An Electrostatic Lower Stator Axial-Gap Polysilicon Wobble Motor Part II: Fabrication and Performance

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Abstract—This paper presents the fabrication and first performance characteristics of electrostatically driven axial-gap polysilicon wobble motors. The fabrication is based on a four-mask process using polysilicon surface-micromachining techniques. Three-twelve-stator-pole wobble motor designs have been realized with rotor radii of 50 and 100 μm. Motors have been operated successfully at driving voltages as low as 6 V at speeds up to 150 rpm. The motor performance is characterized by gear ratio measurements and measuring starting and stopping voltages. Motor lifetimes of several million wobble cycles, comparable to operating times of several hours, have been obtained.

Index Terms—Electrostatic, fabrication, micromotor.

I. INTRODUCTION

The fabrication of electrostatic micromotors is mainly based upon sacrificial layer etch techniques in combination with polysilicon and plated microstructures. Most successful designs are side-driven, salient-pole, and wobble motors [1]–[5]. Unfortunately, side-drive designs are less suitable for thin-film fabrication techniques, with respect to torque generation. As thin-film thickness is often limited to a few micrometers, the rotor-to-stator overlap is very small. This results in small driving torques in the range of a few picoNewtonmeters for side-driven salient-pole motors and a few tens of picoNewtonmeters for side-driven wobble motors. Furthermore, in most side-drive designs, the rotor is completely surrounded by stator poles. This makes it difficult to access the rotor for mechanical power take off and has resulted in the development of outer rotor designs [6], [7].

A motor design that is inherently more compliant to thin-film fabrication techniques is the axial-gap micromotor design. However, first fabrication attempts did not result in functional prototypes because of axial instabilities and axial electrostatic clamping forces perturbing radial motion [1]. A first functional axial-gap motor design was presented by Paratte [8], [9]. Bulk micromachining and later electroplating techniques were used to fabricate a rotor structure, which was assembled together with a pin axis and a stator structure to form the complete micromotor.

The operation principle is based on the transformation of an axial rocking motion into a rotation of the rotor. A slightly inclined rotor is tilted by electrostatic forces toward an excited stator pole, which is located below the rotor. By proper commutation of stator poles this will result in a rocking motion comparable to a coin flipping on a table. This rocking motion is transformed into a rotational motion because of a small difference in the radius of the rotor and its resultant contact point circle at the stator poles. Therefore, a lower stator axial-gap wobble design exhibits a large gear ratio and large rotor-to-stator overlap, which results in a large torque generation and small angular displacement steps. As the stator poles are located below the rotor, the rotor is easily accessible for power take off toward other planar structures.

In this paper, a fabrication process based on polysilicon surface-micromachining techniques and first performance characteristics of electrostatically driven axial-gap lower stator polysilicon micromotors is presented. Details of the fabrication process and experimental results on measured gear ratios, starting and stopping voltages, and motor lifetime are given. This paper forms Part II of a set of two papers dealing with electrostatic lower stator axial-gap polysilicon wobble motors. Preceding to this paper, Part I focuses upon design and modeling aspects of electrostatic lower stator axial-gap wobble motors [10].

II. FABRICATION

The micromotor fabrication is based on a four-mask process using polysilicon surface-micromachining techniques. The fabrication sequence is schematically shown in Fig. 1. The fabrication starts with a (100) p-type 3-in silicon wafer. The first step is deposition of a 1-μm-thick stress-reduced silicon-nitride layer Si₃N₄ by low-pressure chemical-vapor deposition (LPCVD) from a 70-sccm SiCl₂H₂ and an 18-sccm NH₃ flow at 850 °C and a pressure of 200 mTorr. The next step is the deposition of a 0.5-μm-thick polysilicon layer, grown by LPCVD at a temperature of 590 °C, a pressure of 250 mTorr, and a silane flow of 50 sccm. This polysilicon layer is heavily doped with boron by solid-source drive-in diffusion for 1 h at 1150 °C. This yields a sheet resistance of about 70 Ω/□. After boron diffusion, the BSG layer is stripped in a buffered hydrofluoric (HF) solution. After patterning, the doped polysilicon layer forms the stator poles [Fig. 1(a)]. Again, a 0.5-μm-thick stress-reduced LPCVD silicon-nitride layer is deposited that serves as an insulator between the stator and rotor.

