A Fabrication Process for Electrostatic Microactuators with Integrated Gear Linkages

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Abstract— A surface micromachining process is presented which has been used to fabricate electrostatic microactuators. These microactuators are interconnected with each other and linked to other movable microstructures by integrated gear linkages. The gear linkages consist of rotational and linear gear structures, and the electrostatic microactuators include curved electrode actuators, comb-drive actuators, and axial-gap wobble motors. The micromechanical structures are constructed from polysilicon. Silicon dioxide was used as a sacrificial layer, and silicon nitride was used for electrical insulation. A cyclohexane freeze drying technique was used to prevent problems with stiction. The actuators, loaded with various mechanisms, were successfully driven by electrostatic actuation. The work is a first step toward mechanical power transmission in micromechanical systems. [213]

Index Terms—Actuator, electrostatic, fabrication (process), microgear.

I. INTRODUCTION

WITH IMPROVING performance and fabrication techniques, micromechanical actuators are merging into the field of mechanical power transmission for driving purposes. It has been previously shown that multilevel linkages can be fabricated by dissolved wafer, bond, and assembly techniques [1]. Two silicon wafers are successively processed, aligned, and bonded to a glass wafer and then dissolved in ethylene diamine pyrocatechol (EDP) to free micromechanical mechanisms. Other examples of assembled devices that transfer mechanical power are magnetic micromotors, where Permalloy and polymethyl metacrylate (PMMA) parts are fabricated with sacrificial lithografie und galvano abformung (LIGA) techniques, which are subsequently assembled with submicron tolerances [2]. Axial-gap wobble motors have also been fabricated from electroplated nickel rotors that were coupled to miniature pinion and gear trains using assembling techniques [3]. Devices where mechanical linkages have been integrated with actuator fabrication are vibromotors, where a slider is driven by oblique impact of resonant comb structures [4], and a comb-drive-based microengine, where the linear motion of comb structures is converted into a rotary motion of an output gear by connecting rods [5]. These latter processes have the advantage of batch fabrication without the need for assembly of multiple wafers requiring alignments, bonding, etc., or the addition of other separately fabricated parts.

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Fig. 1. Cross-sectional view of a wobble motor with external gear teeth. A circular reduction is used in order to prevent gear teeth from touching the stator surface and obtaining a smooth rocking motion.

In this paper, a fabrication process is presented, where different types of surface micromachined electrostatic actuators are fabricated in one process. These are interconnected and linked to other microstructures using gear mechanisms without the need for assembling techniques. In our previous work, several electrostatic actuators that can generate relatively large forces, torques, and displacements have been developed and fabricated using surface micromachining techniques. Examples are bistable curved electrode actuators [6], linear comb-drive actuators [7], and axial-gap wobble motors [8]. Mechanisms include gear trains, linear gear racks, sliders, and spring structures. First, experimental results have shown operational actuators and functional micromechanisms—for example, electrically powered micromotors drive gear trains and gear racks. In the latter case, a transformation of rotational into linear motion is obtained.

II. DESIGN ISSUES

A. General Design Issues

Since the fabrication of the comb-drive actuators and curved electrode actuators is relatively simple and can be done in a one-mask fabrication process [6], [7], this process has been merged into the fabrication process of the axial-gap wobble motor [8]. The micromechanical structures are constructed from polysilicon. Silicon dioxide has been used as a sacrificial layer, and silicon nitride was used for electrical insulation. A cyclohexane freeze drying technique is used to prevent problems with stiction.

The operation principle of a lower stator axial-gap wobble motor is based on an inclined rotor that is supported at its center and rolling on its outer radius. Excitation of stator poles results in an axial rocking motion of the rotor. This rocking motion is transformed into a rotational motion because of a small difference in the radius of the rotor and its resultant

Fig. 2. (a)–(e) Processing sequence for electrostatic actuators with integrated gear linkages.

contact point circle at the stator poles. In contrast to polysilicon side drive motors, where stator poles are surrounding the rotor, the stator poles of the axial-gap wobble motor are located underneath the rotor. This results in a large-torque generation because of a large rotor to stator overlap and a readily accessible rotor for mechanical power takeoff. For a more detailed description of the axial-gap wobble motors, reference is made to [8].

