Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Flat piezoelectric traveling wave ultrasonic micromotor with flexible support structure

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***Abstract*—This paper presents a traveling wave type ultrasonic micromotor based on lead zirconate titanate (PZT). The design of flat structure and flexible support helps to miniaturize the ultrasonic micromotor. The piezoelectric actuation and traveling wave driving satisfy the requirements of the ultrasonic micromotor for large driving capability. Wafer-level MEMS process is conducted in fabrication of the ultrasonic micromotor. Experiments reveal that the ultrasonic micromotor operates at 100.1 kHz with a maximum speed of 3400 rpm. The ultrasonic micromotor has the advantage of miniaturization and feasible integration.**

Keywords—piezoelectric ultrasonic micromotor, traveling wave, miniaturization.

I. Introduction

Piezoelectric traveling wave ultrasonic micromotor is featured with fast response, low driving voltage and high torque to achieve stepping motion and precise control of microactuator, thus widely applying in robots, medical actuators and various aerospace systems [1,2]. The piezoelectric micromotor prepared by the MEMS process is a research trend in recent years, which is an effective method for reducing the integration volume and realizing the integrated formation of the actuator and the gear structure [3,4].

The traveling wave ultrasonic micromotor is characterized in that two standing wave modes are excited in the stator elastic body by external excitation. The two standing wave modes are orthogonal, same frequency and same vibration shape but one quarter wavelength in phase difference [5,6]. The two standing waves are vibrated and superimposed to form a traveling wave in which the particles on stator is performed to elliptical motion. The friction between stator and rotor contact interface drives the rotor or the slider to move [7-9].

Conventional ultrasonic micromotors have problems such as large volume, complicated assembly, and inability to integrate with other structures. With the development of MEMS process technology, the technology of growing and patterning piezoelectric materials on the substrate greatly reduces the volume of the ultrasonic micromotor. The wafer-level production of micromotors further enables miniaturization and integration [10,11].

In this paper, a flat piezoelectric traveling wave ultrasonic micromotor is presented. The micromotor is operated at 100 kHz in B_{13} mode. The support structure of twelve flexible support beams is introduced to the micromotor. The SOI-PZT-based full MEMS micromachining process is applied to micromotor fabrication. Experiments show that the designed and manufactured traveling wave micromotor has excellent static and dynamic performance, combining both miniaturization and large driving capability.

II. Design and Fabrication

The flat piezoelectric traveling wave ultrasonic micromotor has a flexible support structure as shown in Fig. 1. The annular stator is the core structure of the micromotor, which has an outer diameter of 2000 μm and an inner diameter of 800 μm. A circular frame is design at the outer side of the annular stator. The role of the circular frame is to create a buffer zone between the flexible beams and the substrate to reduce possible stress concentrations. The notch is designed at the edge of the stator to accommodate the flexible structure of the support beams. Twelve flexible beams a width of 25 μm connect to the annular stator to the outer circular frame. The twelve flexible beams provide sufficient support for the annular stator while effectively reducing the stiffness of the system. Twelve sector electrodes are designed on the surface of stator to excite the traveling wave by four way excitation.

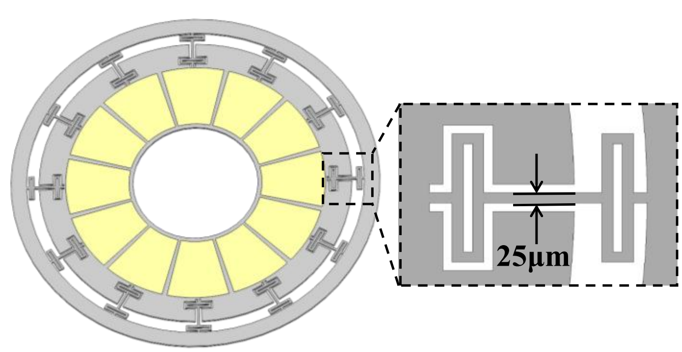

Fig. 1. Basic structure of the annular stator and design of flexible support for the ultrasonic micromotor.

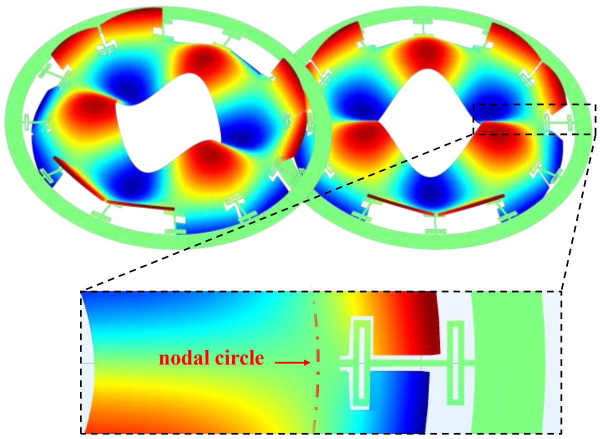

Fig. 2. The two B_{13} modes of the designed micromotor stator, showing a detail of the flexible beam with almost no displacement.

