AN ELECTROSTATIC LOWER STATOR AXIAL GAP WOBBLE MOTOR: DESIGN AND FABRICATION

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SUMMARY

The fabrication, initial modelling and first results of an electrostatic lower stator axial gap wobble motor are presented. The four mask fabrication process is based on polysilicon surface micromachining techniques. Three to twelve stator pole wobble motor designs have been realized with rotor radii of 50 and 100 micrometer. A theoretical model predicts torque generations in the nNm range at high electrostatic fields. Motors have typically been operated between 10 and 20 Volts. Initial experimental results are presented.

INTRODUCTION

Because of large estimated driving torques, initial micro mechanical motor design and fabrication attempts have been axial-gap architectures [1,2]. However these designs suffered from instabilities in tilting and to a lesser extent in vertical perturbations and fabrication complexity, that finally led to the development of radial-gap or side-drive micromotors [3-5]. In most cases a radial-gap design consists of a pinned rotor structure that is surrounded by a number of stator poles. By proper commutation of the charge distribution, on the stator electrodes and the rotor, continuous motion of the rotor can be achieved. Two designs were successfully realized: salient pole- and wobble motors. Although the performance of these micromotors is still emerging, they suffer from two principle drawbacks. Firstly, the rotor-stator overlap is small which results in small driving torques; typically a few pNm for salient pole micromotors and a few tens of pNm for wobble motors. This is merely the result of the rotor and stator thickness that is generally only a few microns. Secondly, it is difficult to implement the radial gap design in a mechanical system for transduction purposes. In outer stator designs the stator completely surrounds the rotor making it difficult to transfer the mechanical energy to a mechanical structure by planar fabrication techniques. While for inner stator designs it is difficult to make the electrical stator connections [6,7].

A number of different side-drive wobble motors have been investigated [5-9]. Wobble motors are able to generate larger driving torques compared to salient pole micromotors because of their gear ratio. The gear ratio increases the driving torque at the cost of a decreasing angular speed. A further advantage of wobble motors is that friction is expected to be lower because of a rolling motion instead of sliding at the bearing.

A lower stator axial gap wobble motor design can probably solve some of the limitations of the radial-gap or side-drive design. This design was first presented by Paratte [10,11]. The tilting-, vertical- and radial rotor instabilities of this lower stator axial gap design are constrained by the bearing and stator geometry. The larger rotor to stator overlap results in a larger torque generation and successful drive of a gear train has already been realized by a hybrid design based on electroplating and assembling techniques [12]. In this paper a new fabrication process is presented as well as estimated torque generation for this type of micromotors. The motor design and fabrication process lends itself for future on-chip micromotor driven micro mechanical systems.

OPERATION PRINCIPLE

The motor is sketched in fig. 1. The rotor is resting, at the center, at a pin- or ball bearing. When a potential difference between the rotor and one of the stator poles is applied, the rotor will be pulled down towards a contact point at the angular center of the excited stator pole. This results in an inclined position of the rotor.

Fig. 1 Sketch of the operation principle.

Switching to other stator poles will move this contact point around and the rotor is forced to roll at it's outer radius resulting in a rocking motion. Because of a difference in radius between the rotor and the resulting contact point circle, the rotor will be rotated by a small angle after one sequential activation of all stator poles.

GEAR RATIO

For small rocking angles ($d \ll R$) the harmonic reduction ratio of the angular velocity between the stator and rotor is given by the nominal gear ratio n_0 (fig. 2):

$$n_0 = \frac{2 R^2}{d^2 - 2 d h_b} \quad (1)$$

Fig. 2 Modelling the gear ratio.

where R is the rotor radius, d is the axial gap distance at the rotor center and h_b is the height of the bearing pin. Note that the gear ratio is negative because the rotor rotates in a direction opposite to the excitation direction of the stator poles. When the bearing pin height is equal to d , equation (1) reduces to $-2(R/d)^2$.

TORQUE GENERATION

The tilt angle of the rotor is very small. Therefore the electrostatic field can be assumed to be vertical. Furthermore, fringing fields have been neglected and the rotor is assumed to be rigid.

The torque generated by the motor can be found from the derivative of the potential energy with respect to the rotor angle α . This results in the following expression for the torque:

$$\tau = -\frac{1}{2} \int_{\varphi_1}^{\varphi_2} \int_{R_i}^{R_o} \frac{\epsilon_0 r^2 \sin(\varphi - \alpha) V^2}{\left(\frac{R}{d} \left(1 - \frac{r}{R} \cos(\varphi - \alpha) \right) + \frac{d_{ins}}{\epsilon_r} \right)^2} dr d\varphi \quad (2)$$

where α is the angle of the rotor contact point, φ is the angle of the stator pole from φ_1 to φ_2 , r is the radius of the stator pole from R_i to R_o , d_{ins} is the thickness of the insulating layer with a relative dielectric constant ϵ_r between the rotor and the stator and V is the applied voltage between the stator and the rotor.

An example of the single phase torque as function of the rotor angle α is shown in fig. 3 for a three stator pole design. The rotor radius is 100 μm , the gap distance is 2 μm , and the dielectric layer between the stator and rotor has a thickness of 0.2 μm and a relative dielectric constant of 7.5. The outer radius of the stator pole is equal to the rotor radius and the inner radius is equal to half the rotor radius (50 μm). The driving voltage is equal to 100 Volts. The maximum torque generation for this type of motors, at

given dimensions, can be in the range of nNm at high electrostatic fields.

Fig. 3 Single phase torque as a function of the rotor angle for a 3, 6 and 12 stator pole design.

