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IN-SITU STRAIN MONITORING OF MICROMACHINED PARYLENE SPRING FOR FATIGUE TEST

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ABSTRACT

We report the development of a novel in-situ strain-monitoring device for fatigue test of micro parylene springs. Pendulum structures with parylene high-aspect-ratio beams are successfully integrated with an array of detectors using photointerrupters. We demonstrate on-line strain monitoring up to 10^7 cycles, and prove no degradation of mechanical characteristics of the parylene springs. Temperature effect on the mechanical response of parylene springs is also examined. It is found that all the parylene materials examined have the same temperature coefficient of the Young's modulus, and are mechanically stable up to 120 °C.

Keywords: polymer spring, parylene, fatigue test, strain monitoring

1. INTRODUCTION

Parylene is a promising MEMS material for flexible spring applications due to its low Young's modulus and robustness [1]. In our previous reports [2, 3], we successfully develop parylene-C high-aspect-ratio springs, and realize resonant frequency below 100Hz and in-plane displacement over 1 mm. However, little knowledge has been accumulated for fatigue strength of parylene.

In previous studies, it is found that the fatigue property of polymers depends on the crystallinity. The molecular weight of polymer is decreased before any macroscopic change of the material appears, followed by initiation and propagation of cracks [4-6]. The final goal of the present study is to predict fatigue limit of parylene springs under various operation conditions.

Figure 1 shows the molecular structures of parylene. Since parylene-C is decomposed at higher temperature above 100 °C by the reaction with oxygen, high-thermally-stable grade of parylene, diX-SR/HR (Kisco) is also attractive. It is claimed that, whereas the tensile strength of parylene-C is rapidly reduced at 140 °C, that of diX-SR/HR is almost unchanged up to 300 hours [7]. Suzuki & Tai [2] examined the temperature coefficient of the Young's modulus (TCY) of parylene-C, and found that it is constant at 0.6 %/°C between 20-80 °C. However, TCYs of parylene-C and diX-SR/HR at higher temperature remain unknown.

The objectives of the present study are to develop a versatile method for in-situ strain monitoring of micro springs, and to examine fatigue characteristics of the paryelne springs under various temperature conditions.

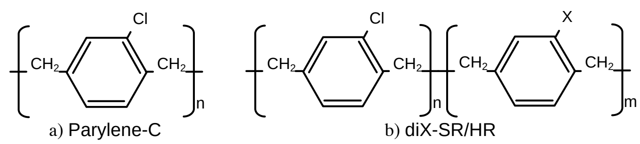

Fig. 1. Parylene molecular structure. a) Parylene-C, b) High thermally-stable grade of parylene, diX-SR/HR [7].

2. EXPERIMENTAL

In the present study, strain in parylene springs is imposed by vibration of the micro pendulum structures. Figure 2 shows the schematic of the present measurement set-up. Micro-machined pendulums with a parylene beam are fixed on an electromagnetic shaker, where sinusoidal oscillation is applied at a given frequency. Amplitude of each pendulum is measured with photo-interrupters, and the strain of the pendulums is estimated on-line. Any mechanical degradation results in changes of amplitude. Four pendulums with different lengths are integrated on a single chip, so that fatigue tests under four different strain conditions can be made simultaneously. Air temperature inside the fixture is measured with a thermocouple, and kept constant with a heater.

Figure 3 shows the fabrication process for the pendulum structures with free-standing high-aspect-ratio parylene beams [2]. The process start with patterning of 2 μm-thick thermal oxide on a 4" Si wafer. 380-μm-deep trenches are etched into the substrate with DRIE (Fig. 3b). The trenches also define the boundaries of the Si islands to be left. Next, 20-μm-thick parylene is deposited to refill the trenches (Fig. 3d). The parylene film is then etched back using O_2 plasma. After a second deposition of parylene, metal mask is evaporated and patterned (Fig. 3e). After patterning of the parylene film, Si substrate surrounding the springs is etched away with XeF_2 to release the pendulum structures (Fig. 3h).

