MINIATURISED FRICITION FORCE MEASURING SYSTEM FOR TRIBOLOGICAL RESEARCH ON MAGNETIC STORAGE DEVICES

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Abstract

In this paper a silicon head slider suspension with integrated piezoresistive friction force sensors is presented. This device can be used for tribological research on magnetic rigid disk storage devices. Both the tangential and radial friction forces between the slider and disk, as well as a friction induced moment, can be measured simultaneously. Furthermore the normal load on the head slider can be measured.

The paper focuses on design considerations and the realisation process of the suspension. Friction measurements are included to illustrate the feasibility of the system.

Introduction

In rigid disk data storage devices a read/write head is mounted on a slider which is pressed on the disk by means of a metal suspension (see figure 1). During rotation of the disk a hydrodynamic air film is formed between the slider and the disk (typically 100 nm thickness), which reduces friction and wear. However, during starting as well as during deceleration of the disk (Contact Start Stop), the slider is in contact with the disk which results in high friction forces. When the slider starts to fly the friction forces decrease rapidly to a nearly constant low level that is typical for the flying condition. At present, normal operation conditions are in this flying region, but developments to higher storage densities will lead to a lower slider flying height and eventually contact between slider and disk during normal operation (contact recording).

As illustrated in figure 2, the friction force induced on the slider is a function of the disk velocity. The shown curve is, however, a time average of the actual friction force on the slider. The actual friction force is a dynamical quantity which extends over a certain frequency spectrum. Periodical waviness and texture in the disk surface will result in higher frequency components and at high disk velocities the fast solid contact interactions (collisions) between the slider and the disk will result in very high frequency components. As will be explained below, accurate measurement of such a dynamic friction force may be difficult or impossible due to the limited bandwidth of conventional friction force measure equipment. In a method commonly used to measure the friction forces, the slider/suspension assembly is mounted onto a flexible arm on which piezoresistive strain gauges are placed [2,3]. The sensitivity and resolution of such a measurement set-up are (among other parameters) determined by the gauge factor of the strain gauges and the stiffness of the flexible arm. The resolution can be increased by decreasing the stiffness of the system. If the system is considered as a single degree of freedom system, the resonances of such a mass-spring system are also determined by the stiffness k of the flexible arm - together with the mass m of the slider/suspension assembly (\( \omega_0 = \sqrt{k/m} \)). It can be shown that accurate measurement of frequency components higher than this resonance frequency is rather difficult, which means that the resonance frequency of the mass-spring system limits the bandwidth of the measurement equipment (typically 1 kHz).

It follows that there is a competition between the resolution (low stiffness) and the bandwidth (high stiffness) of the
measuring system. So, an increase in system performance (high resolution and bandwidth) can not be found in adjusting the system stiffness. The bandwidth, however, is determined by the stiffness and the slider/suspension mass. Therefore, the bandwidth can be increased by decreasing the equivalent mass. From this it follows that placing the strain gauges as close as possible to the slider will yield the highest bandwidth because in that case the equivalent mass is only determined by the small slider mass. Moreover, by making smaller sensors the resolution can be increased without affecting the system stiffness, as will be shown further on. The objective of the friction measurement system described in this paper was to increase the resolution and the bandwidth by replacing the conventional slider suspension by a silicon suspension. By using micromachining techniques a suspension with integrated strain gauges can be realised with mechanical properties, such as stiffness, resonance frequencies, comparable to a conventional suspension. In such a suspension the strain gauges can be made very small and may be placed very close to the slider.

Except for an increase in sensitivity and bandwidth of such a system, there are some additional advantages:

1. To obtain a desired resolution in a conventional measuring system, the stiffness of the flexible arm has to be rather low. However, this lower system stiffness promotes friction induced vibrations which influence the actual friction measurements [6]. This influence is reduced in the presented design because the system stiffness equals the system stiffness of a conventional suspension.

2. In conventional friction measuring systems generally only the friction force component in the tangential direction (with respect to the disk) is measured, with sensors located far away from the point where this force component acts on. However, the relative movement of the (rotating) disk surface with respect to the slider surface is not purely a linear motion. Friction between the surfaces will lead to a friction force with components in both tangential and radial direction as well as a friction induced moment on the slider. Selective measurement of a desired force component (with respect to other force components) is best accomplished close to the point where the force components act on. Moreover, integration of strain gauges in the gimbal system of the slider suspension enables direct measurement of all friction force components. For accurate wear studies and studies of the slider movement due to friction or slider disk interactions, monitoring of all friction force components may be of great importance.

