In Situ Measurement of Mechanical Properties of Polyimide Films Using Micromachined Resonant String Structures

Yong-Jun Kim and Mark G. Allen, *Member, IEEE*

***Abstract*—Two *in situ* measurement schemes, using micromachined resonant string structures, for the measurement of the polyimide residual stress and polyimide/metal adhesion durability have been developed. The residual stress of polyimide films, DuPont PI-2555 and PI-2611, have been measured using a bulk micromachined string structure. According to the Rayleigh's method, the resonant frequency of a polyimide string can be related to the film stress. By measuring the resonant frequency of these polyimide strings, the residual stresses have been calculated. The measurement results of various strings have been compared with conventional measurement results, which shows that they are in good agreement.**

Also, a noble scheme to quantize the adhesion durability between a polyimide film and a metal film has been developed. This scheme is based on a polyimide/metal bimorph string structures, fabricated using a surface micromachining technique, vibrating with an alternating potential. The change of resonance profile of this string structure can be related to the degradation of adhesion strength at the polyimide/metal interface. Various polyimide/gold string structures have been fabricated using a surface micromachining with Cu sacrificial layers, and the resonant qualities have been monitored. Notable changes of resonant Q-factor and resonant frequency, due to the degradation of adhesion between the metal and polyimide, have been observed after 10^8 cycles (string vibration) for the polyimide/gold bimorph strings. The changes of resonant Q-factor and resonant frequency over a time period (vibration cycles) have been monitored.

***Index Terms*—Adhesion, *in situ* measurement, micromachining, residual stress, resonant structure, string.**

I. Introduction

There has been great interest in the mechanical properties of thin films [1], [2]. It is very important to know, at the design stage, the mechanical properties of thin films in order to select the proper material, and in order to control the mechanical properties by appropriate processing steps [1]. For example, one of the most important mechanical properties of thin films is residual stress [1], [3]. This residual stress can produce buckling of the film or bending of the substrate, which makes the subsequent processes more difficult or which might cause operational failure of the fabricated devices. Therefore, the choice of a thin film must be based on the knowledge of its residual stress in various situations. In particular, since the mechanical deflection of a thin film is largely affected by the stress, this knowledge of residual stress is more critical in some microelectromechanical systems (MEMS) where the film of the interest is designed to be a moving part [4].

However, it is very hard to predict these properties from a process sequence at present, since they are strongly affected by deposition conditions and possible subsequent fabrication processes. Hence, several techniques for measuring the mechanical properties of thin films have been proposed. Some of these techniques were based on the buckling behavior of thin films [5], [6], which are appropriate for measurement of compressive stresses. Since many thin films are usually in a tensile stress state, alternative methods are required for their assessment.

Conventionally, two well-developed measurement schemes have been widely used to measure the polyimide film stress. The residual stress in a film on a substrate can be determined by measuring the bending curvature of the substrate [2], [7]. For example, after a high temperature deposition, the difference of the thermal expansion coefficients between the substrate and the film can induce different stresses on the substrate and the film. This stress difference causes the substrate to bend. By relating the amount of bending to the film stress, the residual stress of the film can be measured. Another measurement scheme is the load-deflection method. By finding the deflection profile of a membrane as a function of pressure, various mechanical properties of polyimide thin films can be determined [3].

Numerous researchers have used resonant structures for measuring thin film mechanical properties [8]. A measurement scheme using resonant structures has several advantages over the previously-mentioned methods. First, it has good sensitivity: a very small shift of the resonant frequency can be easily detected. Second, it is easy to monitor the measurement process. Third, its measurement setup is relatively simple. Fourth, lifetime or fatigue analysis can be easily performed. Therefore, it is reasonable to develop a resonant scheme for polyimide thin film mechanical property measurement. In this research, two measurement schemes are proposed, one to measure the residual stress of a polyimide film and one to

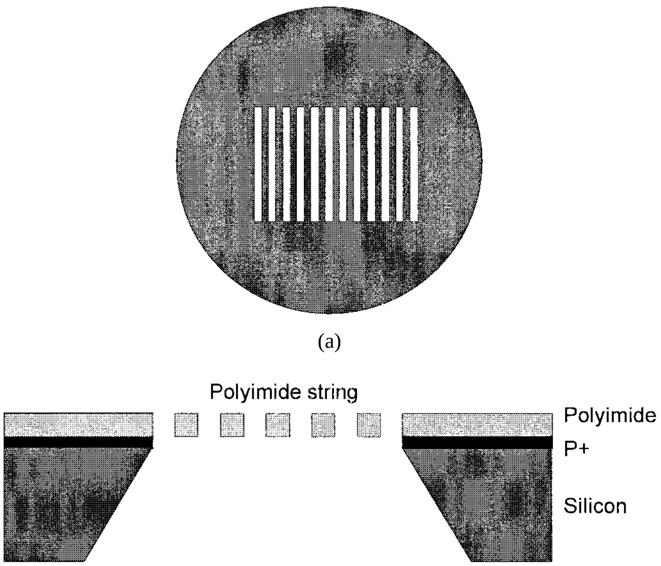
---

Manuscript received September 1, 1998; revised March 1, 1999. This paper was recommended for publication by Editor J. Morris upon evaluation of the reviewers' comments. This work was supported in part by the National Science Foundation through the Georgia Tech/NSF Engineering Research Center in Electronic Packaging, Contract EEC-9402723.

Y.-J. Kim is with the Opto-Mechatronics Laboratory, Corporate R&D Center, Samsung Electronics Company, Ltd., Suwon City, Kyungki-Do 442-742, Korea.

M. G. Allen is with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0269 USA.

Publisher Item Identifier S 1521-3331(99)04648-6.



(a)

(b)

Fig. 1. (a) Top view and (b) cross-sectional view of a resonant string structure.

determine the adhesion durability between a polyimide film and a metal film.

II. STRESS MEASUREMENT USING BULK-MICROMACHINED RESONANT STRING STRUCTURE

A resonant string structure fabricated using bulk micromachining techniques has been investigated for measuring residual stress of a polyimide thin film. Fig. 1 shows a schematic view of a string completely released on top of a silicon wafer. Since the polyimide string is released from the substrate, the string is free to vibrate, for example, due to excitation by incident acoustic waves. By measuring the frequency of vibration, and using the Rayleigh criterion [9]–[10], the residual stress of the polyimide string can be determined.