Figure 4 shows photos of the test structures. Beam width of the pendulums is 30 μm and the beam length *L* is 3, 2.95 2.9, and 2.85 mm. When the beam is bending, the maximum strain occurs at the beam junction.

Figure 5a shows a snap shot of the parylene pendulums. Amplitude of the mass is chosen larger than the side of the mass, so that one on/off signal is obtained at each cycle. The transit-time of the mass through the photointerrupter is monitored with a digital oscilloscope, and immediately converted to the maximum strain of each beam and recorded continuously (Fig. 5c).

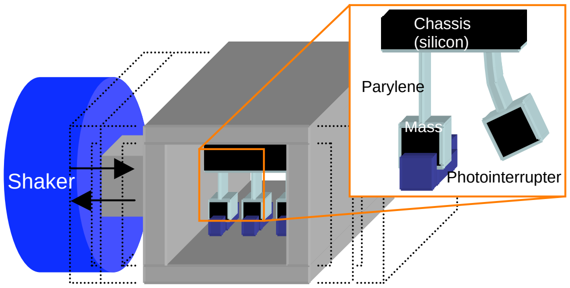

Fig 2. Fatigue test set-up with on-line strain monitoring. Micromachined parylene pendulums are mounted on an electromagnetic shaker. Photo-interrupters mounted on the fixture are employed for amplitude measurement. Air temperature inside the fixture is regulated by a heater.

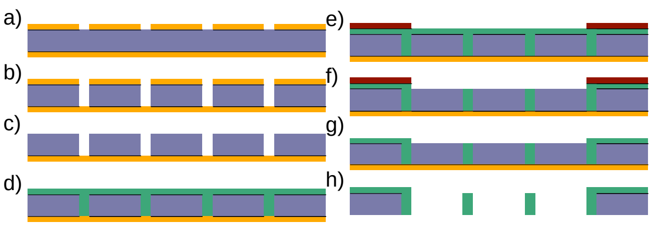

Fig. 3. Process flow. a) Patterning of thermal oxide with BHF, b) Etch trench by Deep RIE, c) Strip top SiO2, d) Parylene deposition, e) Metal mask patterning, f) Parylene etch-back with O_2 plasma, g) Strip metal mask, h) Bulk silicon etching with XeF_2 and release structures.

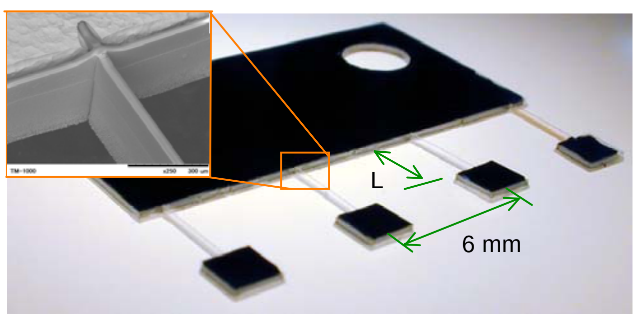

Fig. 4. Test chip with 4 pendulums. Parylene-C beam width is 30 μm. Beam lengths from left to right are 3.00, 2.95, 2.90 and 2.85 mm. Dimension of the mass is 1.5 mm x 1.5 mm. The inset is a SEM image of the beam junction.

3. RESULTS AND DISCUSSION

Figure 6 shows the frequency response of the parylene pendulums near their resonant frequencies. Oscillation frequency is chosen in such a way that the amplitudes of all the pendulums are large enough to be measured with the photodetectors. In this particular sample, amplitude of the 2.9 mm pendulum is too low. This is probably because there is residue of Si on the beam. Amplitudes at the 60 Hz for 3, 2.95 and 2.85 mm pendulums are respectively 2.17, 1.71 and 1.23 mm.

Since amplitude of the pendulums is very large, the strain becomes a nonlinear function of the stress [8] as shown in Fig. 7. At 60 Hz, strain for the 3, 2.95 and 2.85 mm pendulums is respectively 0.58, 0.46 and 0.35%, which is smaller than the yield strain of parylene-C (3%).

