Electromagnetic Micro x-y Stage for Probe-Based Data Storage

Jae-joon Choi, Hongsik Park, Kyu Yong Kim, and Jong Up Jeon

Abstract— **An electromagnetic micro x-y stage for probe-based data storage (PDS) has been fabricated. The x-y stage consists of a silicon body inside which planar copper coils are embedded, a glass substrate bonded to the silicon body, and eight permanent magnets. The dimensions of flexures and copper coils were determined to yield 100 μm in x and y directions under 50 mA of supplied current and to have 440 Hz of natural frequency. For the application to PDS devices, electromagnetic stage should have flat top surface for the prevention of its interference with multi-probe array, and have coils with low resistance for low power consumption. In order to satisfy these design criteria, conducting planar copper coils have been electroplated within silicon trenches which have high aspect ratio (5 μm in width and 30 μm in depth). Silicon flexures with a height of 250 μm were fabricated by using inductively coupled plasma reactive ion etching (ICP-RIE). The characteristics of a fabricated electromagnetic stage were measured by using laser doppler vibrometer (LDV) and dynamic signal analyzer (DSA). The DC gain was 0.16 μm/mA and the maximum displacement was 42 μm at a current of 180 mA. The measured natural frequency of the lowest mode was 325 Hz. Compared with the designed values, the lower natural frequency and DC gain of the fabricated device are due to the reverse-tapered ICP-RIE process and the incomplete assembly of the upper-sided permanent magnets for LDV measurements.**

Index Terms— **Probe-based data storage, micro x-y stage, electromagnetic force, copper coil, electroplating.**

I. INTRODUCTION

Since 1990, the storage capacity of hard disk drive has been drastically increased with an annual rate of 60% due to the development of new head fabrication processes, new materials for recording media, and high precision actuator control techniques, etc. Recently, however, it is expected that magnetic storage can not be used for storage capacities exceeding 100-200 Gb/in^2 in areal density because of the superparamagnetic limit [1].

After the development of scanning tunneling microscope in 1982 by Binnig and Rohrer, many researches on probe-based data storage (PDS) [2-11] have been conducted to overcome this superparamagnetic limit and to achieve an tera~peta bit/in^2 areal density. Most of such research activities are, however, focused on the development of the new read/write mechanisms, such as charge trap [2], phase change [3,6], conductance change [4,7], piezoelectric response [5,10,11], and indentation of polymer [8,9], and research activities on the development of micro stages that will carry recording media for PDS [12-14] are scarce. To achieve a PDS with an extremely high areal density, the stage with a very large displacement and nanometer-scale resolution is desired. Moreover, for portable applications, the low power consumption and the input voltage limitation pose serious constraints for the design of such stage. Hence, a cost-effective fabrication process and assembly techniques must be considered as well.

Recently Cornell research foundation, Inc. and IBM have developed micro stages for the application of PDS [13-15]. The former has fabricated an electrostatically-driven x-y stage and the latter an electromagnetically-driven stage with five degrees of freedom. In general, even though electrostatic stages have low power consumption compared with the electromagnetic counterparts, they have smaller displacements and require larger driving voltages. Since electrostatic forces are relatively small, thousands of electrodes have to be employed to get a large displacement. Therefore, the

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J.-J. Choi, H. Park, K. Y. Kim, and J. U. Jeon are with the MEMS Lab., Samsung Advanced Institute of Technology, San 14-1, Nongseo-ri, Kihung-eup, Yongin-si, Kyonggi 449-712, Korea.
(e-mail: jeon@sait.samsung.co.kr)

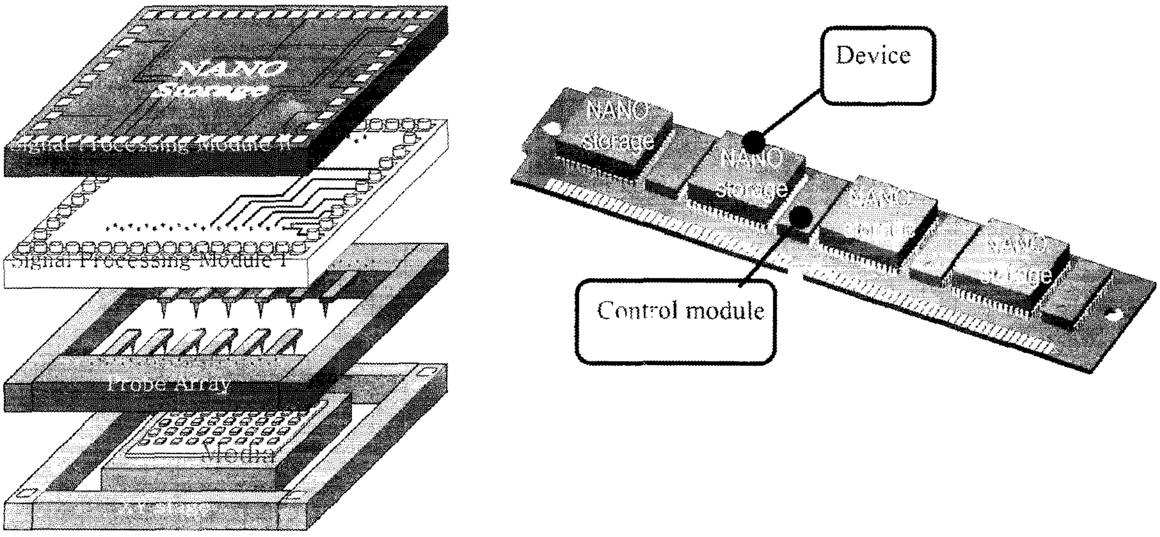
area efficiency of storage device in case of electrostatic type stage is very poor compared to electromagnetic type counterpart. IBM developed an electromagnetic micro stage employing very wide and thick copper coils to prevent heat generation and to reduce the power consumption caused by electromagnetic excitation. The thickness and width were 380 μm and 84 μm, respectively. To make the thick copper coil, several subsequent fabrication processes – for example, oxide bridge formation to suspend silicon trench, two steps of wet etching, copper electroplating and one step of dry etching – were used. Also 9 coils and 6 permanent magnets for this stage were needed to implement a five degrees of freedom motion. Such a complex structure and numerous processing steps are not desirable for the mass production of micro stage.