A. Fabrication of a Bulk Micromachined String Structure

Fig. 2 shows simplified fabrication steps of a bulk micromachined resonant string structure. The fabrication starts with a $2''\langle 100\rangle$ silicon wafer. A 5-μm thick heavily boron-doped layer is deposited on the polished side to be used as an etch-stop layer. A silicon dioxide film 5000 Å in thickness is thermally grown on both the front and back side of the silicon wafer to protect it from a bulk etching solution (a). The polished side of the wafer is protected with a fully cured photoresist layer. The back side of the wafer is patterned to form an opening for a hole using conventional photolithography. The exposed oxide is etched using a buffered oxide etching (BOE) solution. A 20% KOH solution at 56 °C is used for anisotropic bulk etching of the silicon substrate, and the etching rate is 19–21 μm/h (b). Since the resulting silicon membrane is very fragile, the following processes must be performed with special care.

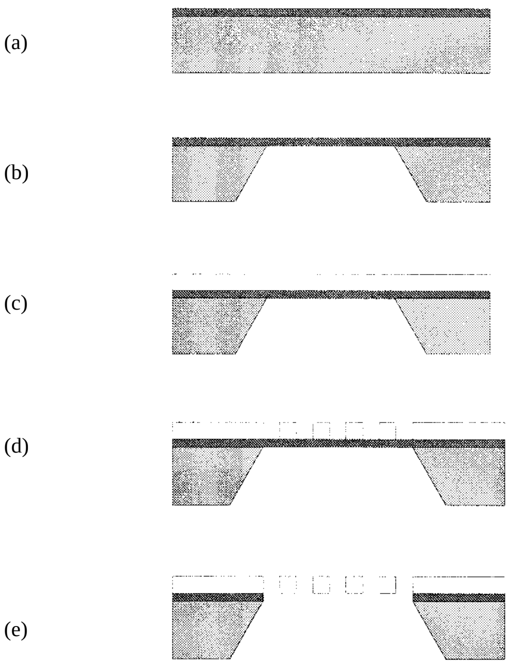


Fig. 2. Simplified fabrication steps of the resonant string structure. (a) Starting with p+ doped silicon wafer. (b) Anistropic etch in 20% KOH. (c) Spin cast polyimide. (d) Pattern polyimide using 100% O2 RIE. (e) Remove silicon membrane using RIE.

A polyimide film of DuPont PI-2611 or 2555 is spin coated at 3000 rpm for 30 s and cured in a convection oven, with N_2 at 350°C for 1 h. This results in an approximately 3 μm-thick polyimide layer (c). After depositing a 2000 Å aluminum mask layer, photolithography for the string pattern is performed. The aluminum mask is defined using a solution of phosphoric, acetic, and nitric acids (PAN etching solution). A 100% O_2 RIE is used to etch the polyimide to form a string pattern. These etching conditions result in a good anisotropic profile of polyimide etching. The aluminum mask is removed using a dilute HF solution (d). The wafer is installed in an RIE machine upside down to etch the backside. RIE etching with a mixture of gases, 90% CF_4 and 10% O_2, is used to etch the boron doped layer from the backside (e). Since this RIE etches the polyimide, the polyimide structure can be etched after the boron doped layer is removed. Therefore, accurate estimation of the etching rate and total etching time is needed in order to prevent overetching.

Several string structures with various string lengths have been designed and fabricated using bulk micromachining techniques. Fig. 3 shows a fabricated resonant string structure. Each string was 30 μm wide, and of a uniform length within a given sample. Differing samples had string length varying from 3–10 mm. The lengths of these strings were determined such that the resonant frequencies were within the audio frequency regime.

B. Residual Stress Measurement of Polyimide Thin Films

From Rayleigh's method of resonant analysis, it is known that the first resonant frequency of a string under residual tensile stress is given by [9], [10]

$$f_r = \frac{1}{2L}\sqrt{\frac{\sigma}{\rho}} \tag{1}$$

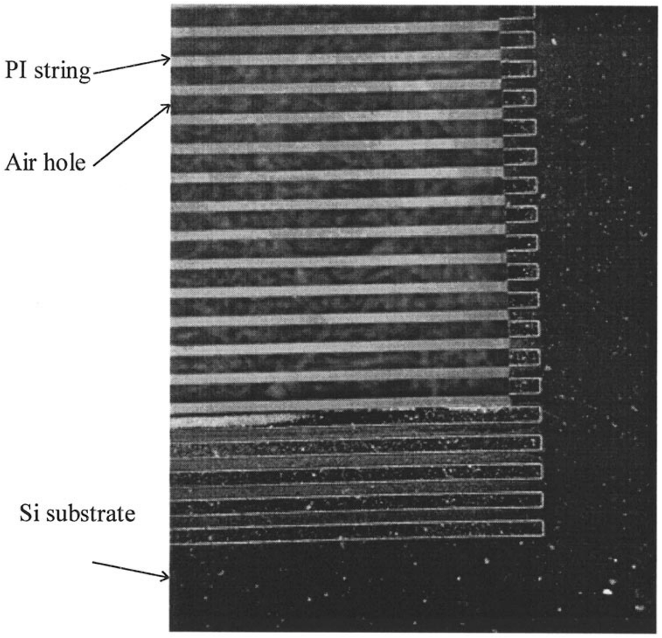


Fig. 3. A resonant string structure on a Si wafer, 30 μm wide and 40 μm spaced.

where L is the length of the string, ρ is the density, and σ is the residual stress. By measuring the first resonant frequency using the technique described above, the residual stress can be calculated using this equation.

Fig. 4 shows a schematic of the test apparatus used for resonant frequency measurement of a string structure. The wafer with polyimide strings was excited with acoustic waves generated from a piezoelectric audio speaker. The sound waves pass through the strings where they are sensed by a high-sensitivity ceramic microphone. When the frequency of the excitation acoustic wave is matched to the mechanical resonant frequency of the string, an energy transfer occurs that induces the string vibration. Thus, a reduction of the transmitted energy will occur, which results in a decreased signal at the microphone. By sweeping the frequency of the incident acoustic wave and locating the frequency where the transmitted energy, i.e., microphone output, is a minimum, the mechanical resonant frequency of the string can be located. The overall management of this experiment, including sweeping frequencies for the function generator, equalization over sweeping frequency range, and detecting and processing the output signals, was performed by a personal computer. It should be noted that this method of string excitation allows assessment of the resonant frequency without contacting the string or depositing any potentially stress-changing electrodes on the string.

