Plasma Etching Based Processes for the Fabrication of Micro Structured Linear Guide

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Keywords: inductively coupled plasma etching, barrel plasma etching, micro structure, linear guide

Abstract

This abstract is focused on the fabrication of low friction silicon micro guides. The novelty of this work is related to the fabrication process using an inductively coupled plasma etching and a barrel etching process for silicon micromachining. This simple technology allows the fabrication of silicon micro guides with only two photolithographic steps. Micro patterns on support structures of the stationary parts were fabricated to minimize the contacting area of the micro linear guide and as a result to reduce a sliding friction as well as a coefficient of friction.

1 Introduction

Friction is an unavoidable characteristic of mechanisms comprising movable components which are in contact with each other. The effects of friction increase significantly as the system dimensions decrease. Therefore, friction becomes critical on the microscale and is one of the fundamental limitations in the design and implementation of reliable, efficient MEMS devices.

In the last decade various types of actuating principles used in micromachines have been reported [1, 2]. Great efforts have been made to improve the reliability of the devices but the understanding of friction, wear and other related phenomena is still insufficient. Several guide and support structures based on two categories were demonstrated for use in micromachines: contact and non-contact type bearings. In contact type bearings, support structures are in direct contact with the moving parts. Due to the tribological contact, the reliability of such devices suffers drastically from friction and wear. The non-contact type structures use more complicated mechanisms like electrostatic [3], electromagnetic [4] or aerostatic bearings [5]. These systems show much less friction and wear compared to contact type systems, however, as major drawbacks, their fabrication is rather complex and the stability of the moving plate falls off. In spite of less friction, contact type rolling motion ball bearings also have a serious disadvantage [6]. The unpredictable, mixed movement between rolling and sliding motion of the balls causes instability of the moving plate. Therefore, tribological guides seem to be well suited for MEMS applications, due to the fact that the guide mechanism is relatively simple, whereas the structures can be fabricated with a couple of photolithographic and etching steps. In addition, the guide structures provide a stable and robust support for the moving plates.

Micro linear guides are inevitable parts of active micro systems driven by micro linear motors. A micro linear guide was designed in order to reduce the static and also the kinetic friction between the moving micro plates. Concerning the previously developed silicon linear micro guides [7], both the moving and the stationary plate were fabricated by wet chemical etching. The typical V-grooves of (111)-planes provide a self-alignment between both plates. An average coefficient of friction (COF) of the linear guide of 0.2 was determined. Because of the small size of micro actuators, the resulting driving force of micromachines is very limited, so that the friction of the guides has to be reduced as far as possible. To achieve a COF of less than 0.1 optimized linear guides are needed.

Several approaches have been introduced to improve the tribological behavior of sliding motion, such as mono- or multilayer coating of lubricating films [8]. Another approach is the optimization of contact areas, due to the fact that the COF verifiably depends on the topography of contact areas. A COF of sliding friction of 0.04 can be observed when the contact area is reduced to 1 % [9]. Thus, the further development of the micro linear guide is focused on the reduction of the contact area. Using plasma based etching processes the contact area of micro structures can easier be controlled as in wet chemical etching.

This paper focuses on the fabrication of silicon micro guides using a dry etching based process. The novelty of this work is related to the fabrication process. It uses an inductively coupled plasma etching process (ICP) and a barrel etching process for silicon micromachining and allows the production of monolithic micro structures. ICP etching is used to fabricate the main support structures and barrel etching is used to pattern the contact area on top of these structures.

2 Micro linear guides

A basic concept of linear guides consists of two matching long parallel tracks on a stator (stationary plate) and grooves on a slider (moving plate), which can be fabricated using micromachining techniques, such as wet chemical etching of silicon. A schematic view of the previous design of the micro linear guide is shown in Fig. 1. Parallel V-grooves are etched into the moving plate (5 mm x 5 mm x 0.45 mm) made of a (100)-silicon wafer. On the stationary plate, V-shape tracks are also etched wet chemically. The gap between both plates is determined by the opening size of the masking layer.