The annular micromotor is designed to operate in B_{13} mode at 100 kHz, as shown in Fig. 2. The B_{13} mode means that one nodal circle and three nodal diameters appear in operation of micromotor. The three nodal diameters correspond to three pairs of peaks/valleys of the traveling wave. One nodal circle indicates that a circular area exists on the entire stator with a displacement of almost zero. Therefore, the circular area is designed to be the junction of the flexible beams and the annular stator. No matter how the traveling wave propagates, the vibration on flexible beams is small. This design not only reduces the influence from support structure (flexible beams) on the traveling wave vibration shape and system frequency, but also reduces the loss caused by the energy transfer from the annular stator through the support structure to substrate. Therefore, the designed piezoelectric traveling wave ultrasonic micromotor is capable with high traveling wave quality and high Q value.

The section structure of the ultrasonic micromotor is shown in Fig. 3. The entire stator structure consists of 25 μm silicon and 3 μm PZT. The SOI-PZT-based full MEMS micromachining process is applied in fabrication of the micromotor. First, PZT layer with upper and lower Pt electrodes are grown on a standard SOI wafer. Subsequently, the patterning is sequentially etched down from the top Pt, PZT to lower Pt, until the SOI top silicon etching is completed. Finally, the back silicon of the SOI is etched to form the suspended structure of the annular stator, the flexible beams and the circular frame. The standard all-MEMS process ensures high precision, controlled residual stress and batch production. The fabricated ultrasonic micromotor is exhibited in Fig. 4.

III. Results and Discussions

The piezoelectric ultrasonic micromotor is packaged and integrated as shown in Fig. 5. A machined silicon rotor ring is placed with preload force on the surface of the stator. Four-channel sinusoidal signals with phase difference of 0°, 90°, 180° and 270° are applied to the 12 sector electrodes in sequence to excite the traveling waves of three pairs of peaks/valleys in B_{13} mode. A series of experiments are carried out to study the static and dynamic performances of the micromotor.

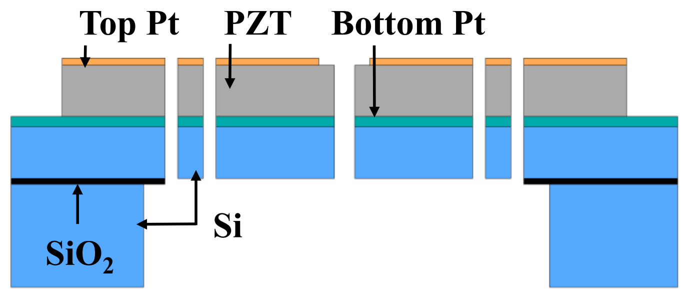

Fig. 3. The sectional view of the stator structure and material layers for the piezoelectric micromotor.

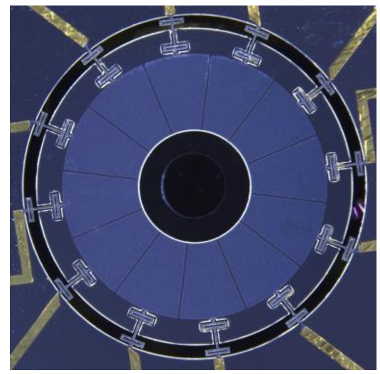

Fig. 4. The fabricated annular stator by wafer-level full MEMS process.

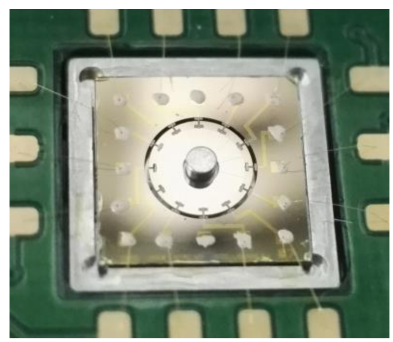

Fig. 5. The packaged micromotor with position limited on the PCB.