Contact windows are opened in this Si₃N₄ layer by reactive ion etching (RIE) in a CHF₃/O₂ gas mixture in order to make contact with the stator poles later on [Fig. 1(b)]. Now, a 2-μm SiO₂ layer is grown by plasma-enhanced chemical-vapor
deposition (PECVD) from a SiH₄/N₂O gas mixture at 300 °C, a pressure of 650 mTorr, and RF power of 60 W [Fig. 1 (c)]. The ball bearing is now formed by one lithography step and dry etching of the SiO₂ and Si₃N₄ sandwich layer, and dry isotropic underetching of the silicon wafer. This is done by RIE with the SiO₂ layer using CHF₃ at a pressure of 20 mTorr and a RF power of 50 W and the Si₃N₄ layer by RIE using a CHF₃/O₂ gas mixture at a pressure of 10 mTorr and a RF power of 75 W. The resist layer is removed by O₂ plasma ashing, and the silicon is underetched by dry isotropic etching in a SF₆/N₂ gas mixture at 100 mTorr and 50 W [Fig. 1(d)]. Next, a 1-μm-thick SiO₂ layer is deposited by LPCVD from tetraethyloxysilane (TEOS) at 700 °C and a pressure of 400 mTorr [Fig. 1(e)]. This layer defines the spacing of the bearing and defines together with the first SiO₂ layer the gap between the rotor and stator. Now the rotor is constructed. This starts with the deposition of a 2-μm-thick LPCVD polySi layer that is also doped by diffusion as described before. The anneal step also reduces the residual stress of the polySi layer. After stripping the BSG layer in BHF, a sheet resistivity of about 6 Ω/□ is obtained. The cross section of a ball bearing like groove at this point is shown in Fig. 2.

The motor operation requires a rigid rotor design with respect to vertical deflections in order to prevent rotor deformation by axial electrostatic forces and stiction problems between the rotor and stator surface. To increase the stiffness...
of the rotor a 6-μm-thick amorphous silicon layer is deposited by sputtering in Ar. This layer is annealed in a N₂ atmosphere at 450 °C for 1 h to reduce residual stress [11]. A 0.6-μm-thick PECVD silicon-oxide layer is deposited that serves as an etch mask for the silicon sandwich layer. After patterning the silicon oxide by RIE using CHF₃ gas, the polysilicon is anisotropically etched using a SF₆, O₂, and CHF₃ gas mixture [Fig. 1(f)] [12]. The accumulated layers at the backside are stripped by dry etching, followed by a standard cleaning procedure. The sacrificial layers are etched in an HF (50%) solution for 37.5 min, DI rinsed, and spin dried. The last step is the evaporation of a 1-μm Al backside metallization layer [Fig. 1(g)]. The final result is shown in Fig. 3.

A suitable center pin bearing for the rotor is the flange bearing design [13]. However, this requires lithography over the patterned rotor structure. To prevent problems with photoresist step coverage a ball bearing design has been used. The ball bearing is, however, not self-aligned like the flange bearing design, but alignment within 1 μm should be possible and is not considered to affect the motor performance strongly. At this point, no experimental or theoretical optimization in order to minimize the rotor thickness has been done. For sufficiently thin rotors or good photoresist step coverage, a flange bearing design for these type of motors could also be realized. Note that the ball bearing design can also be realized with LIGA or other moulding and electroplating techniques.

III. EXPERIMENT

To verify micromotor static and dynamic models, it is necessary to measure the torque and rotor transient response as it moves from one stator pole to the next. Unfortunately, measurement of the generated torque and detailed experimental measurement of rotor step transient is difficult for wobble micromotors, since torque measurements require mechanical power transmission, and the rotor displacement associated with a step transient is very small. Instead, the characteristic gear ratio of a wobble motor can be easily measured [13]–[17]. The gear ratio of a wobble motor is defined as the ratio of the electrical excitation frequency to the rotor rotational frequency. Also, starting and stopping voltages can be determined from which frictional torques can be extracted. Starting voltages are measured by increasing the driving voltage and observing at what voltage a motor starts to rotate. Similarly, the stopping voltages are measured by decreasing the driving voltage and observing at what voltage the motor operation fails. The motor lifetime was defined as the time to failure in which a motor could be operated at a fixed driving voltage.

To operate the electrostatic motors a programmable power supply, which controls the driving schemes has been realized. The driving frequency of the square-wave signal of four independent output phases can be varied between 15 Hz and 10 kHz using the internal clock generator. Higher driving frequencies can be obtained by using an external clock generator. The amplitude of the driving voltage can be set between 0–100 V. The power supply is connected to the bonding pads of the stator poles using a probe station. The movements of the motor are recorded using a microscopic setup that includes a camera and video recorder. Rotational speeds can be easily determined by video replay, from which the gear ratio is calculated. Frequently used excitation schemes are shown in Fig. 4. Unless otherwise stated, single-pole excitation schemes have been used in our measurements. Stator designs with a larger number of poles than the number of power supply phases are driven by symmetrically skipping the additional stator poles. Measurements have been performed in air under class 100 000 conditions after storage periods up to several months.