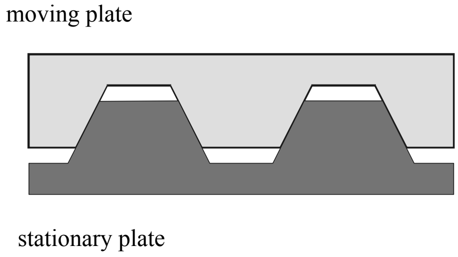

Fig. 1. Schematic view of the wet chemically etched linear guide

For this design the contact area is on the (111)-plane of the etched surface which assures the lateral accuracy between stator and slider. Therefore, undercut of the (111)-plane has no effect on the fitting accuracy of the guide. Preliminary investigations of sliding friction of flat and patterned specimens have shown that the patterned specimens have lower static as well as kinetic friction as the flat specimens. For this reason, the long V-shape tracks of the stator are micro structured to exhibit small bosses. Fig. 2 shows a micro guide with micro structured rails on the stationary plate and V-grooves on the moving plate.

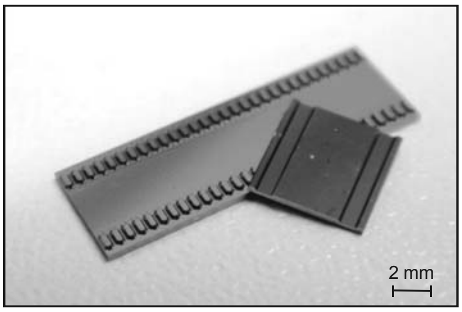

Fig. 2. Stator with micro structured rails and slider of a silicon micro linear guide

Through the micro structures of the rails the contact area was reduced from 2.6 mm² to 1.3 mm² (50 %) and to 0.91 mm² (33 %) by boss distances of 250 µm and 500 µm, respectively. Fig. 3 shows the kinetic COF of the micro linear guides, where the sign of COF denotes the moving direction of the samples. In this experiments the slider was driven in oscillating motion using a friction tester described in [10] with a sliding speed of 100 µm/s and constant normal load of 30 mN.

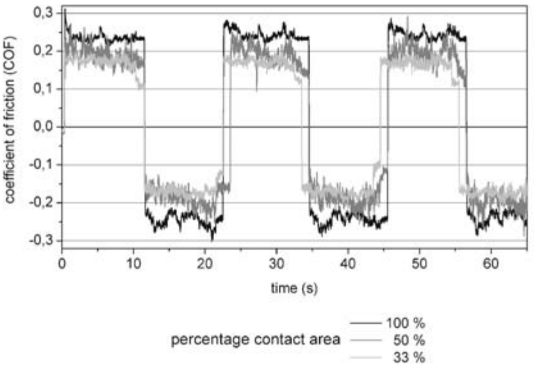

Fig. 3. Kinetic COF of the micro linear guide

The micro guide with a contact area of 33 % has the minimum average COF of 0.17. For a contact area less than 33 %, an even lower COF can be expected. For our requirements, the COF of micro linear guides has to be less than 0.1. Due to anisotropy and undercut, the variation of the shape of micro guides using a wet chemical etching process is very limited. Hence, plasma dry etching processes are the key technologies for fabricating optimized micro linear guides.

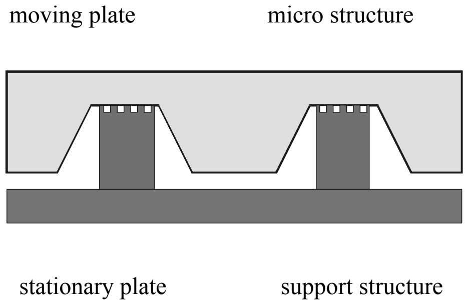

Fig. 4. Schematic view of the plasma assisted etched linear guide

Fig. 4 shows a schematic view of the micro linear guide, the stator of which is fabricated by plasma dry etching. The V-grooves of the slider are still produced using wet chemical etching, but instead of the (111)-plane the contact surfaces of this linear guide are on the bottom of the grooves. A groove depth of 10 µm has been defined, so that the bottom width closely fits into the support structures. The cylindrical support structures of the stator are fabricated by ICP dry etching. The top surfaces of the structures are used as the contact area, which are patterned into an array of bosses with a diameter of 10 µm using isotropic barrel etching. The accuracy of the V-grooves depth determines the laterally fitting tolerance of the guides.

