Proceedings of IMECE2009 2009 ASME International Mechanical Engineering Congress and Exposition November 13-19, Lake Buena Vista, Florida, USA

IMECE2009-11076

IMPROVED FABRICATION OF AN INTEGRATED ELECTROMAGNETIC SECOND STAGE MICROACTUATOR FOR A HARD DISK RECORDING HEAD

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ABSTRACT

Key mechanical requirements for advanced Hard Disk Drive (HDD) recording heads are a minimal flying height and a perfect track following. By applying Micro Electro-mechanical Micro Systems (MEMS) technology, a Slider with an Integrated Microactuator (SLIM) enabling both in a cost competitive way was created. This paper describes the fabrication process for the system's electromagnetic microatuator and emphasizes the technology enhancements achieved after a process redesign.

INTRODUCTION

A precondition to achieve an optimal recording density is a hard disk recording head which provides both a flying height adjustment and a second stage actuation capability for fine tracking [1-3]. To fulfill these requirements in a cost competitive way, a slider with an integrated microactuator (SLIM) was proposed [4]. A variable reluctance (VR) electromagnetic microactuator integrated into a pico formfactor slider (1,240 μ m x 990 μ m x 300 μ m) activates a mounting platform which has a chiplet attached to it. The chiplet carries the read/write element. The microactuator is capable of moving the read/write element up and down (for head-to-disk spacing adjustment) as well as on an arc in lateral direction (allowing second stage actuation) [5]. Figure 1 shows a schematic representation of the SLIM design compared to a commercial slider.



Fig.1. Comparison of a commercial silder and SLIM.

While the initial microactuator fabrication run of the SLIM device delivered functional parts [6], there was still room for technology improvements. A fabrication issue causing a major

yield hit was a step at the rim of the epoxy based embedding. It turned out difficult to reliably remove the seed layer required for the electrodeposition of the coil layers and pole structures by ion milling, which resulted in short circuits. A double mask change solved this issue. In addition, the processes for patterning the vertical insulation layers were improved significantly. By accomplishing a better reference for defining the end of the planarization process, the layer thicknesses could be adjusted with a higher accuracy and repeatability. Furthermore, the photolithography and electroplating processes were optimized with respect to a steeper flank angle and higher quality of the deposited structures.

MICROACTUATOR DESIGN

Based on Finite Element Method (FEM) analysis results achieved by the software tool ANSYSTM Multiphysics, the optimal dimensions for the microactuator were determined [6]. The technological aspects of the thin-film fabrication were taken into account during the simulations. Important parameters for the fabrication are aspect ratio and flank angle, which are defined by the photolithography processes. The resulting microactuator consists of two subsystems, each featuring a U-shaped soft magnetic core and two double-layer spiral coils for the excitation (Fig. 2).



The total size of a subsystem is 438 μ m x 282 μ m x 61 μ m (length x width x height). Each pole carries a double-layer coil with a conductor thickness of 40 μ m. The total number of turns of a microactuator subsystem is 20. The thickness of the magnetic core is 20 μ m and the thickness of the flux closure 10 μ m. A cross section through the microactuator is shown in Fig. 3. For this actuator design, a 2-D simulation predicted a magnetic force of about 355 μ N at an air gap of 2.5 μ m between the poles and the top flux guide while exciting the coils with a current of 175 mA. A 3-D simulation resulted in a magnetic force of about 340 μ N for the same air gap.



Fig.3. Cross section through the electromagnetic microactuator.

MICROACTUATOR FABRICATION

Basics

The microactuator was fabricated using thin-film technology under clean-room conditions. Since the energy converted by a microactuator is proportional to its volume [7], High Aspect Ratio Microstructure Technology (HARMST) was applied for the actuator fabrication.

The materials employed were NiFe45/55 for the magnetic flux guides and magnetic poles, Cu for the coils, low stress Si₃N₄ for the vertical insulation between the coil layers as well as between coils and core, and a photosensitive epoxy (SU-8TM) for embedding. The latter also accomplishes the lateral insulation between the coil windings. To achieve a constant layer thickness as well as flat surfaces, Chemical-mechanical Polishing (CMP) was applied. As mentioned before, permalloy NiFe45/55 was chosen as magnetic material since previous investigations proved its suitability for actuator applications [8, 9]. It has a saturation flux density of 1.6 T and a high relative permeability. By using Si₃N₄ deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) for the vertical insulation, the total height of the microactuator could be minimized. Compared to the use of SU-8TM for the vertical insulation, Si₃N₄ allows a reduction of the total height of the actuator from 90 μ m to 61 μ m. Furthermore, the Si₃N₄ deposited by PECVD shows excellent edge coverage, minimal tensile stress, and a good transfer of the Joule's heat created in the coil.

