行政院國家科學委員會專題研究計畫成果報告

鏡面可調式內視鏡的研究
子計畫一：內視鏡用微馬達的研究（Ｉ）
Development of Micromotor for Endoscope Mirror Control (I)

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中文摘要

本文主要是研究微馬達的設計與製作。在製程考量方面，我們選擇了和半導體製程最為相容的表面微細加工技術，設計製作了一個靜電側邊驅動搖晃動式微馬達。我們並對此種設計提出改進之道，搭配上改進的製程，以期能提高微馬達製作的良率並使微馬達的效能提昇。其中有兩個主要的改進：其一是蝕刻阻擋的製作使得中央固定軸不至於在結構釋放的過程中被破壞，此一蝕刻阻擋並可以形成轉子接地的通路，減低轉子與下方基材間的電位差和吸力。其二是採用混合層來構成軸承間隙。我們利用濕氧化層的高均勻性與電漿輔助化學氣相沈積氧化層不消耗矽之特性來得到厚度為一微米的軸承間隙，此間隙可以有效克服反應離子蝕刻造成的結構鎖死並可能提供轉子一個供上的提昇力。在製程方面的努力與設計上的修正使我們製作出馬達主要的結構：分離且可動的轉子、定子、及聯結轉子與錨的軸承。但是由於反應離子蝕刻機台的效能不佳，結構邊壁的垂直度仍有待提昇。此外，我們亦建立了適用於此馬達設計的力矩數學模型。而利用此數學模型可以估計出在理想操作條件下微馬達的輸出力矩。

關鍵詞：靜電式微馬達、晃動式微馬達、表面微細加工、反應離子蝕刻

1. Abstract

This thesis focuses on the design and fabrication of micromotors. By using the surface micromachining technique, we designed and fabricated an electrostatic side-drive wobble micromotor. Moreover, we also made improvements on micromotor design and fabrication processes. There are two major new ideas: the first is the fabrication of the etching stop which protects the bottom of the anchor from being damaged during releasing. With this etching stop, an additional electric path from the rotor to the substrate is also established. This electric path is always effective and would reduce the potential difference between the rotor and the substrate. The second is the 1 μm bearing clearance composed by a mixed-layer, a wet oxide and a PECVD oxide layer. The former has the advantage of high conformality while the latter consumes no polysilicon. This thick bearing clearance can solve the interlocking problem posed by the non-uniform RIE process and may induce a lift force on the rotor. Due to the efforts on process and the modified design, we fabricated a micromotor with the free moving and separated rotor, the stator, and the bearing connecting the rotor and the anchor. But because of the low performance of the RIE machine we've used, the sidewalls were not vertical as expected. Improvements on this process step is required. In addition to the design and the fabrication process, we also established the torque model for our micromotor geometry. By using this model we can estimate the driving torque of the micromotor under ideal operation conditions.

Keywords: electrostatic micromotor, wobble motor, surface micromachining, RIE

2. Introduction

Surface micromachined micromotors have been extensively developed since the late 80's. From Trimmer's [1,2] original design of wobble mini-motor to the very recently micromotor designs [3-7], we can see great improvements on both process facility and performance. Maybe the driving torque of surface micromachined micromotors is not as large as those fabricated with thick-film techniques such as LIGA [8,9] or micro-assembly, but monolithic techniques still possess the greatest possibility for system integration. Among all fabrication techniques, surface micromachining has the advantage of being compatible with IC process, which means the ease for system integration and batch processing. After all, a micromachined device with on-chip circuitry is what really called MEMS.