Because the rotor of the axial-gap wobble motor makes an axial rocking motion and is rolling on its outer radius, some adjustments are necessary when external gear teeth are added. By an additional etch step, a circular reduction is created in the rotor structure (see Fig. 1). Now, the rotor will roll on this circular reduction and can have an arbitrary outline. The rotor and gears can rotate and rock in axial directions using a ball bearing, while for linear movements a slider bearing was applied using slots that are etched into the silicon wafer. The motor rocking motion places a constraint on the thickness of the gears and, therefore, the gear thickness should be larger than two times the thickness of the sacrificial layer below it. In our fabrication process, a sacrificial layer thickness of about $2\ \mu\text{m}$ and a gear thickness of about $6\ \mu\text{m}$ were used.

B. Tooth Design

Gears are an efficient way to transmit mechanical power at almost any speed ratio desired. Parallel axis gears transmit power with greater efficiency than any other form of gearing. The most common type of gear is the spur gear, which has teeth on the outside of a cylinder, which are parallel to the cylinder axis. This type of gear can be fabricated relatively easy using anisotropic etching techniques.

A conjugate tooth shape is needed in order to transform motion with constant angular velocity. Involute and cycloidal tooth shapes are conjugate tooth profiles. However, cycloid gearing requires center distances to be maintained in order to obtain conjugate action, where involute profiles maintain conjugate action, even with variations in gear center distances [9]. The gear ratio is a constant and can be found from the ratio of gear teeth numbers. It can be applied to all types of gears with conjugate and nonconjugate gear tooth surfaces and corresponds to the ratio between the gear revolutions. Only in cases of conjugate tooth profiles is the velocity ratio equal to the gear ratio. If not, the gears transform rotation with a varying instantaneous velocity ratio.

Fig. 2. (Continued.) (f)–(i) Processing sequence for electrostatic actuators with integrated gear linkages.

In this first approach, no optimization has been done on gear design. Because of limitations in our present mask layout program and pattern generator, gear teeth with a trapezoidal shape have been used. This will negatively affect the performance of our gears. However, at this stage the main goal is the development of a fabrication process for integrated electrostatic actuators and gear linkages and to demonstrate the feasibility of these micromechanical gear linkages in order to transfer mechanical power.

In our design, two different gears have been used. The largest gear has 36 teeth and a base radius of $100\ \mu\text{m}$, which also forms the rotor of electrostatic axial-gap wobble motors. Smaller gears have 18 teeth and a base radius of $50\ \mu\text{m}$. The total depth of the gear teeth is $11\ \mu\text{m}$, the thickness is $6\ \mu\text{m}$, and a pressure angle of 20° has been used. In order to ensure proper patterning and etching, a minimum clearance of $2\ \mu\text{m}$ between engaged gear teeth and a bearing clearance of $1\ \mu\text{m}$ has been used. As a result, gear backlash will be relatively large.

III. FRICTION AND WEAR

Although some work has been done on aspects like friction, wear, and lubrication of micromechanisms [10]–[19], many issues with regard to tribological properties, design,

Fig. 3. Scanning electron microscope (SEM) photograph of an axial-gap wobble motor with gear teeth driving a smaller gear wheel. The rotor and smaller gear have a base radius of 100 and $50\ \mu\text{m}$, respectively. The four stator pole contact pads are located around the rotor. Holes in the rotor and gear structure are used to enhance the sacrificial-layer etching.

and operation of microsystems are unexplored and need to be investigated. Frictional effects should be minimized by a proper bearing design and a suitable gear tooth profile set, resulting in a lateral pure rolling motion between gear teeth.

Fig. 4. Close-up of the gear teeth. The gear teeth have a thickness of $6\ \mu\text{m}$, a depth of $11\ \mu\text{m}$, and a diametrical pitch of $18.5\ \mu\text{m}$. A minimum clearance of $2\ \mu\text{m}$ between the teeth of different gears has been used to ensure proper etching and patterning. No optimization of the gear design has been done at this stage, and the trapezoidal shape of the spur gears is clearly visible.

Fig. 5. SEM photograph of an axial-gap wobble motor (with eight stator poles) connected to a gear rack, resulting in transformation of the rotational into linear motion.

The use of low-friction materials [15], [17], [18] and lubricants [20]–[23] seems to be promising applications. However, one should bear in mind that the operation of axial-gap wobble motors is based upon friction between the rotor and stator surface.

The lifetime of gears and micromotors is limited by wear [8], [10], [11]. Friction and wear studies using a specimen-on-disc [15], [19] have been performed and indicate that diamond-like carbon is an attractive material with respect to friction and wear properties. The wear mechanism of brittle materials such as diamond-like carbon (DLC), SiO_2 , Si_3N_4 , and single-crystalline silicon (SCS) was found to be dominated by asperity fracture, and wear of polysilicon is dominated by asperity deformation [19]. In general, wear has been found to follow macroscopic theory, where materials of highest hardness show the lowest wear rates, and wear rate is dependent on contact pressure.

