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MECHANICAL RESPONSE EVALUATION OF HIGH-THERMALLY-STABLE-GRADE PARYLENE SPRING

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ABSTRACT

Mechanical response of high-thermally-stable-grade parylene (diX-SR/HR) is investigated for flexible spring applications. Pendulum structures with a high-aspect-ratio beam are microfabricated using different parylene materials, and their amplitude and stress at resonant oscillation are measured. Based on fatigue tests and measurements of the temperature coefficient of Young's modulus, MEMS structures with diX-SR/HR are proved to have better thermal tolerance than parylene-C, while they have almost the same mechanical properties as parylene-C.

INTRODUCTION

Parylene (poly-para-xylylene) is a MEMS-compatible polymer with favorable physical properties, and used for various applications [1-5]. Especially, parylene-C has good mechanical properties such as low Young's modulus and large yield strain [6, 7]. Suzuki & Tai [8] develop a microfabrication technology for high-aspect-ratio parylene-C beams, and realize spring structures with low resonant frequency and large oscillation amplitude.

However, the glass transition temperature T_g of parylene-C is around 50 ºC [9], and parylene-C degrades in oxygen environment for temperature above 100 ºC. Thus, the continuous service temperature of parylene-C is 80 ºC, which is lower than the requirement for applications such as automotive ones. Rapid thermal cycling beyond T_g may also causes reliability issues due to tensile stress build-up [10]. Fluorinated parylene, i.e., parylene-AF4 or parylene-HT [11] has excellent thermal stability, but its elongation to break is much smaller than that of parylene-C [6].

Recently, diX-SR/HR, high-thermally-stable grades of parylene, are released by KISCO. It is reported that diX-SR/HR bulk films have similar mechanical properties with parylene-C, while their tensile strength is almost unchanged even at 140 ºC for 400 hours.

Fatigue is also important issue to be considered for MEMS springs/structural members. For instance, springs used for vibration-driven energy harvesting devices [12] will experience up to 10^{10} cycle oscillations during its lifetime. Unlike metals, fatigue process of polymer is complicated; their degradation mechanisms include scission of molecular chains and partial re-crystallization [13-15]. Thus, experimental evaluation for the fatigue characteristics is also necessary.

In the present study, MEMS-compatibility of diX-SR/HR is investigated. In addition, the mechanical properties of MEMS springs including long-term stability and thermal coefficient of Young's modulus (TCY) are examined in a series of experiments.

DESIGN AND MICROFABRICATION

In order to evaluate diX-SR/HR, we adopt micro pendulum structures supported with a high-aspect-ratio parylene spring [8]. Figure 1 shows the schematic of the present measurement method. Micromachined pendulums with a parylene beam are fixed on an electromagnetic shaker, where sinusoidal oscillation is applied at a given frequency. Strain in the parylene beams is imposed by vibration of the pendulum. Amplitude of each pendulum is measured with photointerrupters, and the strain is estimated on-line. Any mechanical degradation results in changes of the amplitude. Since four pendulums with different beam lengths are integrated on a single chip, mechanical response tests with four different values of strain can be made simultaneously.

Figure 2 shows the fabrication process. The process starts with DRIE of 350-μm-deep trenches using a 1.5-μm-thick SiO_2 mask (Figs. 2a-c). The trenches also define the boundaries of the Si islands to be left. Next, the trenches are filled with parylene (Fig. 2d). The deposition condition of diX-SR/HR is the same as that of parylene-C; the pyrolysis temperature and the deposition pressure are respectively 690 ºC and 20 mTorr. Deposition rate of diX-SR/HR with this setting is the same as that of parlene-C. After the parylene deposition, the metal mask is patterned (Fig. 2e) followed by O_2 plasma etch of the parylene film (Fig. 2f). After stripping the metal mask (Fig. 2g), Si substrate surrounding the beams is etched away with XeF_2 to release the pendulum structures (Fig. 2h).

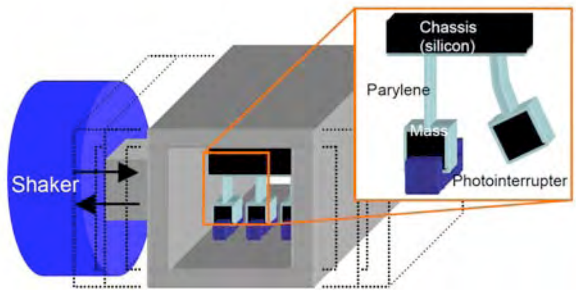

Figure 1: Measurement set-up with on-line strain monitoring.