To increase accuracy of the measurement and reduce possible measurement errors, the speaker, string, and microphone were shielded with acoustic absorption foam, which minimizes outside interference and reduces echoes and chamber resonance. Since the frequency characteristic of the apparatus, including the speaker, chamber, microphone, and amplifier, is not uniform across the sweeping frequency range, a frequency equalization method was employed. The measurement of transmission as a function of frequency was taken on a wafer without a string, and this measurement result was used to equalize the apparatus spectrum over the sweeping frequency range. A computer algorithm was developed to realize the aforementioned equalization over the sweeping frequency range. Also, the output signal was fed into a nonlinear low-pass filter to exclude the occasional spike-type errors.

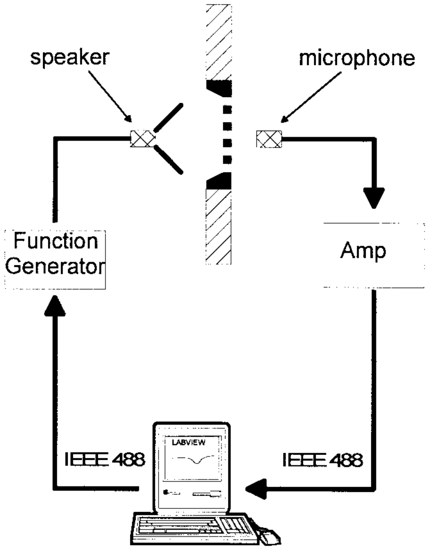


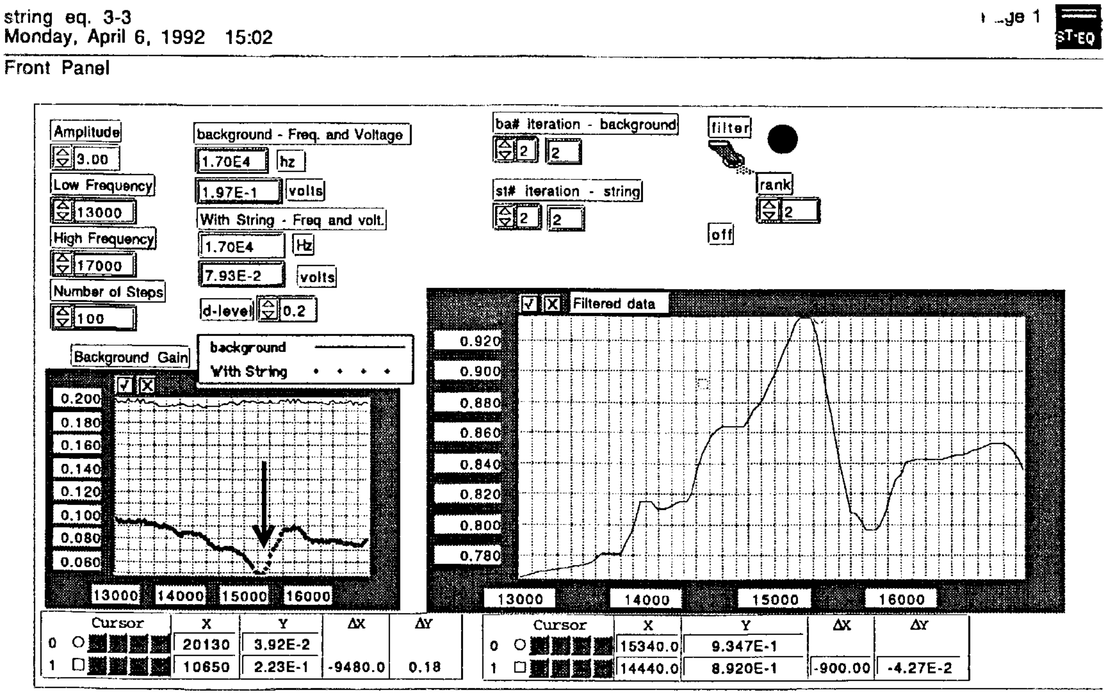
Fig. 4. Test apparatus for resonant frequency measurement of string structure

C. Results

Fig. 5 shows an actual computer screen of the program, LabView$^{\mathrm{TM}}$, used to control the experiment. This DuPont PI-2555 string was 5.6 mm long and the observed resonance frequency was 15.2 kHz, resulting in a calculation of residual stress of 40.6 MPa. A summary of the measurement results is shown in Table I. Even after 72 h of string vibration, there was no significant changes of resonant profile of the string, which indicates that the change in mechanical properties of the polyimide string is minimal. The results have been compared with another stress measurement technique that measure the substrate bending due to the film stress. A commercially available measurement system, Flexus$^{\mathrm{TM}}$, was used to measure the residual stress of various polyimide films, and the residual stresses of PI-2555 and PI-2611 are 40 and 4.6 MPa, respectively. The measurement results were in good agreement with the conventional measurement apparatus (Table II). Also, since the measurement results for several strings with different lengths were relatively consistent, the measurement theory can be validated.

III. ADHESION STRENGTH MEASUREMENT USING SURFACE-MICROMACHINED STRING STRUCTURE

Another set of important mechanical properties of thin films is their adhesion properties in various situations. In a polymer-metal multilayer structure, a polyimide layer has interfaces with silicon substrates, various dielectric films, or metals, which requires good adhesion properties between these



string eq. 3-3
Monday, April 6, 1992 15:02
Front Panel

Amplitude 3.00
Low Frequency 13000
High Frequency 17000
Number of Steps 100
background - Freq. and Voltage 1.70E4 hz 1.97E-1 volts
With String - Freq and volt. 1.70E4 Hz 7.93E-2 volts
d-level 0.2
ba# iteration - background 2 2
st# iteration - string 2 2
rank 2

Cursor	X	Y	ΔX	ΔY
0 ○	20130	3.92E-2		
1 ☐	10650	2.23E-1	-9480.0	0.18

Cursor	X	Y	ΔX	ΔY
0 ○	15340.0	9.347E-1		
1 ☐	14440.0	8.920E-1	-900.00	-4.27E-2

Fig. 5. Actual output of transmission data (DuPont PI 2555). The string has 3 μm thickness, 30 μm width and 5.6 mm length. The observed resonance frequency is 15.2 kHz, resulting the residual stress of 40.6 Mpa. The density, ρ, used in calculation was 1.4 [1].