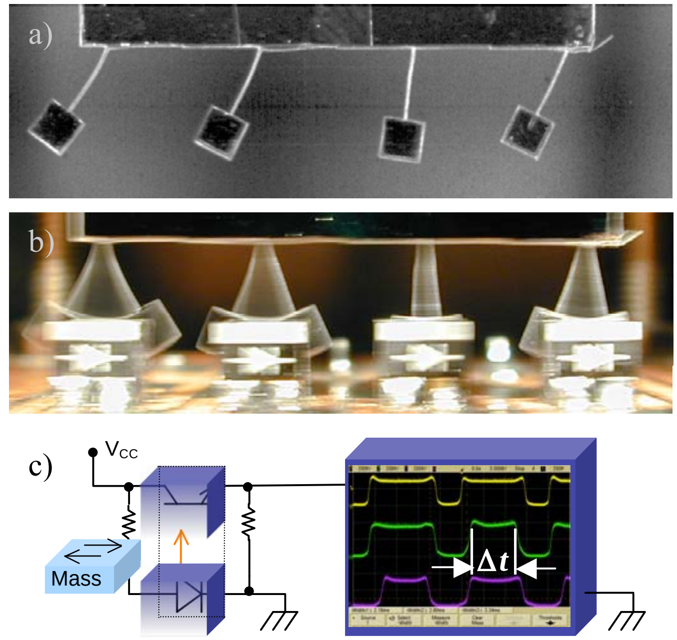

Fig. 5. Parylene-C pendulum structures in motion at 60 Hz. External amplitude of the shaker is 0.6 mm_{p-p}. a) Snap shot, b) Long-exposure photo with the photodetectors, of which spot diameter is 0.15 mm. Amplitude and strain of pendulums are computed based on the transit-time Δt. c) Read-out circuit with the photointerrupters and output signals taken with an oscilloscope.

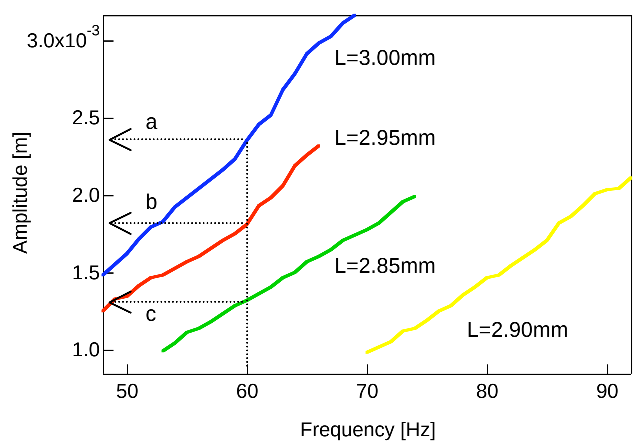

Fig. 6. Frequency response of parylene-C pendulums measured with the photointerrupters at a large external amplitude of 0.6mm_{p-p}. Amplitudes at 60 Hz oscillation for the 3, 2.95 and 2.85 mm pendulums are respectively a) 2.17, b) 1.71 and c) 1.23 mm.

Figure 8 shows the strain under cyclic loads up to 10^7 cycles at constant room temperature of 27 °C. No apparent change of the strain is found for all the pendulums examined. For bulk polymers, 10^7 cyclic loads are large enough to lead mechanical degradation, if the strain is larger than the fatigue limit [4]. Therefore, it is conjectured that the fatigue limit of parylene-C beams is higher than 0.58%.