3. The use of silicon and micromachining techniques is an important step towards the integration of the suspension/slider/head system. As an example of integration, the metal signal tracks to the head/slider and the strain gauges are easily integrated in the gimbal construction. Such integration may become important because the conventional signal wires as depicted in figure 1 affect more and more the rotational gimbal stiffness if the system is miniaturised.

**Design considerations**

**Design criteria**
The design criteria for the suspension can be specified by careful investigation of the conventional disk/slider/suspension system (especially the gimbal construction), in combination with the desired properties of the friction measurement system.

Figure 1 gives the system set-up of a conventional stainless steel slider suspension. The appropriate slider load to press the slider against the disk (about 70 mN) is provided by a spring region near the base of the suspension. The slider is mounted to the suspension via a gimbal construction with a very low pitch and roll stiffness (rotation around the x and y axis), needed for good flying characteristics and to adjust aligning deviations between slider and disk. These stiffnesses should be negligible (= 1000 times smaller) with respect to the roll and pitch stiffness induced by the air film between the slider and disk during normal operation.

The gimbal construction should be rigid for translation in x and y directions. This will result in a large bandwidth of the measuring system (25 kHz). The gimbal construction should also be rigid for translation in the z direction and rotation around the z axis.

Another important design restriction is set by the maximum peak forces (or applied deformations) that should be resisted by the construction, without approaching the yield strength of silicon. For the translation components, the peak forces are specified by the expected maximum forces on the system. For rotation around the x and y axes, a maximum rotation of the slider can be defined by the maximum parallel alignment error between suspension and disk; stresses in the construction should not exceed the yield stress due to this rotation.

The described mechanical properties of the gimbal construction can be generalised to a spring constant and a maximum force or displacement for each of the six degrees of freedom, see table 1.

The last essential design restriction is the possibility to integrate strain gauges in the construction, in such a way that the friction force components can be measured in a sensitive and selective way.

<table>
<thead>
<tr>
<th>direction</th>
<th>spring constant</th>
<th>max. force or displ.</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>$k_x &gt; 1.1 \times 10^5$ N/m</td>
<td>$F_{x,\text{max}} = 200$ mN</td>
</tr>
<tr>
<td>y</td>
<td>$k_y &gt; 1.1 \times 10^5$ N/m</td>
<td>$F_{y,\text{max}} = 200$ mN</td>
</tr>
<tr>
<td>z</td>
<td>$k_z &gt; 350$ N/m</td>
<td>$F_{z,\text{max}} = 100$ mN</td>
</tr>
<tr>
<td>$\theta_x$</td>
<td>$k_{\theta_x} &lt; 6.2 \times 10^{-5}$ Nm/rad</td>
<td>$\theta_{\theta_{\text{max}}} = 2^\circ$</td>
</tr>
<tr>
<td>$\theta_y$</td>
<td>$k_{\theta_y} &lt; 2.2 \times 10^{-5}$ Nm/rad</td>
<td>$\theta_{\theta_{\text{max}}} = 2^\circ$</td>
</tr>
<tr>
<td>$\theta_z$</td>
<td>related to $k_x$ and $k_y$</td>
<td>related to $F_x$, $F_y$</td>
</tr>
</tbody>
</table>

**Piezoresistive force sensor**
The basic principle of a piezoresistive force sensor is drawn in figure 3. The force that acts on the cantilever beam induces a bending moment $M$ in the beam. This beam can be part of a mechanical construction, such as an accelerometer or friction force sensor; it can be both a single or a double clamped beam. The bending moment results in longitudinal strains in the beam (in the y direction), positive at the top side and negative at the bottom side of the beam. In the x direction, the

![Piezoresistive force sensor](image)

Figure 3. A cantilever beam with strain gauge for force measurement.
The influence of each of these four steps on the sensitivity and for a force component

In this work a Wheatstone bridge was used to sense the resistors have the same value in unstrained condition, a very forces that act on the 'table'. If only one force component acts

resistance, the output voltage of the bridge equals:

Figure 4 shows an example of a mechanical construction in which cantilever beams with strain gauges are used to measure forces that act on the 'table'. If only one force component acts on the table that has to be measured, the situation is rather simple. The situation is more complicated if various force components act on the system, and one or more of these components should be measured as sensitive as possible, and selective with respect to the others. In such a case, it is important to optimise the system as a whole.