3 Fabrication of micro linear guides

The slider and stator are fabricated form a 4”-silicon wafer with a thickness of 450 µm. For fabricating the slider a 600 nm silicondioxide layer is deposited on both sides of the silicon wafer, which is used as masking layer for wet chemical etching. In the photolithography step the etch mask is carefully aligned parallel to the primary flat of the wafer. After the etching process using 40% KOH solution at 80 °C and removing the silicondioxide layer, the wafer is cut into small pieces of 5 mm x 5 mm.

For fabricating the stator using a plasma based dry etching process a standard photoresist can be directly used as masking layer. A positive resist is applied on both sides of the silicon wafer. The etch mask for barrel etching is patterned using standard photolithography on the top side of the wafer. The resist on the other side protects the wafer from the reactant gas. A mild oxygen plasma treatment is used to remove rest of resist left behind after development. For transferring the pattern to the wafer a barrel plasma etching process with CF_4 and O_2 mixture as reactant gas is used. The etch depth of 3 µm is reached in 5 min by gas flow rates CF_4/O_2 of 200/15 sccm and an rf power of 400 W.

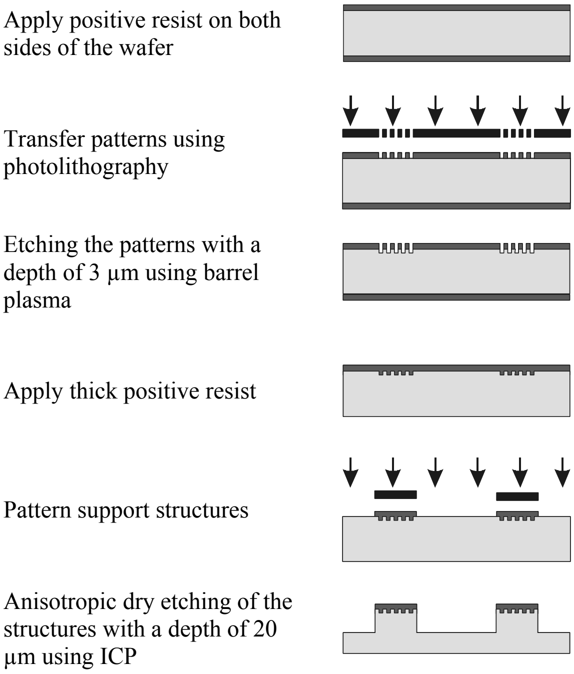

Fig. 5. Fabrication steps of slider

After removing the resist, the wafer is cleaned using standard RCA procedure. Then, a thick positive resist is applied on the top side of the wafer. We use the thick resist as a masking layer and to protect the pattern from the following etching step. In the second step of the fabrication a deep ICP etching process is used to produce vertical anisotropic support structures. Typically, the ICP dry etching process uses SF_6 as main etching gas and C_4F_8 as passivating gas. The C_4F_8 generates a thin fluorocarbon polymer film as sidewall passivating layer. To achieve a high uniformity the etch rate of ICP is set to 1.2 µm/min. By 17 min. etch time a depth of 20 µm can be achieved. In the last step, the resist is removed and the wafer is cleaned using RCA procedure. Fig. 5 illustrates briefly the fabrication steps of the slider.

4 Fabrication Results

The barrel plasma etching is isotropic and thus the pattern will be undercut by roughly the same amount as the etch depth. Hence, the boss diameter of etched patterns is smaller than the designed diameter of 10 µm. For an etch depth of 3 µm an average diameter of 5 µm can be measured. Furthermore, the etched surface is slightly rougher in comparison to the surface of the top of the micro pattern as shown in Fig 6.