TABLE I
MEASURED RESONANT FREQUENCY AND RESIDUAL STRESS USING VARIOUS RESONANT STRING STRUCTURES

Polyimides	Length(m)	Resonant Frequency (Hz)	Residual Stress (Pa)
PI-2555	8.50E-03	1.02E+04	4.21E+07
PI-2555	1.00E-02	8.40E+03	3.95E+07
PI-2555	5.6E-3	1.52E+04	4.06E+07
PI-2611	5.6E-3	5.400E+03	5.121E+06
PI-2611	6.8E-3	4.152E+03	4.464E+06

TABLE II
COMPARISON OF MEASURED RESIDUAL STRESS WITH CONVENTIONAL METHOD

Polyimides	Flexus	Resonant String
PI-2555	40 MPa	41 MPa
PI-2611	4.6 MPa	4.75 MPa

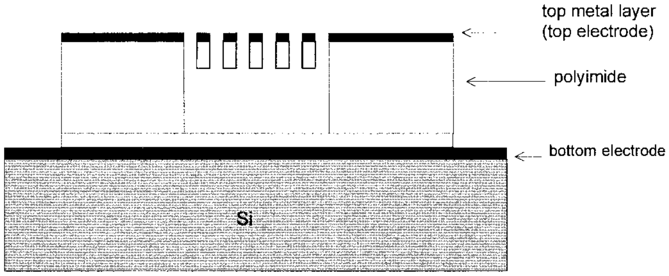


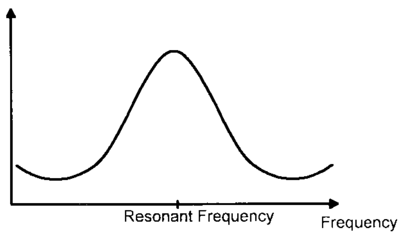
Fig. 6. Cross section of a string structure for adhesion property measurement. This will be excited by sinusoidal electrostatic force.

materials and polyimide films. Good adhesion is essential for the film to endure subsequent chemical and thermal processes and to guarantee stable operation of the completed devices after fabrication. Micromachining fabrication often requires thick polyimide film deposition and high aspect ratio metal structures, in which the adhesion property is even more important. Another difficult yet important quantity to measure is the long-term durability or reliability of the adhesion, especially in aggressive environments. Because the knowledge of adhesion durability is very important in the estimation of device reliability, especially in a microactuator or a microsensor where mechanical movement is inevitable, a measurement scheme which can produce a quantitative result is essential.

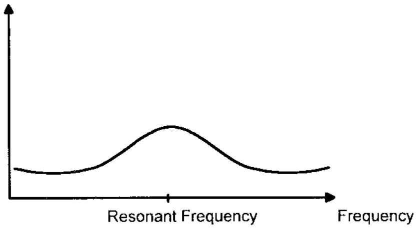
A string structure was designed and fabricated using a surface micromachining technique to measure the adhesion durability between a polyimide film and a metal layer. This structure is a vibrating bimorph strip consisting of polyimide with a metal layer on top, that vibrates with a sinusoidal electrostatic force. Fig. 6 shows a schematic of this string structure for adhesion durability measurement. This string will vibrate due to an alternating electric potential applied between the top and bottom electrodes.

A. Adhesion Durability Measurement Scheme

The bimorph string consists of two layers, a metal layer that will be used as an electrode, and a polyimide layer. An alternating electrostatic potential applied to the top and the bottom electrode can generate a vibration of the polyimide string. As



When t=0, relatively high Q-factor

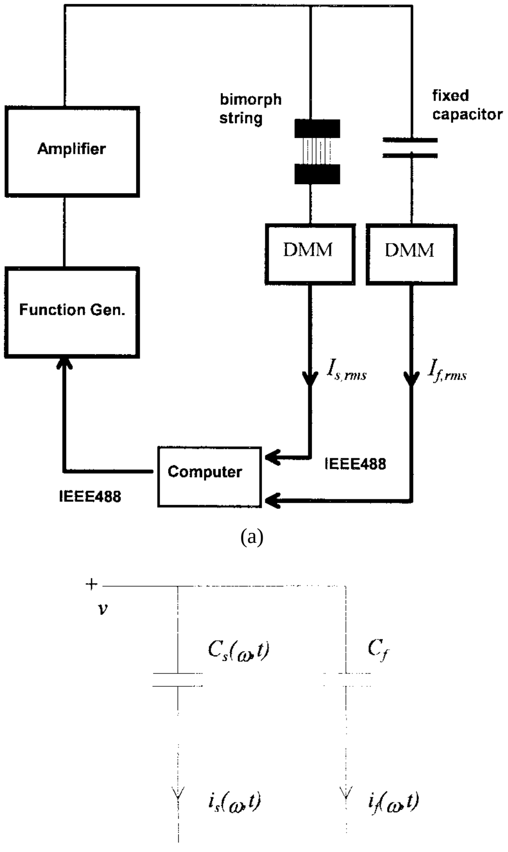


When t=T (T > 0), relatively low Q-factor

Fig. 7. Qualitative dependence of Q-factor of resonance on the adhesion of thin metal films to polyimide strings. Well-adhered films will have minimal interfacial dissipation and high-Q resonance characteristics. Poorly adhered films will have substantial interfacial dissipation and low Q resonance characteristics.

long as the adhesion between the metal and polyimide is good, the quality factor of the resonance will be relatively high, as shown in Fig. 7. If the adhesion between metal and polyimide begins to fail, substantial dissipation at the polyimide/metal interface will begin to occur, which can be thought of as energy dissipated by the two poorly adhered surfaces rubbing against each other. The result of this dissipation will be lowering the quality factor of resonance. The time for the adhesion to degrade to a certain quality factor can be related to the fatigue strength of the polymer/metal interfaces. The vibrating strings can be placed in aggressive environments to determine the effects of accelerated aging on adhesion. In this way, the durability of adhesion of various polyimide/metal interfaces can be determined. Since the particular structure of this set of surface micromachined string does not rely on adhesion of the string ends to a substrate (i.e., the string ends are "built in" to a "wall" of polyimide), and since the acoustically-vibrated polyimide strings described previously showed no change in vibration characteristics over adhesion measurement time scales, it is reasonable to attribute change in Q-factor of the vibrating bimorph to metal/polymer adhesion.