IV. RESULTS AND DISCUSSION

Table I shows measured starting and stopping voltages for motors with radii of 100 and 50 μm and four-stator poles using a single-pole open-loop excitation at a frequency of 100 Hz. The effect of the driving frequency, the driving voltage, and operating time on the gear ratio of the wobble motors has been

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**Fig. 4.** Excitation schemes used for driving micromotors.
TABLE I
MEASURED STARTING AND STOPPING VOLTAGES OF SEVERAL MOTORS
WITH A FOUR-POLE-STATOR DESIGN AND ROTOR DIAMETERS
OF 50 AND 100 μm. A SINGLE-POLE OPEN-LOOP EXCITATION
WITH A SQUARE-WAVE VOLTAGE SIGNAL AT 100 Hz WAS USED

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Radius [μm]</th>
<th>Starting Voltage [V]</th>
<th>Stopping Voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>6.0</td>
<td>4.4</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>8.1</td>
<td>5.9</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>8.1</td>
<td>5.1</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>7.4</td>
<td>5.6</td>
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<tr>
<td>5</td>
<td>50</td>
<td>13.1</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>21.9</td>
<td>18.5</td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>16.7</td>
<td>12.0</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>19.9</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Fig. 5. Gear ratio as a function of the excitation frequency measured for three different micromotors with a rotor radius of 100 μm.

Fig. 6. Measured gear ratio as a function of the driving voltage for two samples with a rotor radius of 100 μm. Data has been fitted by the formula given in (22).

Fig. 7. Gear ratio versus operation time in millions of wobble cycles for two motors with a rotor radius of 100 μm. Both motors have been operated at 15 V with a driving frequency of 500 and 100 Hz. Total operation time until motor failure was 3.5 h for sample 14 and 6.5 h for sample 15.

measured. The results are shown in Figs. 5–7. Experimentally determined gear ratios varied between 130–200 for the 50-μm rotor radius designs and between 600–1000 for the 100-μm rotor radius designs. The large variation is due to the high sensitivity of the gear ratio to variations in the rotor radius as a result of underetching, to variations in the gap spacing and to changes in the bearing height because of etch and thin-film nonuniformities.

A. Starting and Stopping Voltages

The static and dynamic frictional torque of the motor can be derived from the measured starting and stopping voltages (see Table I). The thickness of the sacrificial layers defining the gap spacing of these samples [10, eq. (3)] was measured to be 2.3 μm, and the thickness of the silicon-nitride layer was measured to be 0.46 μm. The motor will stop when the frictional torque equals the generated torque. The minimum torque can be found from the torque coverage of the applied excitation scheme [10]. For the four-stator-pole design and a single-pole excitation, the minimum torque point is generated when the rotor contact point is at approximately 0.2 rad from the angular center of the stator poles [10]. The static friction is calculated to be equal to 0.71 and 0.48 pNm for the four-stator-pole motors with rotor radii of 50 and 100 μ, respectively. In the same way, the average torque to overcome the dynamic friction is equal to 0.43 and 0.25 pNm for, respectively, the small and large four-stator-pole motors. The larger motors have smaller frictional torques in contrast to their larger dimensions. This is a somewhat unexpected result. A possible reason may be the larger rocking angle of the small motors that leads to more friction at the ball bearing. Therefore, the individual frictional forces at the contact point and the bearing of the rotors cannot be extracted from these measurements. Rotor designs with identical rotor diameters, but different bearings radii are expected to be more suited for extracting the frictional forces at the contact point and the bearing. The measured frictional torques are somewhat lower compared to side-driven wobble motors [13].

B. Frequency Dependency

The gear ratio as a function of the driving frequency has been measured for three different motors and is shown in
C. Voltage Dependency of the Gear Ratio

The voltage dependency of the gear ratio is shown in Fig. 6. The gear ratio increases with increasing driving voltage. This behavior is opposite to the behavior of side-driven wobble motors, where the gear ratio decreases with increasing driving voltage as a result of a reduction in slip. It was observed that the gear ratio decreases somewhat when, instead of a double-pole excitation, a single-pole excitation scheme is used. As rotor slip leads to an increase of the gear ratio and double-pole excitation will always operate at large normal forces, which exclude rotor slip, another effect must be responsible. Furthermore, our model predicts that the motors will normally operate under no-slip conditions [10]. It is suggested that the axial electrostatic field will result in a deformation of the rotor structure. As illustrated in Fig. 8, this will result in a small decrease of the contact point radius, which results in an increase of the gear ratio. Motors that are excited over a larger region will exhibit a larger deformation explaining the increase in gear ratio when double-pole excitation is used. The axial electrostatic forces are quadratically dependent on the applied voltage [10]. Therefore, the measured dependency has been fitted by the following:

\[ n = n_0 + \gamma V^2. \]  

As shown in Fig. 6, the experimental data can be fitted well by this equation. A change in gear ratio from 800 to 1500 is related to a change in the contact point radius of only 0.05%. Additional measurements on rotors with different stiffnesses or coupled electromechanical simulations of the rotor deformation are necessary to verify our suggestion.