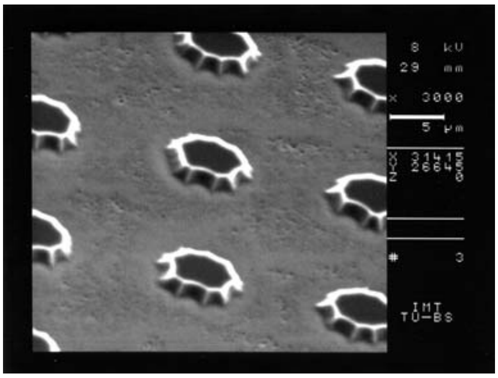

Fig. 6. SEM picture of the micro pattern using barrel plama etching process

In fact, the undercut of the pattern due to the isotropy of barrel etching is a desired effect. Various diameters of the pattern can be achieved by varying the etch depth. Furthermore, changing of the process parameters, e.g. plasma source power, pressure, gas flow, etc., also influences the etch rate. Using the 2^2 factorial experimental design technique, the effect on the etch rate of the momentous parameters, plasma source power and CF_4 flow rate, has been determined. The experiments are performed by a constant chamber pressure of 10 mTorr, O_2 flow rate of 20 sccm and an etch time of 5 min.

The highest etch rate of 600 nm/min. can be achieved by a plasma source power of 400 W and a CF_4 flow rate of 200 sccm, as shown in Fig. 7. A higher etch rate can be reached with low CF_4 flow rate. Furthermore, the source power and CF_4 flow rate do not interact to each other.

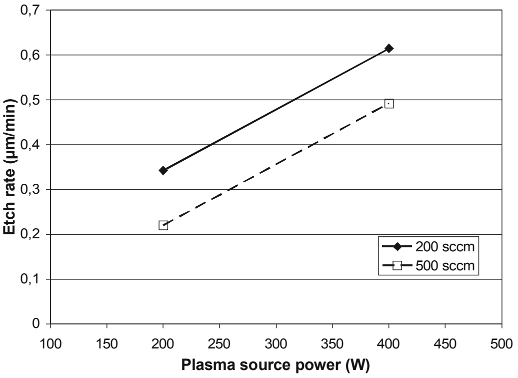

Fig. 7. Silicon etch rate versus source power and CF_4 flow rate

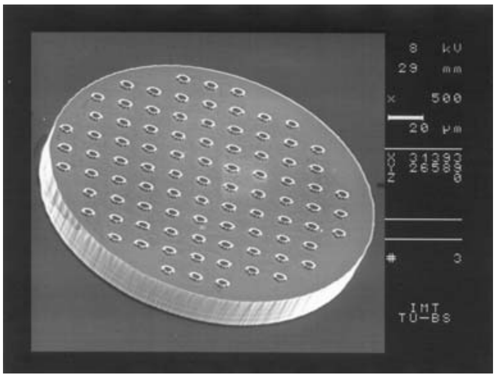

Fig. 8. SEM picture of a patterned cylindrical support structure with a diameter of 200 µm

Fig. 8 shows a patterned support structure with a diameter of 200 µm. The ICP dry etching process with a low etch rate assures a high uniformity and a high aspect ratio. For 20 µm etch depth the overall deviation of the depth is less than 2 µm over the whole 4” wafer. The thick resist can be used as a reliable masking layer, especially for this application, due to the short etching time of 17 min. For very deep etching or long process times (more than 30 min.) the resist will be damaged because of the high process temperature which causes the decrease of lateral accuracy and surface quality of the etched structures.

5 Experiment results

Two different designs of the micro linear guilds are tribologically investigated using the friction tester. Both designs have the support structures with a diameter of 200 µm and a distance to each other of 2.5 mm, so that the moving plate with a length of 5 mm is placed on only four support structures. The first design has a flat surface on the top of the support structures of the stationary plate. For the second design the micro pattern is fabricated on the top surface of the support structures. The moving plates which have a mass of 19.5 mg, with wet chemically etched V-grooves are used for both designs. Furthermore, both the stationary plates and moving plates were coated with a thin amorphous carbon (a-C) layer with a thickness of 0.5 µm used as a dry lubricating layer. The moving plate is placed on the stationary plate, which moves for 1 mm with a velocity of 100 µm/s. The dynamic friction force is simultaneously measured using a micro force probe [11]. All measurements are performed in steady room environment at a temperature of 25°C and a relative humidity of 35%RH.

Different weights are applied onto the moving plate to study the effects of the normal load on the friction force. The four measurements are made at each weight on diverse positions of the linear guides. Fig. 9 shows the friction force versus the normal load. Each point in the diagram represents the average friction force of each experiment.