In a piezoresistive force sensor, different steps in the transformation from force to an output voltage can be distinguished, which can be optimised one by one. First of all, the type of construction determines how the different force components are transferred to the cantilever 'measurement beams'. Secondly, the dimensions of the measurement beams and the location of the strain gauges on these beams determine how the different force components are transferred to one strain in each of the strain gauges. Thirdly, the gauge factor of the strain gauges (determined by the type of strain gauges and the processing parameters of the strain gauge material) influences the sensitivity. Fourthly, the read-out electronics can be used to separate the desired force components from the resistance variation of several strain gauges. This is only possible if these measurements form an independent system of the desired force components. In our case a Wheatstone bridge with four different strain gauges was used.

The influence of each of these four steps on the sensitivity and selectivity will be investigated, starting at the last step.

Wheatstone bridge

In this work a Wheatstone bridge was used to sense the resistance changes. Under the assumptions that the four resistors have the same value in unstrained condition, a very small relative resistance variation, and a very small series resistance, the output voltage of the bridge equals:

where \( V_{oc} \) is the voltage supply across the bridge. From this expression follows that the sensor has a maximum sensitivity for a force component \( F \); if this force component induces strains in \( R_1 \) and \( R_2 \) that are equal but opposite from strains in \( R_3 \) and \( R_4 \) (e.g. at both edges of a normal loaded clamped beam). On the other hand, if an unwanted force component \( F_j \) induces strain in the strain gauges, this component can be suppressed by strategic positioning of the strain gauges so that \( \Delta R_1 + \Delta R_2 - \Delta R_3 - \Delta R_4 = 0 \). However, this way of suppression is not very effective because exact subtraction of the signals to zero is difficult (due to alignment errors, variation of resistance and gauge factor, etc.).

Piezo resistivity

Assuming a biaxial strain field \( (\varepsilon_x, \varepsilon_y) \) in a piezo resistor, the relative resistance change can be written as [8-10]:

where \( G_l \) and \( G_t \) are the longitudinal and transverse gauge factors. The resistance change in metal strain gauges is dominated by a change of geometrical dimensions, which means \( G = 1 \). In semiconductor strain gauges \( G \) is much higher due to a strain induced bandgap change which causes a change of conductance (\( G = 50 \)). This effect is strongly anisotropic in mono-crystalline silicon, whereas it shows a lower but rather isotropic effect in polysilicon.

By using semiconductor strain gauges with a relatively high resistivity in combination with metal connection lines, very small and sensitive strain gauges can be created. No loss of sensitivity will arise due to high series resistances, which would reduce the sensitivity by a factor of \( R_\sigma/(R_\sigma + R_{tune}) \). This effect necessitates the use of area consuming meander structures in metal strain gauges. Polysilicon strain gauges were used because they can be deposited on a wide range of insulators, whereas monocrystalline ones should be defined by p-n junction isolation which limits their performance. For polysilicon, the gauge factor, the resistivity and the temperature coefficient of the resistivity are all strongly dependent on the doping level [10]. Optimisation of these factors for p-doped material lead to a small variation of doping levels (1·10^19 - 2.5·10^{19} cm^{-3}) and corresponding resistivities that could be used, at a high value of \( G_t \). The final resistance of a strain gauge could be chosen within a range of 1 - 100 k\( \Omega \) by varying the resistivity and the dimensions of the strain gauge. Note that this resistance does not influence the sensitivity directly, but it plays an important role in the optimisation of the signal to noise ratio of the sensor [1].

Force-strain transformation

The static force-strain transformation of a measurement beam, \( H_{f,s} \), can be written as (see also figure 5):

where \( H_{f,s} \) stands for a proportionality factor between the displacement and the strain in the strain gauge, and \( k \) for the spring constant. If the strain gauge is small, the strain \( S \) in the sensor due to a displacement \( x \) of the tip can be regarded constant over the sensor area. The strain sensitivity \( H_{s,s} \), can easily be deduced:

where \( S \) denotes the strain, and \( d \) and \( l \) the thickness and length of the beam respectively. The spring constant of the beam is given by:

where \( E \) is Young's modulus, \( I \) is the second moment of area, \( I = \frac{d}{4} \), and \( k \) is the spring constant.
where \( E \) denotes the elastic modulus and \( w \) the width of the beam. From equations (4) and (5) it can be seen that, under the condition that \( d^2w/l^2 \) is kept constant, smaller beam dimensions will lead to a higher strain sensitivity without changing the stiffness of the beam. This is an important additional advantage of using micromechanics to miniaturise (friction) force sensors. The strain gauge is located at a position of maximum stress and strain on the beam, which should be kept well below the yield stress of silicon to prevent fracture. Therefore, the limitation in the size reduction, and therefore the limitation of the maximum obtainable strain sensitivity, is determined by the maximum expected forces on the system (in our case as specified in table 1).