D. Time Dependence of the Gear Ratio

The gear ratio-to-operation time dependency of two motors is shown in Fig. 7. The gear ratio first increases, next decreases, and then it remains constant with increasing operation time until motor failure occurs. This behavior is suggested to be caused by wear. Wear at the ball bearing will result in a reduction of the initial bearing length \( h_b \) with \( \Delta h_b \) and a decrease in the axial-gap distance \( d \) with \( \Delta h_b \). Wear at the contact point circle, from surface roughness asperities at the bottom of the rotor and the stator surface, will result in an increase of the initial gap spacing \( d \) with \( \Delta d \). As a result of the wear at the bearing, a decrease in the axial-gap distance with \( \Delta h_b \) will also be present. The expressions for the bearing length and the gap spacing in case of wear become, respectively, \( h_{b\text{wear}} = h_b - \Delta h_b \) and \( h_{d\text{wear}} = h_b - \Delta h_b \). Substitution of these equations into the expression for the gear ratio gives [10], after some simplifications, the following expression for
the change in gear ratio as a result of wear:
\[
n \approx n_0 \left[ 1 + \frac{2h_b \Delta h_b}{d^2 - 2dh_b} - \frac{2(h_0 - d) \Delta d}{d^2 - 2dh_b} \right]
\]
(2)
where \( \Delta h_b \) is the change in the initial bearing length \( h_b \) as a result of wear, and \( \Delta d \) is the change in the initial gap spacing \( d \) as a result of wear between the stator surface and the rotor surface. From (2), it can be seen that wear at the bearing results in an increase of the gear ratio while wear at the contact circle between the stator and rotor surface will lead to a decrease of the gear ratio. Thus, the initial increase and subsequent decrease in the gear ratio with operation time is expected to result from wear at the ball bearing and wear of the rotor and stator surface at the contact circle during a run-in period. At the end of this period when the surface asperities are worn off, the gear ratio remains constant till it stops rotating at the fixed voltage because of increased friction.

The time to motor failure showed large variations for the two process runs that have been fabricated up to now and ranged from several ten thousands up to several millions of wobble cycles for different samples. As in side-driven wobble motors, motor failure may be caused by wear particles [17]. At this point, no SEM inspection of operated motors has been done. More work on wear is needed. Other bearing designs as well as other bearing materials may lead to extended motor lifetime.

V. CONCLUSIONS

Fabrication is based on a four-mask process using polysilicon surface-micromachining techniques. Silicon nitride has been used for electrical insulation between the rotor and stator poles, and silicon oxides were used as sacrificial layers that have been removed in an HF solution. The rotor and stator poles, and silicon oxides were used as sacrificial layers that have been removed in an HF solution. The rotor and stator poles have been constructed from doped polysilicon. To increase the stiffness of the rotor, it is made from polysilicon and a thick-sputtered amorphous silicon film. A new ball bearing design, which is not self-aligned, has been used for the rotor in order to avoid photoresist step coverage problems.

Motors have been successfully operated at driving voltages of a few volts. Their performance has been characterized by measuring the gear ratio and start and stop voltage measurements using single-pole open-loop excitations with square-wave voltage signals. Although some variation in gear data has been observed for different motors, the gear ratio seems to be independent of the driving frequency up to a maximum measured frequency of 10 kHz. The gear ratio was found to be strongly dependent on the driving voltage. It is suggested that this is caused by the mechanical deformation of the rotor that results from the axial electrostatic forces. The gear ratio was also found to be dependent on operation time showing an initial increase and decrease of the gear ratio after which it remained constant until motor failure. This behavior is suggested to result from wear at the ball bearing and the surfaces at the contact point circle. Motor lifetimes varied between a few thousand wobble cycles to some millions of wobble cycles for two different process runs. This resembles operation times ranging from a few minutes to several hours at rotor speeds between a few and several hundred rpm. In order to improve motor performance, wear and motor lifetime should be investigated as well as other bearing designs and bearing materials.

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REFERENCES

Rob Legtenberg, for a photograph and biography, see this issue, p. 85.

Erwin Berenschot, for a photograph and biography, see this issue, p. 86.

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Miko Elwenspoek, for a photograph and biography, see this issue, p. 67.