There was one design among all others in the micromotor's evolution: the SOI-structured one [4]. This type of micromotor is structurally the same with the SIMOX absolute capacitive pressure sensor. It has the inherent advantages of being planar and easy to fabricate. Basically, there are three disadvantages in this design: the foundation of the central anchor is etched by concentrated hydrofluoric acid during the releasing phase. Besides, the electric path from the rotor to the substrate which reduces the potential difference between them may fail after being placed in an oxidizing environment, and the electric shield loses its function. Moreover, the bearing clearance formed by thermal oxidation reduces the thickness of the polysilicon structure, which further reduces the driving torque. For the above drawbacks, we present an modified micromotor design to overcome those problems. First, an etching stop which protects the foundation of the central anchor is fabricated to raise the yield. This etching stop is composed of polysilicon which renders another electric path from the rotor to the substrate. Note that this path is always connected. Second, the bearing clearance is made up by a mixed-layer, a thinner wet and a thicker PECVD oxide layer. The wet oxide layer is formed during the doping process and is as thin as 0.1 μm. The PECVD oxide constitutes the rest thickness of the bearing clearance. Since the gear ratio of this micromotor is dependent on the bearing clearance, we need larger bearing clearance for higher rotating speed.

3. Micromotor geometric and process design

A 4-mask process with several CVD and thermal oxidation layers forms the main part of the fabrication of the micromotors. One PECVD TEOS oxide film serves as the electrical isolation at first. Then we pattern the dielectric with the first mask. The first LPCVD polysilicon layers plays the role of the rotor and the stator. After RIE patterning the rotor, stator, and all interconnections, the oxide at the bearing position is etched to form a space which accommodates the bottom of the bearing. Next the wafer is doped with phosphorous and a thin phosphorous glass is formed on the polysilicon surface. A PECVD TEOS oxide layer is then deposited to the desired thickness of the bearing clearance. The bearing clearance is made by a mixed layer of wet and PECVD oxide because the wet one has better adhesion and step coverage while the PECVD one consumes no polysilicon.

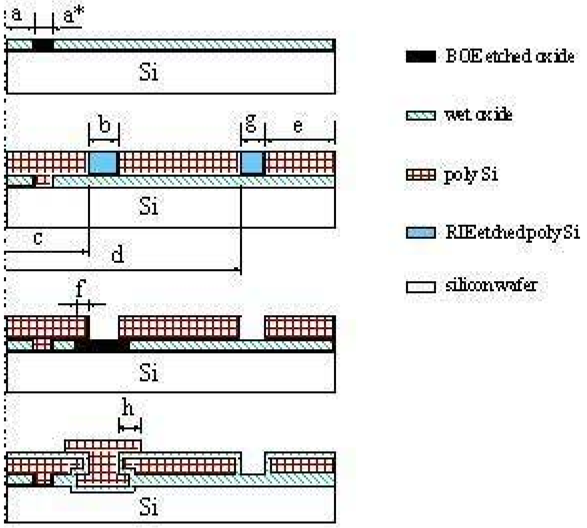

Figure 1 Fabrication process.

Next, the second LPCVD polysilicon layer constitutes the bearing structure. Patterning the top of the bearing and releasing in concentrated hydrofluoric acid finishes the whole process. A simplified plot of the fabrication process is shown in Fig. 1.

4. Micromotor modeling

In this section, we follow Trimmer's work [1] to derive the driving torque for our micromotor geometry, a micromotor with the bearing design as shown in Fig. 2. Starting from parallel plates capacitor and the potential energy stored in the gap, we can estimate the electrical energy stored between the sidewalls of the rotor and the stator-pole. By appropriately choosing the coordinate system, we can obtain the torque formulae in Eq. (1). To our surprise, it's the same as Trimmer's results:

$$\tau(\theta_s)_{driving} = N*\left(\frac{\varepsilon_0 t r_s V^2}{2}\right)\left(\frac{1}{d}\bigg|_{\theta_2} - \frac{1}{d}\bigg|_{\theta_1}\right) \quad (1)$$

$$N = \frac{r_{anchor}}{\delta} \quad (2)$$

$$\delta = \frac{BC}{4} \quad (3)$$

where

τ: driving torque

θ_s: angular position of the excited stator

N: gear ratio reduction between the electrical rotating speed and the real mechanical output