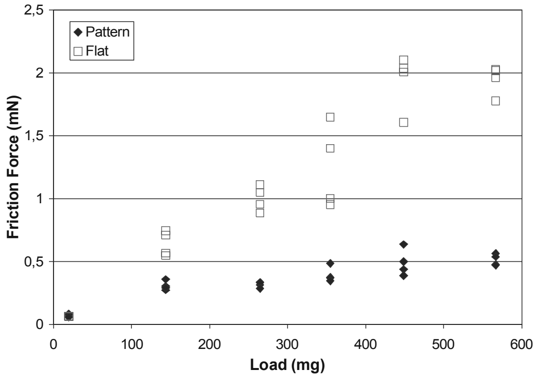

Fig. 9. Friction force of the micro linear guides with and without micro pattern on the support structures with varied normal load

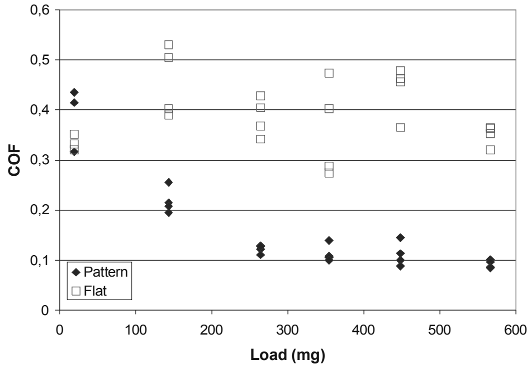

Fig. 10. Dynamic COF of the micro linear guides with and without micro pattern on the support structures with varied normal load

A dynamic friction force of 0.06 to 0.08 mN is measured at the lowest load for both guide designs. In case of increasing normal loads, the friction force of the first design significantly increase compared to the friction force of the second design. Furthermore, a strong scattering of the friction force of the first design can be observed. For the maximum load of 566 mg the friction force of the first design is approx. 2 mN, in contrast to the friction force of approx. 0.5 mN of the second design.

Fig. 10 shows the COF of both designs at the same range of the normal loads. The first design of the linear guides has an average COF in a range of 0.3 to 0.5. The COF of the second guide design has the same amount as the COF of the first design at the minimum load of 19.5 mg. On increasing the normal load the COF of the second design drastically declines at the beginning and approaches approx. 0.1 at the maximum load.

6 Conclusion

This paper presents the development of micro linear guides and the necessity for improvement of their tribological properties. Compared to wet chemical etching, the plasma dry etching process provides more flexibility and more possibilities to design various shapes of micro structures independent of the silicon crystal orientation. With this major advantage plasma etching is used to fabricate tribologically optimized micro linear guides.

We have demonstrated the fabrication process of the micro guide, which can be finished in only two photolithography steps with two different etching processes: barrel plasma and ICP etching. The ICP etching process allows the production of support structures with high aspect ratios and high lateral accuracy. In order to improve the tribological properties of the micro guides, the contact area on top of the support structure has to be reduced by patterning using isotropic barrel plasma etching. Due to the isotropy, the contact area can be varied by etch depth. We have described the effect of two major parameters on the silicon etch rate, the plasma source power and the etching gas flow rate.

Micro guides with various contact areas have been fabricated using the processes described above. The tribological properties of two designs of the linear guides have been investigated. In order to improve the tribological properties of the guides, a dry lubricating coating of a thin a-C layer has been deposited on the contact surfaces. The linear guides with flat support structures exhibit considerably the higher friction force and the COF compared to the guides with patterned support structures. Furthermore, the COF of the guides with flat support structures scatter in a wide range for all applied normal loads. In contrast, the COF of the guides with patterned support structures decrease by increasing normal loads.

The results show, the increase of contact surface pressure by arising normal load and the micro pattern can obviously reduce the dynamic friction force of the micro linear guides. Nevertheless, the further investigations of tribological properties of the micro pattern are necessary. Furthermore, the different forms of the micro patterns can also affect on the tribological properties. The optimization of the form and size of the micro patterns concerning the frictional behavior is hence required, in order to assure the functionality of the linear guides for the application on the active micro systems.

7 Acknowledgements

This work is supported by the Deutsche Forschungsgemeinschaft (DFG) in the framework of the Collaborative Research Center 516 “Design and Fabrication of Active Micro Systems”.

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