A problem related to the axial-gap wobble motor is that the rocking motion of the rotor gives rise to axial motions between the rotor teeth and the teeth of the gear structure that is driven.

Fig. 6. Close-up of the gear rack. The slider is able to move on its bearing along slots that are etched into the wafer. Taking a good look, the circular reduction at the edge of the rotor is visible. Also, the print of the slots below the slider can be seen. After the anisotropic etching of the polysilicon structures, the remaining polysilicon in the slots was removed by an isotropic etch step. At the end of the slider, the remains of this etch step are visible because of mask alignment.

Fig. 7. Cross-sectional view of a linear slider test structure showing the slots and bearing that guide its motion.

This will induce additional frictional forces. The normal force at the tooth surfaces is roughly equal to the excess motor torque divided by the rotor radius. The torque of a motor with a radius of $100\ \mu\text{m}$ can theoretically be in the range of nNm, at high-electrostatic fields [8], leading to normal forces in the $10\text{--}100\ \mu\text{N}$ range. The axial frictional force resulting from the rocking motion is a fraction of this normal force after multiplication by the frictional coefficient of the materials in contact (e.g., 0.3–0.5). This axial frictional force is small compared to the axial electrostatic forces of the motor, which are in the range of mN. Therefore, friction between gears as a result of the rocking motion is not expected to strongly affect motor torque and performance.

IV. FABRICATION PROCESS

The fabrication of electrostatic axial-gap micromotors, comb-drive actuators, and curved electrode actuators, together with integrated gear mechanisms, is based on a seven-mask

Fig. 8. Curved electrode actuator in combination with the wobble motor for fixing the rotor position. When the curved electrode actuator is deactivated, the rotor position is locked.

process using polysilicon surface micromachining techniques. The process steps are illustrated in Fig. 2. Starting material is a (100) *p*-type 3-in silicon wafer. First, a 1- μm -thick stress-reduced silicon nitride layer is deposited by low-pressure chemical-vapor deposition (LPCVD). This is followed by the deposition of a 0.5- μm -thick LPCVD polysilicon layer. This polysilicon layer is subsequently doped with boron by solid-source indiffusion for 1 h at 1100 °C. After boron indiffusion, the borosilicate glass (BSG) layer is stripped in a buffered hydrofluoric acid (HF) solution and the polysilicon is patterned to form the stator poles of the motor and ground planes of electrostatic actuators [mask 1, Fig. 2(a)]. Now, a second stress-reduced LPCVD silicon nitride layer with a thickness of 0.5 μm is deposited, which serves as an insulation layer. In this Si_xN_y layer, contact windows are etched by RIE in a CHF_3/O_2 gas mixture in order to make electrical contact to the stator poles and ground planes [mask 2, Fig. 2(b)]. Next, a SiO_2 layer is grown by plasma-enhanced chemical-vapor deposition (PECVD) with a thickness of 2 μm , which defines the air-gap spacing between the stator and rotor of the micromotor and partly defines the sacrificial layer of the structures [Fig. 2(c)]. Local reductions are etched in this SiO_2 layer using a BHF solution to define the circular region on which the rotors will roll [mask 3, Fig. 2(d)].

The ball bearings and slider slots are formed by RIE etching of the SiO_2 layer using a CHF_3 plasma, RIE etching of the Si_xN_y layers using a CHF_3/O_2 gas mixture, and dry isotropic underetching of the silicon wafer in a SF_6/N_2 gas mixture [mask 4, Fig. 2(e)]. After this, a SiO_2 layer with conformal step coverage is grown by LPCVD from tetraethylorthosilane (TEOS) to define the bearing spacing of the rotor structures [Fig. 2(f)]. In the silicon-dioxide sacrificial layer, anchors for

the electrostatic actuators are patterned by etching in BHF [mask 5, Fig. 2(g)].

Now, the structural layer has to be deposited. In our previous wobble motor fabrication process, a composition of 2- μm LPCVD polysilicon and 6- μm sputtered silicon was used [8]. However, the integration of side-driven structures requires full doping of the silicon, which led to doping problems with the sputtered silicon layer. Therefore, a 6- μm -thick LPCVD polysilicon layer is deposited during a 16-h overnight run. This polysilicon layer is also doped by boron indiffusion as described before. After stripping the BSG layer in BHF, a sheet resistivity of about 3 Ω/square is obtained. A 1- μm -thick PECVD silicon oxide layer is grown that serves as an etch mask for the polysilicon layer and prevents boron outdiffusion in the subsequent annealing step at 1100 °C for 3 h in order to reduce stress gradients as a result of the one-sided diffusion step. The final residual stress is slightly tensile, having a value of about 20 MPa, and beam-end deflections at 1000 μm are less than 1 μm .