ε_0: permittivity of vacuum

t: thickness of the rotor

r_s: radius of the stator inner circumference

V: voltage applied

d: rotor / stator gap

θ_1: starting angular position of the excited stator-pole

θ_2: ending angular position of the excited stator-pole

r_{anchor}: radius of the anchor

BC: bearing clearance

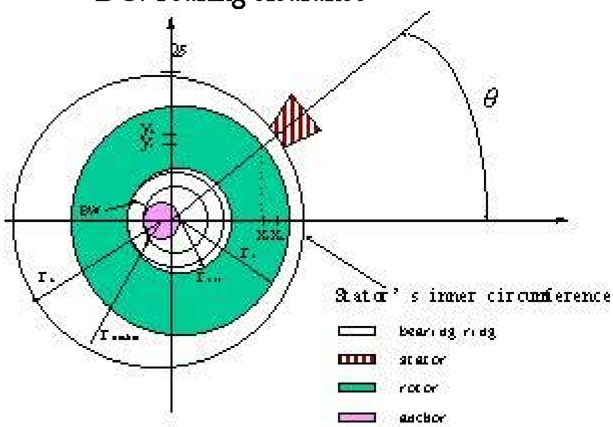

Figure 2. Coordinates and geometric arrangement of a micromotor.

5. Micromotor fabrication

Several runs of micromotor fabrication were carried out. Detailed experimental conditions and results can be found in [10]. The goals of our basic design were all realized. With the etching stop (as shown in Fig. 3), we don't have to worry about that the HF would undermine the anchor. We have an effective electric path to keep the rotor and the substrate at the same potential, which reduces the suction. The polysilicon consumption during the bearing formation is only 0.1 μm, 5 % of the rotor's original thickness. And the torque loss due to the polysilicon consumption is minimal. Fig. 4 shows the final structure of the releases micromotor. However, because of the low performance of the RIE machine we've used, the sidewalls were not vertical as expected. Future improvements on this process step is required.

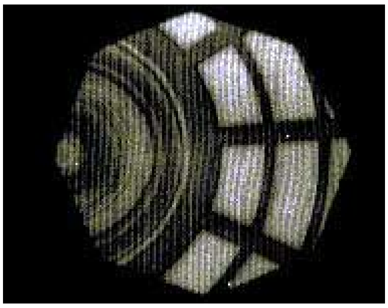

Fig. 3 Patterned rotor/gap/anchor on etching stop.

6. Conclusions

A design of the electrostatic side-drive wobble micromotor is presented with its torque equation derived from an energy-based model. A novel etching stop is designed to render an additional electric path between the rotor and the substrate. With this additional anchor post, the yield is also improved. A mixed oxide layer is used as the bearing clearance for better adhesion and step coverage. The improved design is successfully realized in our laboratory.

7. References

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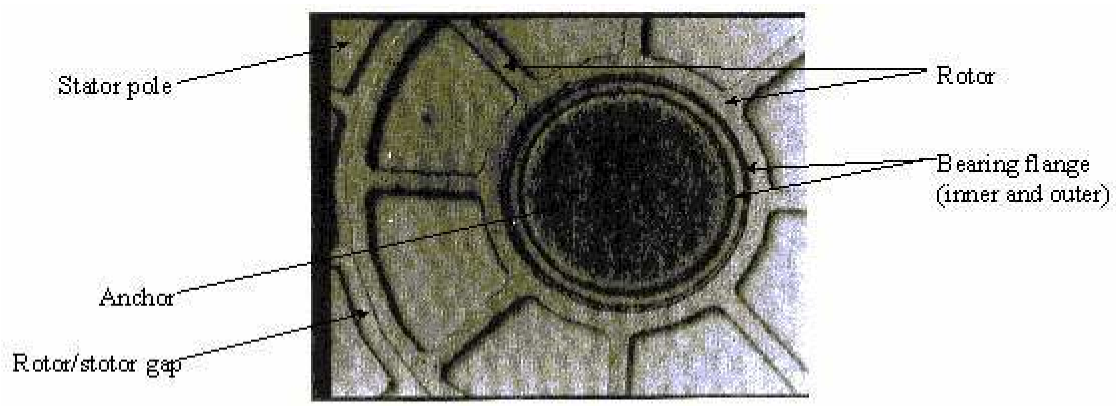

Fig. 4 The released electrostatic side-drive wobble micromotor.