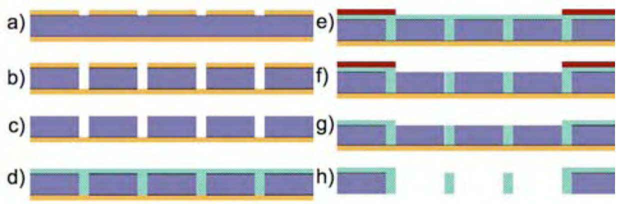

Figure 2: Process flow of parylene high-aspect-ratio springs.

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RESULT AND DISCUSSION

Figure 3 shows photos of the microfabricated parylene pendulums. Beam width and length of the pendulums are respectively 30 µm and 3.85~4.0 mm. Designed value of the resonant frequency is about 30Hz for 3 mm_{p-p} oscillation. The maximum stress of the parylene beam under deflection is located at the fixed end of the beam.

Firstly, thermal tolerance of parylene-C and diX-HR/SR is examined. Figure 4 shows the parylene pendulum structures after thermal annealing at 140 ºC for 5 hours. As clearly seen, little deformation is found in the diX-HR beams, whereas the parylene-C beams are significantly deformed due to thermal softening. Thus, it is confirmed that diX-HR MEMS structures have higher thermal tolerance than parylene-C.

Figure 5 shows the experimental setup for oscillation tests. A test fixture is mounted on an electromagnetic shaker. This system allows simultaneous examination of four test chips including 16 pendulum structures. Air temperature inside the fixture is measured with a thermocouple, and kept constant with a heater.

Figures 6a and 6b show a long-time exposure photo and a snap shot of the parylene pendulums at the resonance. The transit time Δt, in which the mass goes through the photointerrupter, is monitored with a digital oscilloscope, and stored onto a PC (Fig. 6c).

With the oscillation frequency imposed and the measurement data of transit time, the amplitude of pendulums is computed. However, under the present experimental conditions, the beam deflection is very large, so that the conventional linear beam model cannot be used to estimate the strain from the amplitude. We employ a non-linear model [16, 17] including axial elongation of the beam. Figure 7 shows the maximum strain thus obtained, which is located at the fixed end of the beam, in comparison with the stain computed from high-speed camera images of the pendulums. Since the maximum strain estimated from the transit time measurement is in good agreement with the results of the optical measurement, accuracy of the amplitude measurement using the photointerrupter is confirmed. Note that, as also shown in Fig. 7, the linear

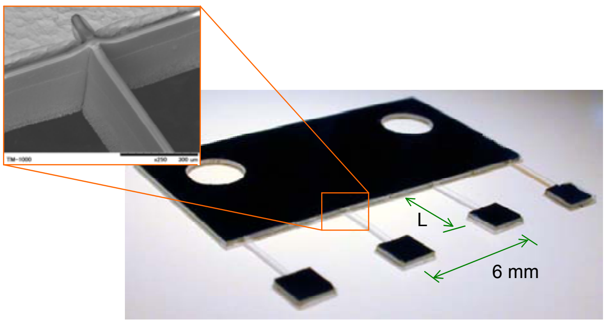

Figure 3: Test chip with 4 pendulums. Parylene beam width is 30 µm. Beam lengths (L) from left to right are 4.0, 3.95, 3.9 and 3.85 mm. Dimension of the mass is 2.0 mm × 2.0 mm. The inset is a SEM image of the beam junction.

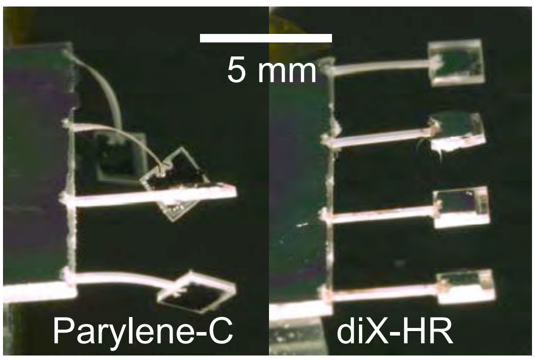

Figure 4: Free-standing parylene-C (left) and diX-HR (right) beams after thermal annealing at 140 ºC for 5 hours. Beam width and height are respectively 30 µm and 350 µm.

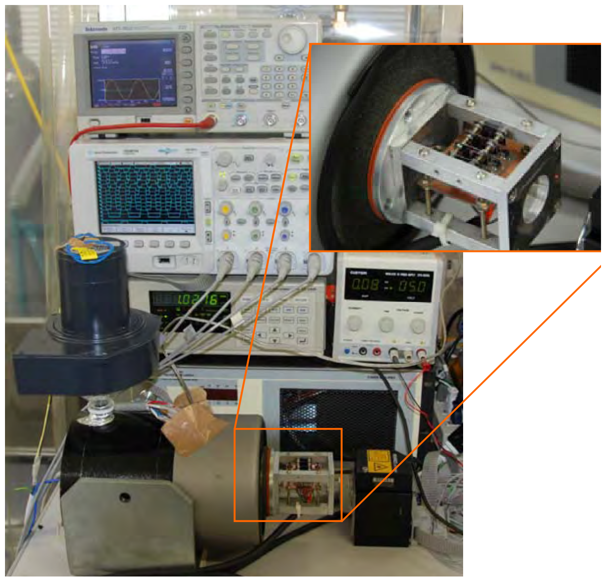

Figure 5: Experimental setup for oscillation tests.