This bimorph string structure can be considered as a simple capacitor. Fig. 8 shows a measurement scheme with equivalent capacitors. It consists of two capacitors, a bimorph string and a fixed capacitor that can not vibrate with the external potential but has the same capacitance as the undeflected string. Fig. 9 shows a cross-section view of the vibrating string. The bimorph string has a bias potential such that the string has an initial deflection, a, as shown in Fig. 9, in order to keep the vibration of the string following a sinusoidal excitation potential. If there is no initial deflection, i.e., $a = 0$, then the string deflection profile will follow the absolute value of the sinusoidal excitation. If a is greater than the deflection amplitude, b, then the deflection profile can be expressed as a sinusoidal function, which will simplify the analysis, and prevent frequency doubling effects due to the always attractive nature of the electrostatic potential.



(a)

(b)

Fig. 8. (a) Measurement scheme with a string (C_s) and a fixed capacitor (C_f) (a) and (b) its equivalent circuit. The amplified currents are measured at each digital multi-meters (DMM) and the resulting RMS values will be fed into the computer. RMS current subtraction will be performed numerically by the computer.

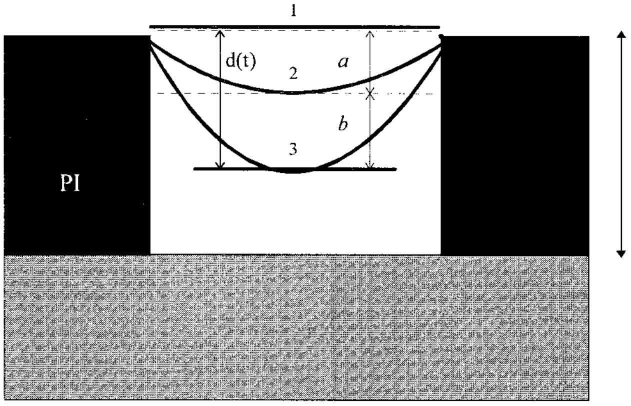


Fig. 9. Cross section of the vibrating strings. String #1 is the undeflected string, string #2 is the string deflected to "a" with a DC bias, and string #3 is the string deflected by the DC bias and AC execution.

Assuming the string is vibrating without bending, the deflection distance $d(t)$ between the string and the bottom electrode can be represented as

$$d(t) = a + b\sin(\omega t), \qquad a > b \tag{2}$$

where a represents the initial deflection due to the dc bias voltage and b is a function of the frequency which shows the deflection amplitude. A normalized deflection distance, $\xi(t) = (d(t)/d_0)$, can be represented as

$$\xi(t) = \frac{d(t)}{d_0} = \xi_0 + \lambda \sin(\omega t) \tag{3}$$

where d_0 is the distance between the undeflected string and the bottom electrode, $\xi_0 = (a/d_0)$ and $\lambda(\omega) = (b(\omega)/d_0)$.

Approximating the deflected string as a parallel plate, the string and the bottom electrode, the capacitance between the string and the bottom electrode can be represented as

$$C = \varepsilon \times \text{area/distance} = \frac{\varepsilon A}{d_0(1-\xi(t))} = C_0\left(\frac{1}{1-\xi(t)}\right) \tag{4}$$

where ε is the dielectric constant and C_0 is a constant capacitance of a capacitor with the string and the bottom electrode separated by d_0. If $\xi \ll 1$, assuming small deflection, then

$$\frac{1}{1-\xi} \approx 1 + \xi. \tag{5}$$

Thus the following approximation of the capacitance, C, can be used:

$$C_s = C_0(1 + \xi). \tag{6}$$

The currents through the vibrating string and the fixed capacitor, i_s and i_f, respectively, can be represented as

$$\begin{aligned} i_s(\omega, t) &= \frac{dC_s}{dt} \cdot v_{\text{ac}} + \frac{dv_{\text{ac}}}{dt} \cdot C_s \\ i_f(\omega, t) &= \frac{dv_{\text{ac}}}{dt} C_0 \end{aligned} \tag{7}$$

where C_s is the capacitance of the string varying with the external electric potential and v_{ac} is the external electric potential applied between the metal layer on the string and the bottom electrode, $v_{\text{ac}} = V_i + V_0 \sin(\omega t + \phi)$.

The RMS value of the string current $I_{s,\text{rms}}$ is

$$I_{\text{rms}} = \sqrt{\frac{\omega}{2\pi} \int_0^{2\pi/\omega} i^2 \, dt}$$

or

$$I_{s,\text{rms}} = \frac{C_0 V_0 \omega}{\sqrt{2}} \sqrt{\left(1 + \left(\frac{V_i}{V_0}\right)^2\right)\lambda^2 + (1 + \xi_0)^2}. \tag{8}$$

The current running through the fixed capacitor $I_{f,\text{rms}}$ can be represented as

$$I_{f,\text{rms}} = \frac{1}{\sqrt{2}} C_0 V_0 \omega. \tag{9}$$

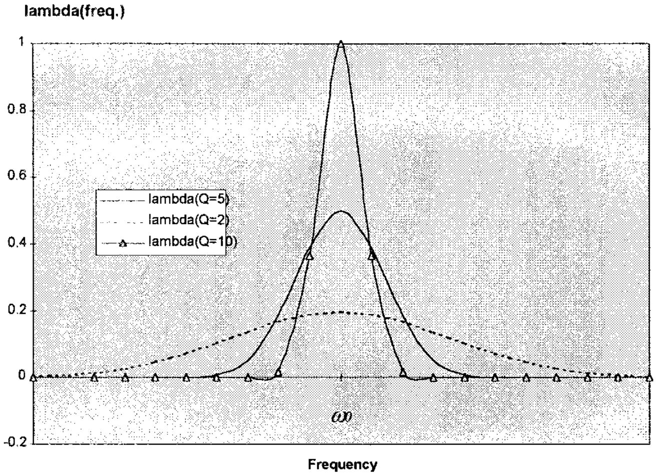


Fig. 10. A profile of the function λ as parameterized by Q.

