown that thermal energy can be converted into electric voltage in ferroelectric material by pyroelectric effect. By using piezoelectric bi-layer cantilevers, the voltage induced by laser heating can be enhanced due to the additional piezoelectric effect of the thermal expansion mismatch of the two layers. The piezoelectric contribution to induced voltage increases with increasing laser power.

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¹S. R. Anton and H. A. Sodano, "A review of power harvesting using piezoelectric materials (2003–2006)," *Smart Mater. Struct.* **16**, R1–R21 (2007).

- ²M. Pozzi, M. S. H. Aung, M. Zhu, R. K. Jones, and J. Y. Goulermas, "The pizzicato knee-joint energy harvester: Characterization with biomechanical data and the effect of backpack load," *Smart Mater. Struct.* **21**, 075023 (2012).
- ³M. Lee, C. Y. Chen, S. Wang, S. N. Cha, Y. J. Park, J. M. Kim, L. J. Chou, and Z. L. Wang, "A hybrid piezoelectric structure for wearable nanogenerators," *Adv. Mater.* **24**(13), 1759–1764 (2012).
- ⁴D. Guyomar, G. Sebald, S. Pruvost, M. Lallart, A. Khodayari, and C. Richard, "Energy harvesting from ambient vibrations and heat," *J. Int. Mater. Syst. Struct.* **20**, 609–624 (2009).
- ⁵J. R. Barnes, R. J. Stephenson, C. N. Woodburn, S. J. O'Shea, M. E. Welland, T. Rayment, J. K. Gimzewski, and Ch. Gerber, "A femtojoule calorimeter using micromechanical sensors," *Rev. Sci. Instrum.* **65**(12), 3793–3798 (1994).
- ⁶C. W. Van Neste, L. R. Senesac, D. Yi, and T. Thundat, "Standoff detection of explosives using photothermal cantilevers," *Appl. Phys. Lett.* **92**, 134102 (2008).
- ⁷H. J. Xiang and Z. F. Shi, "Static analysis for functionally graded piezoelectric actuators or sensors under a combined electro-thermal load," *Eur. J. Mech. A/Solids* **28**, 338–346 (2009).
- ⁸J. W. Yi, W. Y. Shih, and W.-H. Shih, "Effect of length, width, and mode on the mass detection sensitivity of piezoelectric unimorph cantilevers," *J. Appl. Phys.* **91**(3), 1680–1686 (2002).
- ⁹J. Capobianco, W. Y. Shih, and W.-H. Shih, "Methyltrimethoxysilane-insulated piezoelectric microcantilevers for direct, all-electrical biodetection in buffered aqueous solutions," *Rev. Sci. Instrum.* **77**, 125105 (2006).
- ¹⁰Q. Zhu, W. Y. Shih, and W.-H. Shih, "In situ, in-liquid, all-electrical detection of *Salmonella typhimurium* using lead titanate zirconate/gold-coated glass cantilevers at any dipping depth," *Biosens. Bioelectron.* **22**, 3132–3138 (2007).
- ¹¹Q. Zhu, W. Y. Shih, and W.-H. Shih, "Real-time, label-free, all-electrical detection of *Salmonella typhimurium* using lead titanate zirconate/gold-coated glass cantilevers at any relative humidity," *Sens. Actuators B* **125**, 379–388 (2007).
- ¹²A. Markidou, W. Y. Shih, and W.-H. Shih, "Soft-materials elastic and shear moduli measurement using piezoelectric cantilevers," *Rev. Sci. Instrum.* **76**, 064302 (2005).
- ¹³H. O. Yegingil, W. Y. Shih, and W.-H. Shih, "All-electrical indentation shear modulus and elastic modulus measurement using a piezoelectric cantilever with a tip," *J. Appl. Phys.* **101**, 054510 (2007).
- ¹⁴H. O. Yegingil, W. Y. Shih, and W.-H. Shih, "Probing elastic modulus and depth of bottom-supported inclusions in model tissues using piezoelectric cantilevers," *Rev. Sci. Instrum.* **78**, 115101 (2007).
- ¹⁵S. T. Szweczyk, W. Y. Shih, and W.-H. Shih, "Palpation-like soft-material elastic modulus measurement using piezoelectric cantilevers," *Rev. Sci. Instrum.* **77**, 044302 (2006).
- ¹⁶See http://www.webelements.com/periodicity/coefficient_thermal_expansion/ for information about thermal expansion coefficient.
- ¹⁷X. Gao, W. Y. Shih, and W.-H. Shih, "Induced voltage of piezoelectric unimorph cantilevers of different nonpiezoelectric/piezoelectric length ratios," *Smart Mater. Struct.* **18**, 125018 (2009).
- ¹⁸See <http://www.piezo.com/catalog8.pdf%20files/Cat8.22,23,24,25,62,63&64.pdf> for introduction to piezo transducers.
- ¹⁹W. Y. Shih, W.-H. Shih, and I. A. Aksay, "Scaling analysis for the axial displacement and pressure of flextensional transducers," *J. Am. Ceram. Soc.* **80**, 1073–1078 (1997).