Fabrication Steps

For the fabrication of the microactuator, a $525 \,\mu\text{m}$ thick SiO₂ wafer was used. This ultimately requires a thinning to a height of 100 μ m for the application in the SLIM device during system integration [5]. Figure 4 and Tab. I depict a schematic representation and a process sequence, respectively, of the microactuator fabrication sequence. The left column of Fig. 4 shows the steps to form the device itself, while the right column presents utilities like fiducials, leads, and contact pads.



First Level

The fabrication process started with creating the fiducials. Of the magnetic system itself, the bottom magnetic flux guide was fabricated. Furthermore, electrical leads and vias to ultimately serving as contacts between electrical leads and coils were created. For any of these components, first a 50 nm thick Cr adhesion followed by a 200 nm thick Au layer was sputter deposited. Next, a photolithographically patterned photoresist served as micromolds which were filled by electroplating. The material for the flux guide and the fiducials is NiFe, while for the leads and Vias it is Cu. At the end of this process sequence, an Ion Beam Etching (IBE) step removed the seed layer to avoid short circuits (Fig. 4a).

Tab. I. Process steps			
Nmbr	Level	Device	Utility
1	First Level	Bottom	Fiducials,
		magnetic flux	Leads,
		guide	Vias
2	Intermediate	Insulation	
3	Second Level	First coil layer,	
		Poles (first part)	
4	Intermediate	Insulation	
5	Third Level	Second coil	
		layer,	
		Poles (second	
		part)	
6	Final	Protection	Contact pads

The next process step aims at embedding the bottom flux guide. The embedding material is SU-8TM. After the embedding, a Chemical-mechanical polishing (CMP) planarizes the structures created so far.

Intermediate between First and Second Level

To avoid a short circuit between the future coils and bottom flux guide, a vertical insulation layer is required. It was created by a PECVD deposition of a 250 nm thick Si_3N_4 layer. For creating a windows for the poles and vias, the Si_3N_4 layer was patterned by using an etching mask made of a positive tone AZ photoresist, followed by an IBE step and resist stripping (Fig. 4b).

Second Level

In the second level, two things were accomplished: the first coil layer was created and the core's poles were built up to the same top level as the coils. First, as before, a Cr/Au seed layer deposited. Next, AZ micromolds were created was photolithographically, followed by a Cu electroplating step to create the coil layer. Afterwards, the photoresist was stripped and the seed layer was removed by IBE (Fig. 4c). Then, the fabrication of the first part of the magnetic poles started with the sputter deposition of a 400 nm thick NiFe45/55 seed layer with a 50 nm Cr adhesive layer underneath. Next, an AZ photoresist mask was created photolithographically serving as a micromold for the electrodeposition of the first part of the magnetic poles. Then, the photoresist was stripped and the NiFe45/55 seed layer and the Cr layer below were removed by IBE (Fig. 4d). To finish this sequence, the coils and the first part of the magnetic poles were embedded in a lateral SU- 8^{TM} insulation layer. Using CMP, the first part of the magnetic poles and the bottom coil layer were planarized.

Intermediate between Second and Third Level

As before, an insulation layer is required between the second and the third level, this time to vertically insulate the two coil layers. Therefore, another Si_3N_4 layer was deposited

by PECVD serving as vertical insulation between the coil layers (Fig. 4d). The next step was patterning the Si_3N_4 layer to create windows for the poles and the vias (Fig. 4e).

Third Level

In the third level, the second coil layer was fabricated. Furthermore, the core's poles were further increased in height, as before to the same top level as the coils. For fabricating the coil layer as well as the poles, the same fabrication sequence was applied as for the bottom coil layer and the first part of the poles. Figure 4f depicts the completed coil and pole structures. Afterwards, the top coil layer and the second part of the poles were also embedded in SU-8TM and then planarized using CMP.