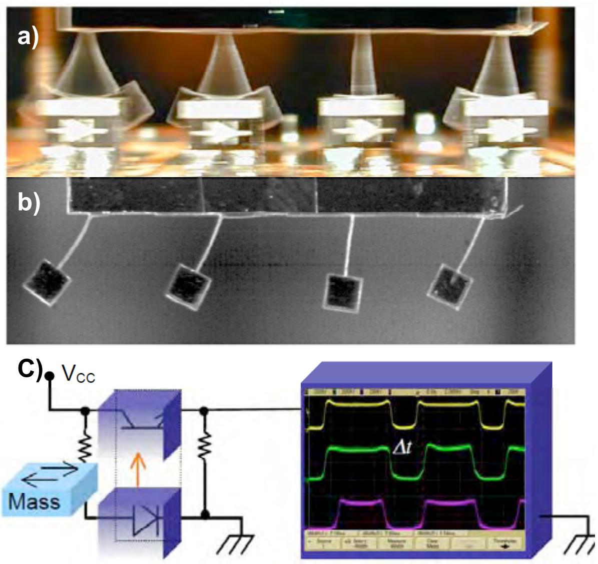

Figure 6: Parylene pendulum structures in resonance at 60 Hz. a)Long-exposure photo, b) Snap shot, c) Read-out circuit with the photointerrupters and output signals taken with a digital oscilloscope.

model considerably underestimates the strain for small transit time, where the amplitude and the maximum strain are both large.

Fatigue characteristics of the parylene beams at room temperature are examined through cyclic load tests, in which the inertia force of the pendulums is kept constant. The strain is monitored by the measurement of transit time as explained above. Since typical strain expected in actual device such as seismic generators [12] is as large as 1%, the maximum strain is set to about 0.4 and 1 %. Since the yield strain of the parylenes is 3 % [6], the maximum strain imposed to the fixed end of the beam is about one third of the yield strain. Figure 8 shows the strain versus the number of cycles. The strain for parylene-C and diX-HR is almost constant without any sudden change up to 10^7 cycles, indicating no mechanical degradation occurs during the test. Therefore, both parylene materials have comparable mechanical durability, although the number of cycles tested is much smaller than the requirement in real applications. Note that the strain slightly varies in time due to the temperature change of specimen.

As mentioned earlier, diX-HR has higher annealing tolerance if compared with parylene-C. We also examine their mechanical properties under different temperature conditions. Figure 9 shows the transit time versus the oscillation frequency for different temperature. External amplitude is kept constant. The valley of each curve corresponds to the resonant frequency at the temperature. Shift in the resonant frequency is due to thermal softening of parylenes, which is represented with the temperature coefficient of Young's modulus (TCY).

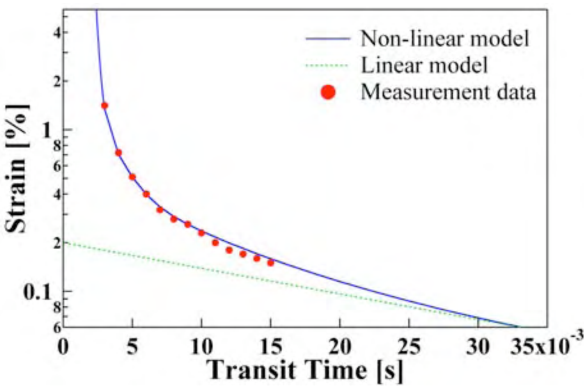

Figure 7: Comparison of the maximum strain at the point of maximum stress on deflecting beams. Beam length is 4 mm and oscillation frequency is 30 Hz.

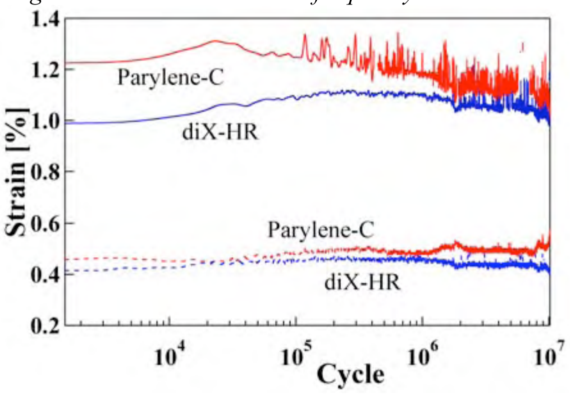

Figure 8: Experimental results for the cyclic load tests of parylene-C/diX-HR beams.