Concerning optimisation of the selectivity, strain due to a force component in the \( z \) direction (figure 3) can be suppressed by locating the strain gauge on the middle line (on top) of the beam. However, this method of force suppression is rather sensitive to alignment errors of the strain gauges.

Construction

The gimbal construction must satisfy the design criteria, and it should be possible to realise the construction using bulk micromachining techniques.

Above, some methods were mentioned that may be used to measure a force component in a selective way. However, the best method is to build a construction in which all force components are mechanically decoupled from the measurement beams, except the force component that should be measured. This has the additional advantage that the dimensions of the measurement beam can be optimised towards the properties of this specific force component (spring constant, sensitivity, max. force, etc.).

In table 2 a comparison is made, based on the presented design criteria, between several planar constructions. The important properties were modelled using linear elastic methods. Of course, all presented properties interact with each other, and one property may be optimised at the expense of another. Note that all constructions need a kind of support in the centre of the slider to define a high stiffness in the \( z \) direction. The combination of low roll and pitch stiffness and a stiffness in the \( z \) direction high enough to apply a normal load without excessive deformation cannot be realised with a planar beam construction.

Only constructions e and f fulfill the desired mechanical properties, but in construction e the forces are not mechanically decoupled from the beams, which means that selective measurement of forces is difficult.

Design

The designed silicon suspension is depicted in figure 5, and is based on construction f in table 2. The slider is glued onto a table which is suspended by the four L-shaped beams. The centre of the table is supported by a flexible support beam bonded to the table. This results in the desired high stiffness in the \( z \) direction, without influencing the other stiffnesses. For a contact recording slider suspension, in which the normal load is considerably lower, the support beam is not necessary. As in a conventional suspension the down force spring is located near the base of the suspension. Strain gauges are located on this spring, which can be used to sense the down force.

The long beams of the gimbal construction have a low stiffness for translation and rotation in all directions, except for translation in their axial directions. These properties result in the desired low stiffness for rotation of the slider. The rotational spring constants for pitch and roll are only determined by the dimensions of the long beams. The short beams play no role for this rotation.

The (friction) forces acting on the slider in the \( x \) and \( y \) directions are decoupled in the gimbal construction. Forces in the \( x \) direction are only opposed by L-beams 1 and 3 because beams 2 and 4 have a very low stiffness in the \( x \) direction, see figure 6. Therefore, short beams 1 and 3 can be used as a couple of measurement beams for \( F_x \), and short beams 2 and 4 for \( F_y \). By adding the force signals of the paired measurement beams play no role for this rotation.

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![Figure 5. Final design of suspension with integrated friction sensors.](image)

![Figure 6. Integration of piezoresistive strain gauges in the gimbal system. Dimensions long beams: length = 1.3 \( \mu \)m, width = 89 \( \mu \)m, thickness = 45 \( \mu \)m; short beams: length = 170 \( \mu \)m, width = 100 \( \mu \)m, thickness = 45 \( \mu \)m.](image)
beams, the corresponding force on the slider can be calculated, and by subtracting the force signals the friction induced moment around the z axis can be determined. This may be done by exchanging the strain gauges in the Wheatstone bridge or by measuring the force signals with two half bridges and subtracting these signals.

The rotation of the slider can be measured with strain gauges on top of the long beams, which measure the surface strains due to the deformation of these beams. If the table rotates around the x axis, beams 1 and 3 bend like double clamped beams (in combination with torsion), and beams 2 and 4 bend more like single clamped beams. This means that the surface strain due to this rotation halfway beams 1 and 3 equals zero, whereas the surface strain of beams 2 and 4 is nonzero at the same positions. This property enables selective measurement of both rotation angles. Unfortunately, the sensitivity of these sensors is too low to sense the variations of microradians during steady flying of the slider, and moreover, the influence of the friction force (which induces axial strain in the long beams as well) on the sensors has to be subtracted to obtain the correct signal.