<u>Final</u>

To complete the device, a protective top layer was created and the contact pads were completed. To do so, a final Si_3N_4 layer was deposited as a protection layer and patterned by IBE to create windows for the pads which are necessary for the electrical contact. For the completion of the contact pads, another Cr/Au seed layer was sputter deposited and then, an AZ micromold was created. Finally, the Cu contact pads were covered by electroplated Ni serving as a diffusion barrier and Au required for the bonding process. Figure 4g depicts a cross section through the completed microactuator.

PROCESS OPTIMIZATION STEPS

In the following, some examples for process optimizations are given. Afterwards, the main issues during the first fabrication run are discussed.

AZ Micromolds for Electroplating

As micromold for the electroplating processes, photomasks were used. These photomasks consisted of the positive tone resist AZ 9260, which is highly viscous and may be applied in a single spin-coating run to a thickness of up to 27 μ m. The AZ layer was patterned by UV depth lithography to create a micromold for the electroplating step. With this positive tone AZ resist, aspect ratios from 5:1 to 7:1 can be achieved. After the electroplating process, the AZ resist was removed by solvents.

During the microactuator fabrication, a single spin-coating step was applied for the different micromolds, only for the top coil layer und the second part of the poles, two spin-coating steps were required. For every mask step, the process parameters like spin-on rate, temperature ramps for soft and hardbake, exposure time, and development time must be adjusted to create a suitable micromold for electroplating. Figure 5 depicts the optimization of micromold for the electrodeposition of the bottom coil layer. All process parameters in Fig. 5a to Fig. 5c are identical, only the exposure time was varied. Figure 5a shows a micromold which is not completely developed after an exposure time of 90 s and a development time of 300 s. With an exposure time of 180 s and the same development time, a suitable micromold coulde be achieved (Fig. 5b). However, an exposure time of 270 s combined with a development time of 300 s disabled the micromold.



Fig.5. Optimization of the exposure time for the bottom coil layer.

Electroplating Process

An important parameter for electroplating is the current density. Therefore, the current applied for the electroplating process depends on the area to be covered and on the type of the deposited material. For example, for the Cu coil layers, a current of 800 mA was used, while 100 mA were required for the Ni fiducials, and only 30 mA for the Au deposition on top of the contact pads. Since the electrolyte is subject to fluctuations, previously to every deposition, a test wafer was processed to prove the deposition rate and the surface quality of Au, Cu, and Ni. Figure 6 depicts a suitable test deposition for bottom coil layer.



Fig.6. Test deposition result for the bottom coil layer.

For the deposition of NiFe45/55, pulse plating was applied to adjust the ratio of 45 at.% Ni and 55 at.% Fe. Suitable results were achieved with 400 mA forward current and 40 mA reverse current with a pulse ratio of 9 ms forward and 1 ms reverse for both parts of the poles, and 600 mA forward current and 60 mA reverse current with the same pulse ratio for the flux guides. Compared to Au, Cu, and Ni, the test depositions for this alloy additionally used to prove the atomic ratio of Ni and Fe with Energy Dispersive X-ray Spectroscopy (EDX) before the proper plating on the actuator wafer was done. Figure 7 depicts an almost perfect EDX result for the bottom flux guides with 44.99 at.% Ni and 55.01 at.% Fe.



Fig.7. EDX result for NiFe45/55 intended for the fabrication of the bottom flux guides.

SU-8[™] Embedding Material

SU-8TM is a high contrast, epoxy based photoresist, which features an excellent chemical and thermal stability. Above 360 nm, the resist has a very high optical transparency and achieves vertical sidewalls in very thick layers. Since the exposed and subsequently cross-linked areas of the layer are rendered insoluble to liquid developers, SU-8TM is left on the wafer and therefore ideal for the embedding of electroplated structures. For the microactuator fabrication, SU-8TM 25 was used. As a drawback, the epoxy SU-8TM cannot provide an insulation layer with a desired thickness of less than 1 µm. In addition, SU-8TM tends to intrinsic stress which affects the reliability of the microactuator since the stress might lead to delaminations of the structures. Therefore, SU-8TM was only used as embedding to fill up the lateral spaces and not for the vertical insulation. For creating a 250 nm thick vertical insulating layer, a PECVD process was applied.

Chemical-mechanical Polishing

Chemical-mechanical Polishing (CMP) is a standard process in the semiconductor fabrication and is also widely used in the fabrication of Micro Electro-mechanical Systems (MEMS). Being a fundamental part of HARMST, CMP enables the fabrication of micro components with rather great building heights in a variety of materials [7, 10].