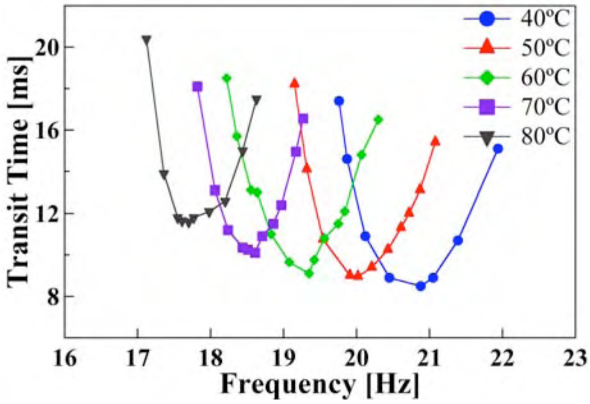

Figure 9: Frequency response of parylene-C pendulums for different temperatures. The minimum transit time of each curve corresponds to the resonant frequency.

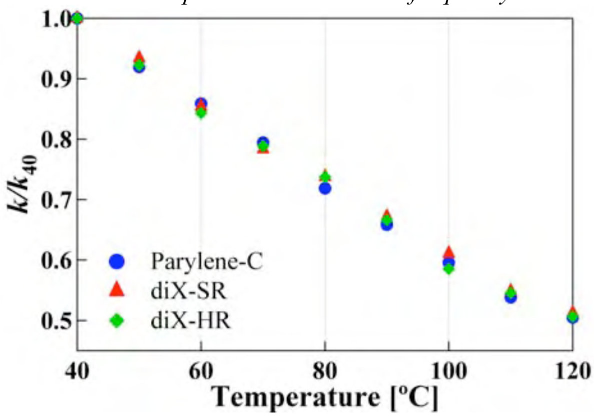

Figure 10: Spring constant normalized with the value at 40 °C. Three different parylene materials have the same TCY of 0.6 %/K.

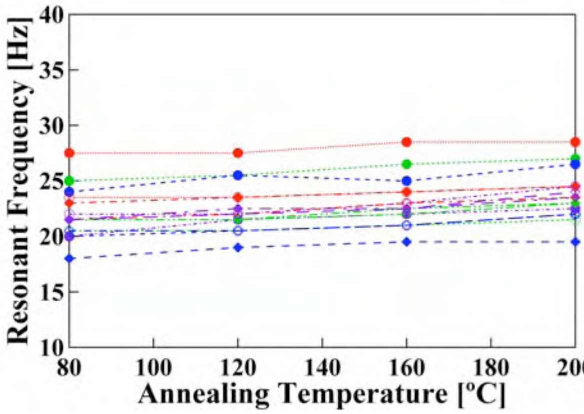

Figure 11: Effect of short-term thermal annealing on the resonant frequency: solid lines, diX-HR pendulums; dashed lines, parylene-C pendulums. Data for 4 pendulums with different beam lengths are plotted for both parylene-C and diX-HR.

Figure 10 shows spring constant of the parylene-C and diX-SR/HR beams. The spring constant is normalized with the value at 40 ºC. The temperature coefficient of Young's modulus (TCY) of parylene-C thus obtained is 0.6 %/K, which is in good agreement with our previous data using leaf-spring structures [8]. It is found that TCY of diX-SR/HR is the same as that of parylene-C. Note that, although the glass transition temperature of parylenes is around 50 ºC [9], no hysteresis of the spring constant is observed up to 120 ºC.

Finally, the effect of short-time annealing, which is expected to occur during fabrication processes or reflow soldering, is examined. Figure 11 shows resonant frequencies after annealing at different temperatures for 5 mins. It is found that the resonant frequency of parylene beams remains almost unchanged after the short-term annealing up to 200 ºC, although it is slightly increased by 1-2 Hz from 80 to 200 ºC.

CONCLUSION

We have developed a cyclic-load test bench for micromachined high-aspect-ratio parylene springs. The mechanical properties of high-thermally-stable-grade parylenes (diX-HR/SR) are examined in a series of experiments. Compatibility of diX-SR/HR to MEMS processes is confirmed. It is also confirmed from an annealing test that diX-HR/SR MEMS structures have higher thermal tolerance than parylene-C. On the other hand, mechanical properties of diX-HR/SR and parylene-C are almost the same at lower temperatures; no mechanical degradation of the beams is observed up to 10^7 cycles at the maximum strain as large as 1%. The temperature coefficient of diX-SR/HR is 0.6 %/K, which is also the same as that of parylene-C. Therefore, since the diX-SR/HR has better thermal stability than parylene-C, diX-SR/HR can replace parylene-C as a MEMS structural material for higher temperature applications up to 120-140 ºC.

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