Thus, the current difference can be represented as

$$\begin{aligned} &I_{s,\text{rms}} - I_{f,\text{rms}} \\ &\quad = \frac{C_0 V_0 \omega}{\sqrt{2}} \left(\sqrt{\left(1 + \left(\frac{V_i}{V_0}\right)^2\right)\lambda^2 + (1 + \xi_0)^2} - 1 \right). \end{aligned} \tag{10}$$

It is expected that the vibration amplitude of the string will be relatively large near resonance as compared to its off-resonance value. An arbitrary choice of λ which captures this behavior is made and is given by

$$\lambda(\omega, Q) = \lambda_0 Q \exp\left\{-Q^2\left(\frac{\omega - \omega_0}{\omega_0}\right)^2\right\} \tag{11}$$

where Q is the resonant Q-factor, λ_0 is the normalized deflection amplitude, and ω_0 is the resonant frequency. A profile of the function $\lambda(\omega, Q)$ with various Q is shown in Fig. 10. This function is symmetrical with the resonant frequency, ω_0, and its shape flattens as the Q-factor decreases.

B. Fabrication of a Surface Micromachined String Structure

Fig. 11 shows a simplified fabrication process for the adhesion measurement string structure. The fabrication begins with a $2''\langle 100\rangle$ silicon substrate with 5000 Å of SiO_2 on both sides. A layer of Ti/Au/Ti (500 Å/5000 Å/500 Å) is evaporated as a bottom metal layer (a). A thick polyimide layer, DuPont PI-2611 or PI-2555, is deposited using multiple coatings and cured in nitrogen at 350 °C for 1 h, which results in 10 μm thickness after the cure (b). The PI layer is etched using 100% O_2 RIE to make a mold for plating a Cu sacrificial layer. The Cu sacrificial layer is deposited using an electroplating technique (c). After depositing a 6-μm PI layer, 2000 Å of gold is deposited, and this layer will be used as a top electrode (d). The string pattern is defined using conventional photolithography techniques, and the gold mask is defined using a wet etching technique. The PI layer is etched in 100% O_2 RIE. The sacrificial metal layer is removed using a wet etching (e). Fig. 12 shows a fabricated string structure for adhesion durability test. The string array is 6 μm thick and

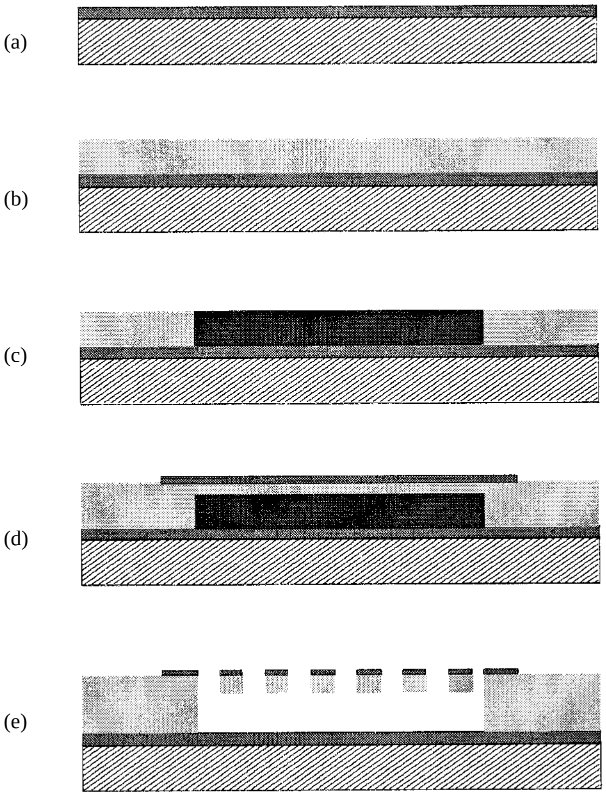


Fig. 11. Simplified fabrication steps. (a) Bottom metal layer (Au) on Si substrate. (b) PI deposition. (c) PI etching, sacrificial layer metal deposition (Cu). (d) PI for string, top metal layer deposition (Au). (e) String definition, sacrificial layer etching.

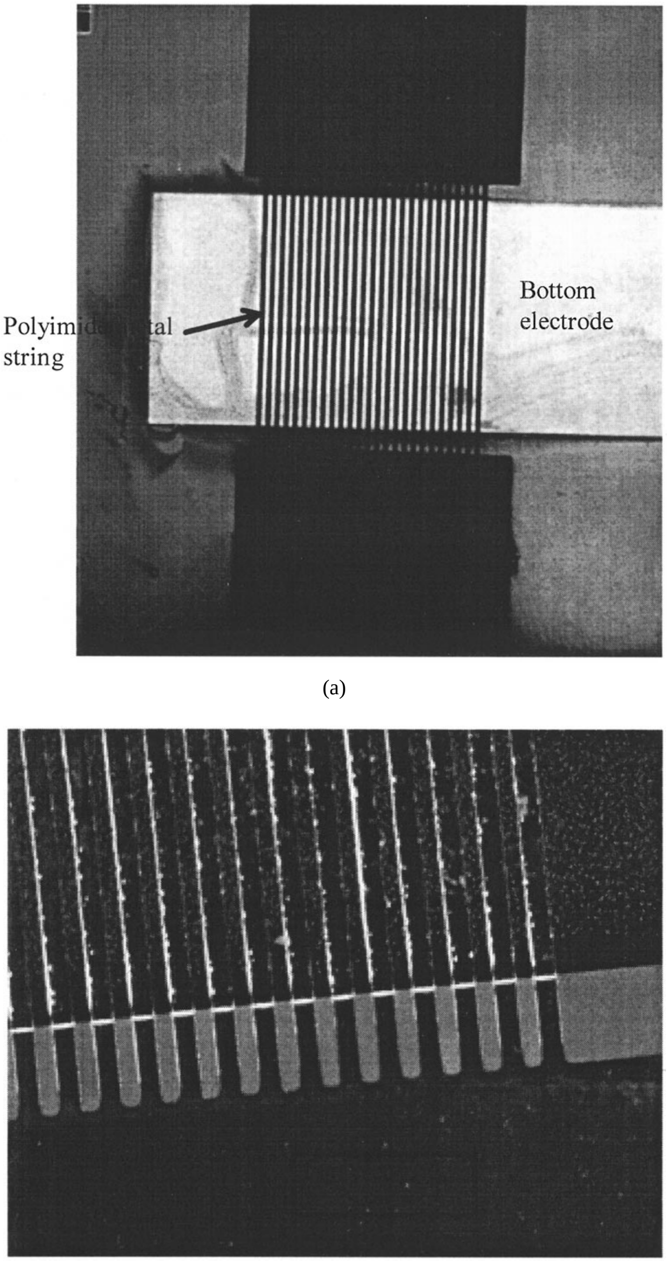
4.5 mm long, and it has a 2000 Å Au layer to be used as a top electrode.