Within the microactuator fabrication, CMP was applied to planarize the surface of the electroplated materials after

embedding in SU-8TM. This process was necessary due to the waviness of the surface after electroplating thus establishing a plane surface for the consecutive processing. During the first fabrication run, the vias, the bottom flux guide, the two coil layers, as well as the first and the second part of the poles were deposited at a height of 25 µm, leaving a nominal stock for CMP removal of 5 µm. The height was then reduced by CMP down to the desired height of $20\,\mu\text{m}$. Since the surface waviness of the electroplated Cu structures is much smaller than for electroplated NiFe45/55, only the Cu structures were used as reference during the second fabrication run. The NiFe45/55 stock of 5 µm for the CMP removal was left untouched, while the one for Cu structures was reduced to 2 µm. As reference structures for the CMP processes, the vias of the electrical leads were used for planarizing during the first level, the bottom coil layer during the second, and the top coil layer during the third. This way the height tolerance of the microactuator could be minimized to $\pm\,1\,\mu\text{m}.$ This was necessary since the actuator building height directly influences the functionality of the SLIM device.

In both fabrication runs, a P. Wolters 3R40 dual-axis polishing machine (adapted for CMP) in combination with an IC1400 pad (with an IC1000 polyurethane upper pad and a gray foam sub pad), and a MSW1500 slurry were used. Figure 8 depicts the first SU-8TM embedding containing the bottom flux guide and the vias (intended for contacting the electrical leads and the coil layers) before (Fig. 8a) and after (Fig. 8b) CMP.



Fig.8. First SU-8TM embedding with the bottom flux guides and vias before (a) and after (b) the CMP step.

Si₃N₄ Vertical Insulation Layer

An inorganic Si_3N_4 insulation layer deposited by a PECVD process covers the whole wafer surface with an even coat and also show an excellent edge coverage. Films with a very low tension (a tensile stress down to 33 MPa) can be achieved by applying frequency mixing [7]. Beside the low tensile stress, another advantage of Si_3N_4 used as insulating material is its relative high thermal conductivity of 29 W/(m*K), which can improve the transfer of the Joule's heat created in the micro coils.

Due to these material properties and since Si_3N_4 allows a reduction of the total height of the microactuator from 90 μ m to 61 μ m compared to the use of SU-8TM, the PECVD process was applied for the deposition of 250 nm thick vertical insulation layers within the microactuator fabrication. But, as mentioned before, SU-8TM was still applied for the lateral embedding.

A challenge during the first fabrication run concerning the PECVD process was a sporadic delamination of the Si_3N_4 layers. To resolve this issue, the process temperature was increased from 100°C to 150°C, which was expected to increase the adhesion of the Si_3N_4 layers. Furthermore, an additional thermal process (hardbake for approximately 30 min at 150°C) for the SU-8TM to remove all solvents contents, was accomplished directly before the PECVD process. After these adjustments, no delaminations were observed anymore.

Another challenge was the patterning of the Si₃N₄ layers to create windows for the connection of the electrical leads and the bottom coil layer, the bottom and the top coil layer, the bottom flux guides and the poles, as well as the first and the second part of the poles. To create these windows in Si₃N₄, it had to be patterned in an etching step requiring an adequate mask. Either wet chemical etching or dry etching may be applied. Since the first method results in an isotropic process leading to an underetching, a directional dry etching process with AZ9260 as etching mask was chosen. For the IBE patterning of the Si₃N₄ layer, a hardbake was necessary to stabilize the resist by thermal cross-linking. Applying a thermal process with a step by step increase to 130°C showed best results. To avoid a damage of the etch mask during the patterning, the current of the ion source was reduced from the standard level of 100 mA to 50 mA. Doing so, the patterning mask remained stable during the IBE process. This is related to the reduced process temperature which is 125°C after 30 min with an ion current of 100 mA and only 85°C after 60 min with a current of 50 mA. Although the etching rate also decreased due to the reduction of the ion current, the resist remained stable during the entire etching process. The process for a 250 nm thick Si₃N₄ layer was completed after approx 60 min. Since a strong thermally cross-linked resist is hard to remove, different removers like AZ Kwik Strip, AZ 100 Remover, NMP (N-Methyl-2-pyrrolidon), and even acetone were tested. The best results could be achieved with an ultrasonic assisted removal applying acetone. Figure 9 depicts the first vertical insulation layer before (Fig. 9a) and after (Fig. 9b) the patterning process.