FABRICATION

The fabrication process requires four masks and is described below. It starts with a (100) p-type 3" silicon wafer. First step is the deposition of a 1 mm thick stress reduced silicon nitride layer by LPCVD from 70 sccm DCS and 18 sccm NH_3 at 850 °C and a pressure of 200 mTorr. The next step is the deposition of a 0.5 mm 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 indiffusion for one hour at 1150 °C. This yields a squared resistance of about 70 Ω . After boron indiffusion the BSG layer is stripped in a buffered HF-solution. After patterning, the doped poly layer forms the stator poles (fig. 4 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 SiN layer by RIE in a CHF_3/O_2 gas mixture in order to make contact with the stator poles later on (Fig. 4 b). Now a 2 μm SiO_2 layer is grown by PECVD from a $\text{SiH}_4/\text{N}_2\text{O}$ gas mixture at 300 °C, a pressure of 650 mTorr and RF power of 60 Watt (fig. 4 c). The ball bearing is now formed by one lithography step and dry etching of the SiO_2/SiN sandwich layer and dry isotropic underetching of the silicon wafer. This is done by RIE the SiO_2 layer using CHF_3 at a pressure of 20 mTorr and a RF power of 50 Watt and the SiN layer by RIE using a CHF_3/O_2 gas mixture at a pressure of 10 mTorr and a RF power of 75 Watt. The resist layer is removed by O_2 plasma ashing and the silicon is underetched by dry isotropic etching in a SF_6/N_2 gas mixture at 100 mTorr and 50 Watt (fig. 4 d).

Fig. 4 (a), (b), (c), (d), (e), (f), (g) Processing Sequence for the wobble motor. More details are given in the text.

Next a 1 μm thick SiO_2 layer is grown by LPCVD from TEOS at 700 $^\circ\text{C}$ and a pressure of 400 mTorr (fig. 4 e). This layer defines the bearing spacing while the first SiO_2 layer defines the gap spacing 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 indiffusion as described above. The anneal step also reduces the residual stress of the polySi layer. After stripping the BSG layer in BHF a square resistivity of 6 Ω is obtained. To increase the stiffness of the rotor a 6 μm thick silicon layer is deposited by sputtering in Ar. This layer is annealed in a N_2 atmosphere at 450 $^\circ\text{C}$ for 1 hour to reduce residual strain. A 0.6 μm thick PECVD silicon oxide layer is grown that serves as an etch mask for the silicon sandwich layer. After patterning the silicon oxide by RIE using CHF_3 gas, the polysilicon is anisotropically etched using a SF_6 , O_2 , CHF_3 gas mixture (fig. 4 f). 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., and are DI rinsed and spin dried. Last step is the evaporation of a 1 μm Al backside metallization layer (fig. 4 g). The result is shown in fig. 5 and 6.

The motor operation requires a rigid rotor design with respect to vertical deflections in order to prevent rotor deformation and stiction problems between the rotor and stator surface. This can easily be accomplished by increasing the rotor thickness. Therefore the rotor structure is stiffened by deposition of a sputtered silicon layer that can easily be grown up to a thickness of several tens of μm . 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 [3]

but alignment within 1 μm should be possible and is not considered to affect the motor performance strongly. For thinner rotors or sufficiently good photoresist step coverage also a flange bearing design for these type of motors can be realized. At this point no experimental or theoretical study on rotor thickness has been done. Note that the ball bearing design can also be realized with LIGA, or other molding and electroplating techniques.

EXPERIMENTAL RESULTS

Motors have been operated using a programmable power supply which controls the driving schemes. The driving frequency and the amplitude for a square wave signal of four independent output phases can, respectively, be varied between 15 and 100 kHz, and 0 to 100 V. Single phase excitation schemes have been used, e.g. *Abc*, *aBc*, *abC* for a three stator pole design. 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 semi-cleanroom conditions after storage periods up to several weeks. The motors appeared to be very rigid and even operated after subsequent lithography and etching steps after the final release in HF.

Starting voltages ranged from 7 to 15 V, and stopping voltages ranged from 5 to 10 V for both rotor radii. Experimentally determined gear ratios varied between 130 and 200 for the 50 μm rotor radius design, and between 600 and 1000 for the 100 μm rotor radius designs.

The motor lifetime is limited from one hour to several minutes, depending on rotational speed that was varied from 0.5 to 500 rpm. Limited lifetime is suggested to result from wear at the ball bearing.

Fig. 5 SEM photograph of an electrostatic axial gap wobble motor with four stator poles. The rotor diameter is 200 μm and rotor thickness is 8 μm .

Fig. 6 SEM photograph the cross section of a ball bearing groove after deposition of the second polysilicon layer. The good step coverage of the TEOS and polysilicon layer is clearly visible.

CONCLUSIONS

An electrostatic lower stator axial gap wobble motor was successfully fabricated by surface micromachining techniques. In contrast to side drive motors, the stator poles are located underneath the rotor instead of surrounding the rotor sides. This results in a higher torque generation and the ability to transfer the mechanical energy for driving purposes. The motor design and fabrication process lends itself for future on-chip micromotor driven micro mechanical systems. Measured starting voltages varied between 7 to 15 V and stopping voltages ranged from 5 to 10 V. Experimental gear ratios around 165 and 800 are obtained for motors with rotor radii of respectively 50 and 100 micrometer. Motor lifetime is suggested to be

limited by wear and ranged from a few minutes to one hour, depending on rotational speeds from 0.5 to 500 rpm.

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