C. Measurement and Results

After the fabrication was completed, the first measurement of the current flowing through the string as a function of frequency was performed over an appropriate frequency range. This allowed the establishment of a baseline Q against which subsequent degradation could be measured. This string was then connected to an alternating voltage source for 1/4 h, in ambient temperature and humidity. Conditions and the frequency behavior was re-measured. These vibration and subsequent measurements were repeated up to 32 h. Exponentially increasing vibration periods, such as, 1/4, 1/2, 1, 2, 4, 8, 16, and 32 h, between measurements were used. After measurements of $I_{s,\text{rms}}$ and $I_{f,\text{rms}}$, the current difference, $I_{\text{measured}} = I_{s,\text{rms}} - I_{f,\text{rms}}$, was calculated. Using these current difference values at each frequency, $\lambda_{\text{measured}}$ was calculated using

$$\lambda_{\text{measured}} = \sqrt{\frac{V_0^2}{V_i^2 + V_0^2}} \cdot \sqrt{\left(\frac{\sqrt{2} \cdot I_{\text{measured}}}{C_0 V_0 \omega} + 1\right)^2 - (1 + \xi_0)^2} \qquad (12)$$

and resulting $\lambda_{\text{measured}}$ has been fitted into a λ function to estimate the resonant Q-factor. Since C_0 and V_0 are known, ξ_0 is the only value to be determined in (12). This value can be determined by an estimation far above resonance using (8) by setting the deflection amplitude, $\lambda = 0$.



(a)

(b)

Fig. 12. A surface micromachined string structure to measure the adhesion property.

Fig. 13 shows the change of $\lambda_{\text{measured}}$ in (12) after the fabrication, after 8 h of vibration, and after 16 h of vibration. As the vibration cycle increases, the output shows the change in the resonant profile, Q-factor and resonant frequency. The measured resonant frequency was 7.2 kHz, which is slightly higher than expected. This can be explained as the effect of metal layer evaporated on the top of the polyimide string. In order to quantitatively determine the

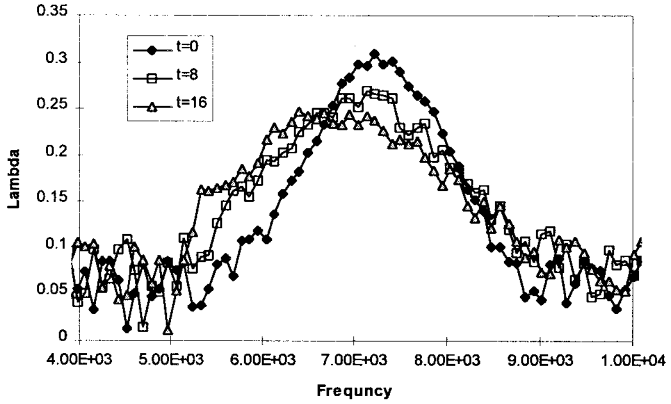


Fig. 13. Output ($\lambda_{\text{measured}}$) of the string measurement after 0, 8, and 16 h of vibrations. As the vibration duration increases, the changes in the resonant frequency and Q-factor have been shown.

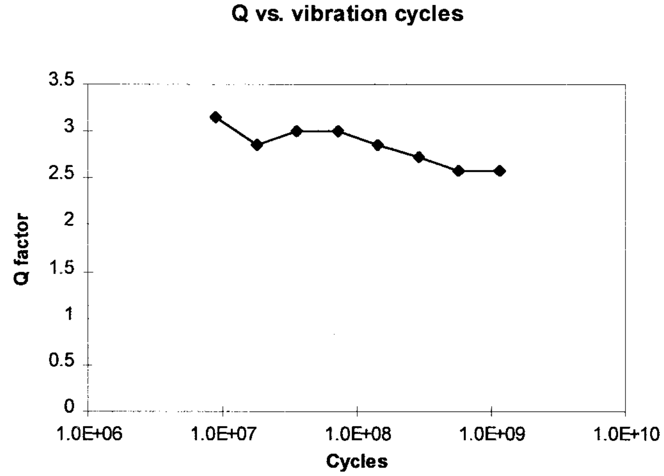


Fig. 14. Change of Q-factors with vibration cycles.

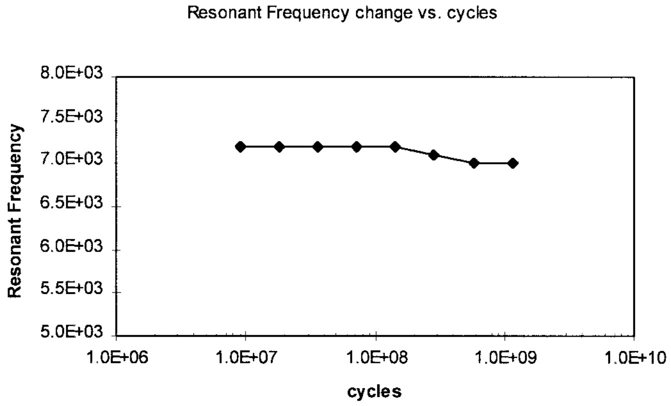


Fig. 15. Change of the resonant frequency with vibration cycles.

Q-factor, a least squares fit of (11) to the data of Fig. 13 was performed. Fig. 14 shows a typical degradation of Q-factors with increasing vibration cycles. After 8 h of vibration, approximately 2×10^8 cycles, Q-factor changes from 3 to 2.4 have been observed. Degraded adhesion due to string vibration also changes the resonant frequency of the bimorph string. Fig. 15 shows the change of resonant frequency with various vibration cycles. After 16 h of vibration, approximately 5×10^8 cycles, a 2.8% change in resonant frequency, has been observed.