Mask Improvements

The main issue during the first fabrication run causing a major yield hit was an inappropriate mask design for the patterning of the first and second Si_3N_4 layer. By using the old mask design, short circuits appeared between the electrical leads caused by an insufficient removal of the seed layer at the SU-8TM edges after the IBE process. Figure 10 compares the

old mask design and the new improved masks for patterning the first and the second Si_3N_4 layer.



Fig.9. First vertical Si_3N_4 insulation layer before (a) and after (b) the patterning process.

Figures 10a and b depict the old mask design. It created a window over the whole area of the electrical leads (bottom white square in Figs. 10a and b). It turned out to be difficult to remove the seed layer for electroplating the coil and pole structures by IBE at the rim, which resulted in residues of the seed layer causing short circuits at the leads. By increasing the size of the insulation containing the electrical leads (black area in Figs. 10c and d), the rim responsible for the short circuits was eliminated.



Fig.10. Old (a, b) and new (c, d) mask design for Si₃N₄ patterning.

Figure 11 depicts the first vertical insulation layer before (Fig. 11a) and after (Fig. 11b) the patterning processes with the improved mask design. The differences to Fig. 9 can be seen clearly.



Fig.11. First vertical insulation layer before (a) and after (b) the patterning processes with the improved mask design.

After implementing the new masks during the second fabrication run, a significantly higher output of functional parts was achieved. Figure 12 shows the completed microactuator after finishing the second fabrication run. While Fig. 12a depicts an optical micrograph of a completed system, Fig. 12b shows an SEM (scanning electron microscope) micrograph of a system after dicing [11, 12].



Fig.12. Micrograph (a) and SEM image (b) of the completed microactuator

MICROACTUATOR EVALUATION

After completing the wafers, the electrical resistance R of the coils was measured. The calculated electrical resistance R of one coil system consisting of double layer coils with five turns per layer and the leads was 1.2 Ohm. The systems from the first fabrication run had a higher electrical resistance ranging from 1.8 Ohms to 2 Ohms. For the second fabrication

run with its optimized process and its improved height control, the electrical resistance was between 1.3 Ohms and 1.5 Ohms.

After wafer dicing, the completed systems were subjected to both an analysis of its physical dimensions, as well as their magnetic capabilities. For determining the building height of the components, in particular the $SU-8^{TM}$ embedding and the Si_3N_4 layer thickness, a cross section was generated by dicing, nanogrinding, and CMP. Figure 13 depicts a cross section of one subsystem of the fabricated microactuator.



An actual functional test of the complete system requires a system integration of the magnetic microactuator with its micromechanics [5]. However, for conducting a preliminary functional test, a test set-up consisting of a diced magnetic microactuator and a matching micromechanics system was used. The microactuator magnetics system was mounted on a Printed Circuit Board (PCB) and electrically connected. The micromechanical part featured an platform carrying a pair of flux guides and suspended on a pair of leaf springs. The micromechanics system was held by a vacuum needle and positioned with respect to the magnetic microactuator by means of an XYZ-micropositioning stages. The test set-up was observed through a stereo microscope and the air gap was adjusted to 30 µm. If the micromagnetic actuator was functional, an excitation of its coils had to result in an attraction of the flux guides. Figure 14 shows a test arrangement of the micromechanical parts before (Fig. 14a) and after the excitation of the microactuator (Fig. 14b), demonstrating the system's functionality.

CONCLUSION

The work demonstrates, that HARMST lends itself for fabricating the micromagnetics for an electromagnetic microactuator for hard disk recording heads. The application of an organic material (SU-8TM) as lateral insulation material and an inorganic material (Si₃N₄) for the vertical insulation enabled a compact coil design. While the initial microactuator fabrication run yielded functional parts, there was still room for technology improvements. By taking advantage of an optimized fabrication processes, the second fabrication run resulted in a substantially improved yield. The appropriate function of the microactuator magnetics could be verified in a number of experimental tests.



Fig.14. Functional test set-up with a magnetic microactuator and a micromechanical part: (a) before actuator excitation; (b) after actuator excitation.

ACKNOWLEDGMENT

This work was sponsored by the European Commission within the Framework 6 Information Society Technologies Programme's Specific Target Research Project (STREP) PARMA (Performance Advances in Recording through Micro Actuation).

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