The stiffness relations of the gimbal system and the down force spring regions have been calculated using the linear elasticity theory for the bending of beams [11]. Calculation models for stiffness, sensitivity, maximum stresses in the construction, and relevant resonance frequencies are used to find the proper dimensions of the construction. These are given in figure 6.

**Realisation**

Figure 7 shows the processing scheme of the suspension. First, two layers of LPCVD Silicon nitride ($Si_3N_4$) with a boron ion beam doped LPCVD polysilicon layer in between are deposited on a 280µm thick silicon substrate (<100>, p-type). The silicon nitride is used as an electrical insulation layer for the strain gauges and as an etch mask in further process steps. The doped polysilicon is used as the piezoresistive material.

In the second step the gimbal and down force spring regions are defined (figure 7a). Therefore, the lower silicon nitride layer and the polysilicon layer are removed from the bottom side of the substrate and the remaining silicon nitride layer is patterned using standard lithography methods. Etching is done with reactive ion etching (RIE) from a CHF$_3$/O$_2$ plasma. The remaining silicon nitride acts as a mask during the etching of the table and down force spring regions to the desired thickness (45µm) in a 25% aqueous potassiumhydroxide (KOH) solution. Next, see figure 7b, the upper silicon nitride layer is removed in a 50% hydrofluoric acid solution and the strain gauges are defined in the polysilicon layer by standard lithography and RIE. Electrical connections are realized by E-beam evaporation of aluminium and patterning by lift-off lithography. The aluminium is annealed for 1 hour at a temperature of 400°C to obtain a good ohmic connection to the polysilicon strain gauges.

Now, the strain gauges and aluminium are protected with a layer of photoresist. The regions where the support holes will be etched (a few steps later) are patterned in this layer of resist that will act as a buried mask. These support holes will be used for a pin-hole connection, when the support is connected to the gimbal construction. The resist is baked for 1 hour at 150°C in a nitrogen environment to evaporate all the solvent from the resist. On this, an aluminium mask is deposited (E-beam evaporation) in which the gimbal construction and the suspension outline is defined, see figure 7c. This pattern is transferred to the underlying layers using RIE from a SF$_6$/CHF$_3$/O$_2$ plasma. Process parameters are chosen such that an optimal anisotropic etch profile is obtained [12,13] resulting in prismatic suspension beams. The aluminium mask is removed by wet etching, so that the buried mask is released. The support holes are etched using a similar RIE SF$_6$/CHF$_3$/O$_2$ plasma that was used for defining the gimbal construction, see figure 7d. Finally, the resist mask is removed by an oxygen plasma.

The support is etched from a separate substrate using the same anisotropic RIE method with an aluminium mask. After dicing, the support is bonded onto the gimbal, see figure 7d. This may be done by anodic bonding, with which it should be possible to bond both the side poles of the support as well as the thin support beam. However, the process for realisation of the support beam is not optimised yet and only rather large dimensions of support beams could be realised (50×50×60 µm). If such a support beam is bonded onto the table, the sensitivity for the friction force will decrease drastically. Therefore, as a first approach, the support is bonded only at the pin-hole connections (at the frame around the gimbal construction) by means of an epoxide glue. Positioning of the support in this way was

![Figure 7. Processing scheme of the silicon suspension.](image)

![Figure 8. (a) Gimbal region of the suspension. The black beam is the silicon support, glued to the gimbal region. A slider is glued to the backside.](image)
A gauge factor of 26 was measured, which is in good agreement with values found by others [8,10]. To calibrate the sensors, the sensitivity of the gimbal construction for the various forces and rotations was measured, and compared with results from modelling. Good agreement was found. Equivalent noise levels were calculated to give an impression of the resolution of the sensors, see table 3.

<table>
<thead>
<tr>
<th>( F_x = F_y , [\mu N] )</th>
<th>( M_{z} , [\mu N , \text{mm}] )</th>
<th>( F_z , [\mu N] )</th>
<th>( \theta_x = \theta_y , [\mu \text{rad}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>70</td>
<td>51</td>
<td>25</td>
</tr>
</tbody>
</table>

The gimbal construction could stand twice or three times the specified maximum forces. However, the down force spring appeared to be the most fragile part of the construction.

Finally, the suspension was tested on a rotating disk, see figure 10. The friction force showed the expected decay at increasing disk velocity, and also higher frequent variations due to irregularities on the disk surface could be measured. These are plotted in more detail in figure 11.

References