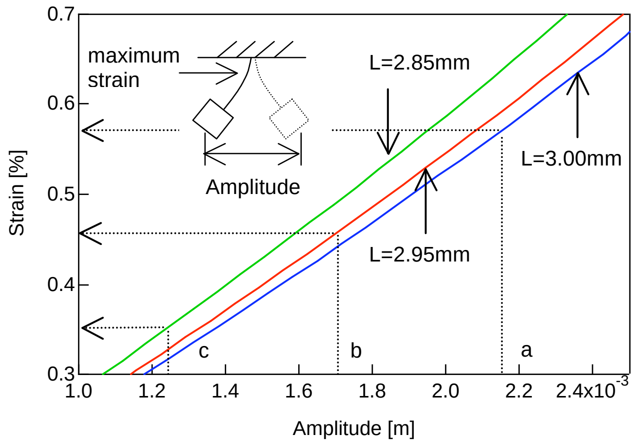

Fig. 7. Maximum strain at the beam junction versus amplitude. Strain is calculated with a nonlinear equation for large deformation of beams [9]. Amplitudes of the pendulums at 60 Hz shown in Fig. 6 respectively correspond to the strain of a) 0.58 %, b) 0.46 % and c) 0.35 %.

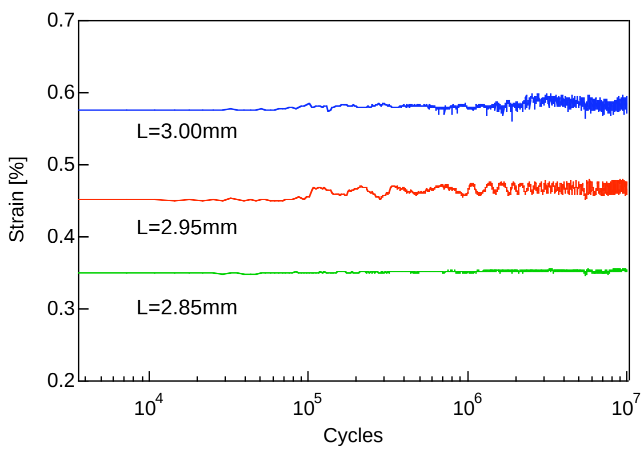

Fig. 8. Experimental results for the fatigue test of parylene-C at room temperature. Strain of the pendulum structures versus cycles up to 10^7, where no change in strain is observed for all the pendulums.

As mentioned above, thermal stability is important for applications such as automotive ones. Table 1 shows the tensile strength of parylene-C, diX-SR and diX-HR for thermal annealing at 140 °C [7]. It is clear that diX-SR/HR have much more tolerant than parylene-C. Note that diX-SR/HR are also compatible with Pb-free soldering. In addition, unlike fluorinated parylene (e.g., parylene-AF4), their deposition rate is as fast as that of parylene-C.

Table 1. Thermal stability of parylene at 140 °C [7]

Annealing Time [hour]	Tensile Strength [MPa]		
	Parylene-C	diX-SR	diX-HR
0	58.8	54.8	52.7
25	64.2	67.2	70.2
50	41.5	72.4	72.4
100	19.3	77.2	68.0
200	6.4	79.0	74.3
300	0	72.0	60.9
400	0	62.5	63.0
500	0	51.9	32.8

Figure 9 shows frequency response of the 3.85 mm-long parylene-C beam for different temperature of 40~80 °C. In this figure, the transit-time is plotted versus the oscillation frequency, where the least transit-time peak (the largest amplitude) corresponds to the resonant frequency at each temperature.

Pendulum structures using diX-SR/HR are also microfabricated using the same process for parylene-C beams. Figure 10 shows the resonant frequency for three different materials. It is clearly shown that the resonant frequency for all the parylene materials decreases with increasing temperature. Since the spring constant is proportional to the square root of the resonant frequency, the temperature coefficient of Young's modulus (TCY) can be readily obtained with these data. It is noted that, although the glass transition temperature of parylene is below 100 °C [9, 10], no apparent thermal hysteresis has been found; after ramping up the sample temperature, the resonant frequency goes back to its original value when it is cooled down to the room temperature.