To verify the theory, the estimation of the string deflection due to the external alternating electric potential was needed. The estimated value of normalized initial deflection, ξ_0, was 0.08, which confirms the small deflection assumption. It is possible that the string deflection, λ, can exceed the initial deflection, ξ_0, at resonance. Since the major point of interest of this scheme is the relative degradation of resonant profile, not the exact value of the Q-factor near the resonant frequency, it is believed that this small deviation from the theory does not have a notable effect on the overall performance of the proposed adhesion measurement scheme, and in any event can be avoided by increasing the DC bias.

IV. CONCLUSION

An *in situ* measurement scheme for measuring residual stress of a polyimide film has been developed and tested. This scheme uses a resonant string structure and Rayleigh's method. The polyimide string on a silicon wafer was fabricated using a bulk micromachining technique and vibrated with the incident acoustic waves. Since a string structure is a simple mechanical member, a simple calculation was used to relate the measured resonant frequency to the residual stress of the polyimide film. Two types of polyimide, DuPont PI-2611 and PI-2555 were used for this measurement and their residual stresses have been measured using various string structures, and these results were in good agreement with previously reported measurement results. Even though this scheme has been demonstrated with polyimide films, this scheme can be applied to any film with tensile stress.

A scheme to measure the adhesion durability between a metal layer and a polyimide film has also been demonstrated. This string structure was fabricated with various polymer/metal multilayer techniques combined with a surface micromachining technique to realize an air gap between the polyimide string and the bottom electrode. As a sacrificial layer, an electroplated Cu layer was used. As the polyimide/metal bimorph string vibrates with alternating electric potential between the top and the bottom electrode, the adhesion in the metal/polyimide interface starts to degrade, and its resonant profile starts to degrade also. By monitoring this degradation of the resonant profile and relating it to the vibration periods, the adhesion durability of a metal/polyimide interface can be determined. This new measurement scheme has been demonstrated with several bimorph string structures of Au/polyimide, and their reproducible measurement results had been presented. After 10^8 cycles of vibration in room temperature, notable changes in resonant Q-factor and the resonant frequency have been observed. Even though a string structure was used as a demonstration, this technique can be used with other mechanical structures, such as cantilever beams or movable plates, which can vibrate with an alternating electric potential.

ACKNOWLEDGMENT

The authors would like to thank C. Ahn, University of Cincinnati, for valuable technical discussions, Dr. K. Martin for the mask fabrication, and the MiRC staff for their assistance.

REFERENCES

[1] S. D. Senturia, "Can we design microbotic devices without knowing the mechanical properties of materials?," in *Proc. IEEE Micro Robots Teleop. Workshop*, Nov. 1987, pp. 3/1-5.

[2] W. D. Nix, "Mechanical properties of thin films," *Metallurgical Trans. A*, vol. 20A, pp. 2217–2245, Nov. 1989.

[3] M. G. Allen, M. Mehregany, R. T. Howe, and S. D. Senturia, "Microfabricated structures for the *in situ* measurement of residual stress, Young's modulus, and ultimate strain of thin films," *Appl. Phys. Lett.*, vol. 51, no. 4, pp. 241–243, July 1987.

[4] Y. W. Kim and M. G. Allen, "Surface micromachined platforms using electroplated sacrificial layers," in *Proc. Transducers '91, Int. Conf. Solid-State Sens. Act.*, 1991, pp. 651-654.

[5] R. T. Howe and R. S. Muller, "Stress in polycrystalline and amorphous silicon thin films," *J. Appl. Phys.*, vol. 54, pp. 4674–4675, 1983.

[6] H. Guckel, T. Randazzo, and D. W. Burns, "A simple technique for the determination of mechanical strain in thin films with application to polysilicon," *J. Appl. Phys.*, vol. 57, pp. 1671–1675, 1985.

[7] Cloud *et al.*, "Processing and Performance of gold MCM's," *IEEE Trans. Comp., Hybrids, Manufact. Technol.*, vol. 16, pp. 724–730, Nov. 1993.

[8] K. E. Petersen and C. R. Guarnieri, "Young's modulus measurements of thin films using micromechanics," *J. Appl. Phys.*, vol. 50, no. 11, pp. 6761–6766, Nov. 1979.

[9] Timoshenko and D. H. Young, *Vibration Problems in Engineering*, 3rd ed. New York: Van Nostrand, 1955.

[10] C. M. Harris, *Shock and Vibration Handbook*, 3rd ed. New York: McGraw-Hill, 1988.

Yong-Jun Kim received the B.Eng. degree in electrical engineering from Yonsei University, Seoul, Korea, in 1987, the M.S. degree in electrical and computer engineering from the University of Missouri, Columbia, in 1989, and the Ph.D. degree in electrical and computer engineering from the Georgia Institute of Technology, Atlanta, in 1997. During his graduate study, his research in micromachining includes thin film *in situ* measurement technique development, integrated inductors and their applications, and inductors for high frequency applications.

Since 1996, he has been with Samsung Electronics Company, Ltd., Suwon City, Korea, and is conducting research of micromachining application to RF devices. His current research interests include the general areas of microelectromechanical systems (MEMS), integrated inductive components and their application, applications of micromachining techniques to packaging or multichip modules, and integrated passives for RF or microwave applications.

Mark G. Allen (M'89) received the B.A. degree in chemistry, the B.S.E. degree in chemical engineering, and the B.S.E. degree in electrical engineering, all from the University of Pennsylvania, Philadelphia, in 1984, and the M.S. and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, in 1986 and 1989, respectively.

Since 1989, he has been with the Georgia Institute of Technology, Atlanta, where he is currently Associate Professor. His research interests include micromachining fabrication technology, magnetic micromachined devices, fluid mechanics applications of micromachined devices, and materials issues in micromachined structures and electronic packages.

Dr. Allen was Co-Chairman of the 1996 IEEE Microelectromechanical Systems (MEMS) Conference. He is a member of the IEEE Electron Devices Society Advisory Committee on MEMS and the Editorial Board of the *Journal of Micromechanics and Microengineering*.