At this point, backside layers are stripped by dry etching. The silicon oxide is patterned by RIE using CHF_3 gas, and the polysilicon is anisotropically etched using a SF_6 , O_2 , and CHF_3 gas mixture [24] [mask 6, Fig. 2(h)]. In order to remove the polysilicon from the slots in which the sliders have to move (see Fig. 6), an isotropic etch step in a SF_6/N_2 gas mixture is needed in addition to the anisotropic etch, while other areas are protected by photoresist (mask 7). After a thorough cleaning procedure, the sacrificial layers are etched in concentrated HF for 50 min. This is followed by dilution rinsing in deionized (DI) water, rinsing in isopropanol, and rinsing in cyclohexane, while preventing the wafers from drying. Now freeze drying is used to remove the cyclohexane at a temperature of -10 °C under a high N_2 flow in order to

Fig. 9. Motors linked to a gear rack suspended by folded flexures of comb-drive actuators. The folded flexures have a length of $500\ \mu\text{m}$, and the total comb length is $1\ \text{mm}$ consisting of 136 fingers with a gap spacing of about $2\ \mu\text{m}$. The gear rack is connected to the movable part of an upper and lower (not visible) comb-drive structure. Such structures could be used to measure output torque and motor dynamics.

Fig. 10. Close-up view of comb-drive structure connected to axial-gap wobble motors from Fig. 9. The small tilt of the wobble rotors is clearly visible in this picture. Also, the gap under the suspended gear rack can be seen.

prevent stiction problems [25]. The last step is evaporation of a $1\text{-}\mu\text{m}$ -thick aluminum backside layer [Fig. 2(i)]. The final result is shown in Figs. 3–12.

V. EXPERIMENTAL RESULTS

First, experiments have shown that the micromotors can successfully drive gear trains and slider gear racks, resulting in, respectively, torque leverage and rotational to linear transformation. Micromotors with a radius of $100\ \mu\text{m}$ were driven at voltages between 15–25 V, which theoretically gives driving torques of 10–25 pNm. Driving frequencies ranged

Fig. 11. XY stage fabricated in the same process run. Using folded flexure designs, the XY stage is able to scan over $60 \times 60\ \mu\text{m}^2$ at driving voltages of about 20 V.

Fig. 12. Close-up of the center of the XY stage from Fig. 11.

up to 500 Hz for motors with four stator poles, which is equal to a rotational speed up to about 10 rpm. Wobble motors with integrated gear linkages have been driven for a few minutes. No investigation of their lifetime and failure mechanism has been performed. Until this work, no integrated micromechanisms that are driven by electrostatic micromotors have been reported [26].

Comb-drive structures and curved electrode actuators in conjunction with micromechanical mechanisms have also been driven electrostatically at driving voltages of 20 and 50 V, respectively.

Variations in operation characteristics of gears have been observed, which are expected to result from the nonconjugate gear teeth profile that has been used. Problems such as gear backlash and impact were also noticed, which were caused by etching and bearing clearances. Furthermore, frictional

problems were encountered with large slider structures (up to 2 mm long). Long sliders could be moved manually by probe needles, but did not slide by electrical powering micromotors. It is suggested that stress gradients clamp long slider structures in their bearing slots, resulting in frictional forces, which are larger than the output force of the motors. Further experimental work is needed to obtain more quantitative results. Problems with friction and wear could be minimized along the lines of a proper bearing design, a suitable gear tooth profile set, resulting in a lateral pure rolling motion between gear teeth and the use of wear-resistant materials at the rotor bearing.

VI. CONCLUSION

A micromachining process for the fabrication of electrostatic microactuators, which are linked with each other and connected to other movable microstructures by integrated gear linkages, has been presented. The fabrication is based on polysilicon surface micromachining and sacrificial-layer etching techniques. First, experimental results show that electrically powered actuators successfully drive various micromechanisms. The work is a first step toward mechanical power transmission in micromechanical systems. Mechanical power transmission of microactuators may strongly increase the number of useful applications and may lead to new possibilities for microelectromechanical systems.

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