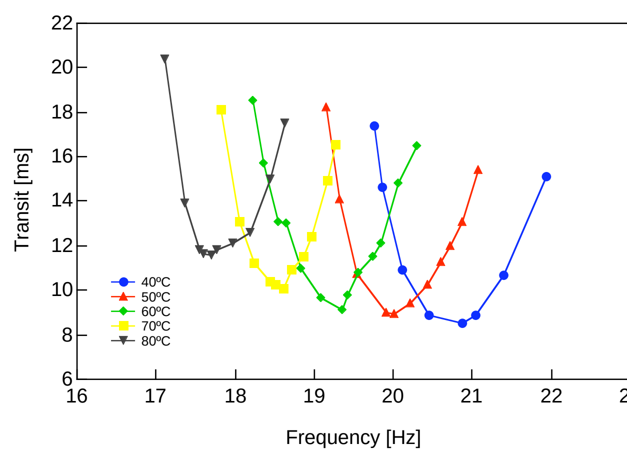

Fig. 9. Frequency response of parylene-C shown by transit-time in temperature change of 40~80°C. Each curve was taken at different temperature. Resonant frequency corresponds to a point of a minimum transit-time.

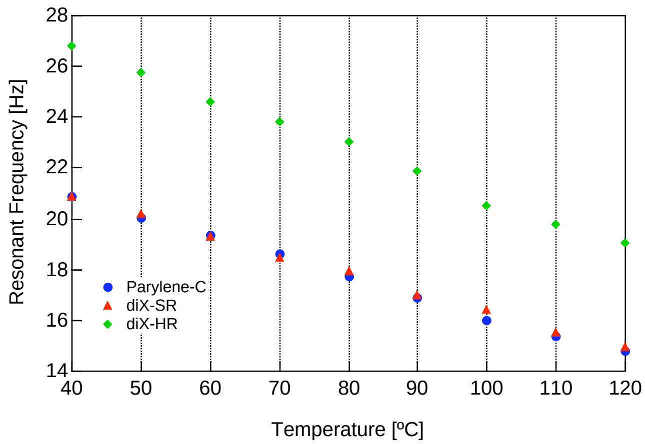

Fig. 10. Resonant frequency for parylene-C, diX-SR and diX-HR versus temperature. The sample temperature was changed upward for each material.

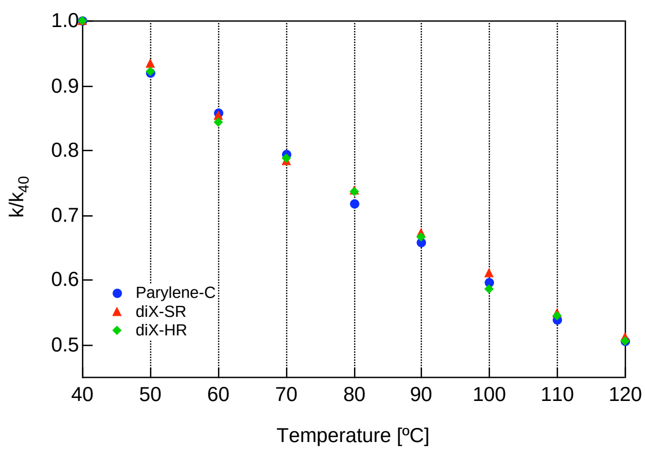

Fig. 11. Spring constant normalized with the value at 40 ℃. Three different parylene materials have the same temperature coefficient of the Young's modulus up to 120 ℃.

In order to compare TCYs for the different materials, the spring constant was normalized with the value at 40 °C. Figure 11 shows the normalized spring constant versus the temperature. It is found that the TCY for all the materials is 0.6 %/°C, which is the same as the value previously reported [2].

4. CONCLUSION

In conclusion, we propose a novel in-situ strain-monitoring device for fatigue test of parylene high-aspect-ratio springs. We successfully measure the strain of parylene beams under cyclic load, and prove that no degradation occurs for the 0.58% strain. In addition, temperature effect on the mechanical response for different parylene grades is examined. It was found that temperature coefficient of the Young's modulus of diX-SR/HR is 0.6%/°C , which is the same as that of parylene-C at least below 120 °C. No short-term degradation nor thermal hysteresis is found for all the materials tested.

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