The amplitude-frequency characteristic of the micromotor is shown in Fig. 6. The resonant frequency of the micromotor is 100.1 kHz and the displacement at the resonant peak is 3.37 μm. This reveals that the traveling wave is excited as expected. The resonant frequency obtained by the test is highly consistent with the design. This also suggests a high manufacturing level in the device fabrication. The quality factor of the system is about 40, which is a very high value in the actuator.

The dynamic performance of the micromotor is mainly the study of rotor motion. The speed of the rotor is gradually increased from standstill with the amplitude of the four-way excitation from zero to 4V. The minimum driving voltage for the rotor is about 1.5 V, and the steady speed at this time is 442 rpm. The relationship between the steady speed of the rotor with voltage is shown in Fig. 7. The speed remains substantially linear as the excitation voltage increases. The speed of the rotor is 3375 rpm at 4V. A good linear relationship suggests that the speed of the rotor can be adjusted by the excitation voltage.

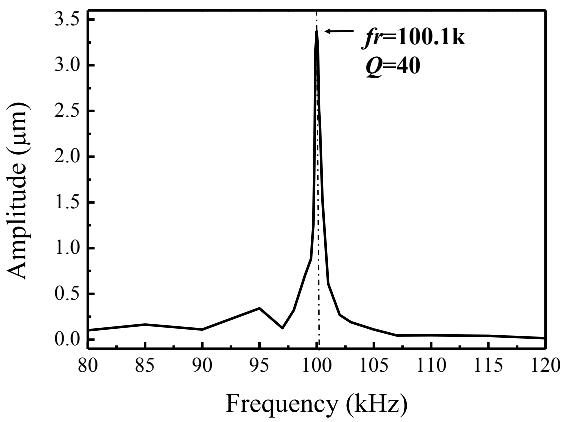

Fig. 6. Frequency domain characteristics of the micromotor stator near the resonant frequency.

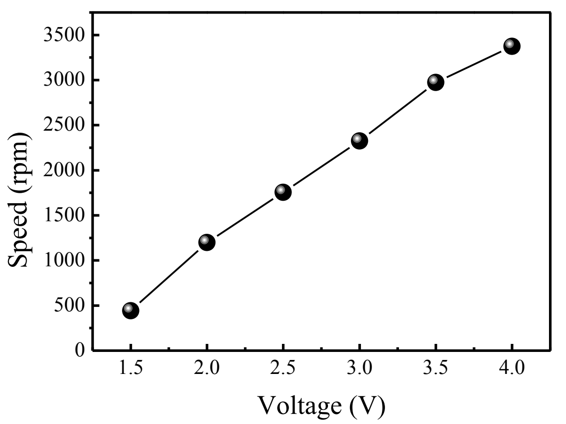

Fig. 7. The relationship between rotor speed in steady state with the starting excitation voltage.

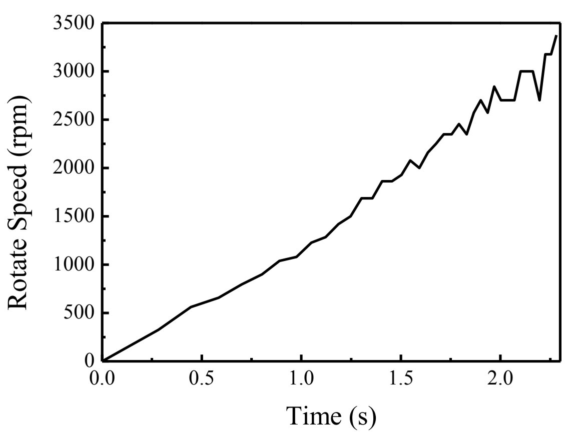

Fig. 8. Speed increase of the rotor with time in start-up process.

The dynamic start-up process of the rotor reflects the stability of the rotor during start-up. The increasing speed of the rotor with time at 4V excitation is shown in Fig. 8. In the early stage of the acceleration process, the rotor rotates very stable due to the preload force. At approximately the maximum speed, the rotor shakes slightly, causing fluctuation to speed. It takes about 2.5 seconds for the rotor to accelerate to maximum speed. The maximum speed is 3400 rpm. The dynamic test results reveal that the piezoelectric traveling wave ultrasonic micromotor has excellent performance.

IV. Conclusion

In this work, a flat piezoelectric traveling wave ultrasonic micromotor is designed, fabricated and tested. The flexible support structure is carefully designed based on research on the operation mode of the micromotor. The full MEMS process provides wafer level and high precision fabrication. The experimental results demonstrate the excellent static and dynamic performances of the micromotor. This indicates that the designed piezoelectric ultrasonic traveling wave micromotor take advantage of both miniaturization and large driving capability.

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