In this paper, we present the design and fabrication results, and the performance test results of our new simple electromagnetic x-y stage which has high aspect ratio copper coils.

II. DEVICE CONCEPT OF PROBE-BASED DATA STORAGE

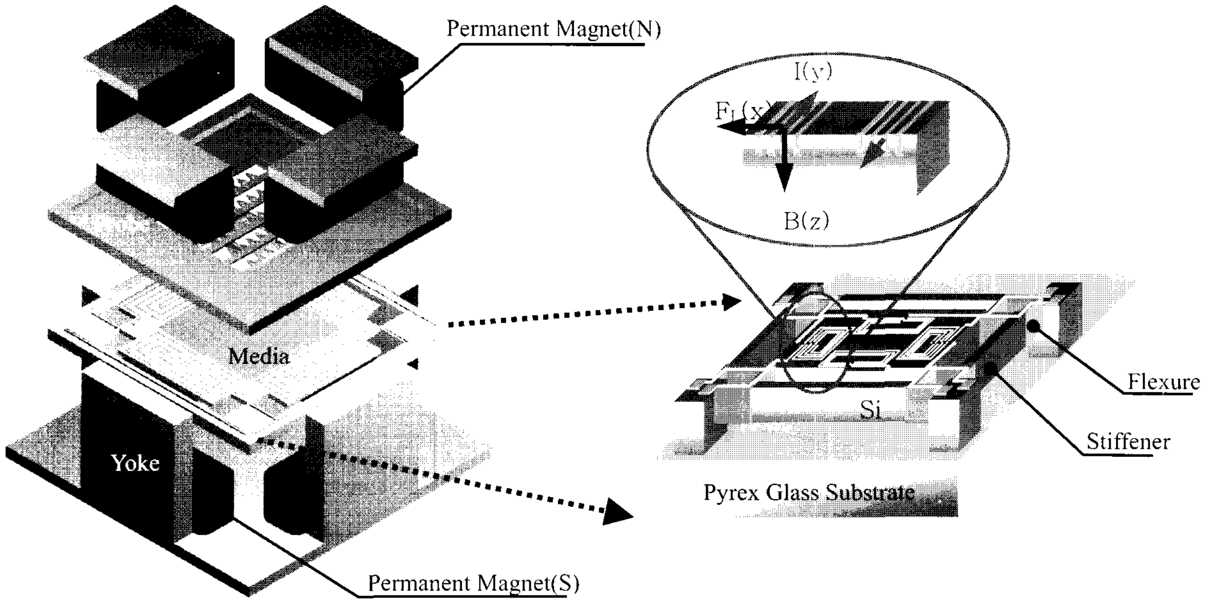
Fig. 1 shows the design concept of our PDS device. In Fig. 1(a), the PDS is composed of 4 layers. The first layer which consists of an x-y stage and storage medium is bonded with the second layer which has miult-probe array. An electromagnetically-driven x-y stage, which has a large driving force compared with a electrostatic one, is chosen so that it exhibits a movement with a range of ±50 μm that corresponds to the pitch of probe array and with a high velocity of 10~100 mm/sec. For the storage media, we have chosen a non-volatileferroelectric material like PZT that is rewritable, easy to implement writing operation and has fast switching time [10,11]. The size of the x-y stage and media are 13×13 and 5×5 mm^2, respectively. The probe array consisting of more than 2000 probes is fabricated by using conventional micromachining technology.

As reported in [11], a data bit less than 100 nm can be written by applying voltage between the probe tip and PZT media. Reading is done by sensing the motion of probe tip which is occurred by the piezoelectric response of poled data bit under the external field generated by the probe tip. The first and second layer are bonded to signal processing module I that has 3-dimentional wiring inside it and finally assembled to the signal process module II (ASIC module) for the signal processing circuit. We are now under the development of PDS with a capacity of over 1 Gbyte (>250 Gb/in^2). Our PDS will be packaged to have the similar form as the semiconductor devices and utilized like a DRAM module inside the personal computer as shown in Fig. 1(b). The total size of the PDS is approximately 2×2 cm^2.



(a) (b)

Fig. 1. Device concept of probe-based mass data storage (PDS). (a) Schematic view. (b) PDS module after packaging.



(a) (b)

Fig. 2. Structure of probe-based data storage (PDS) with electromagnetic micro x-y stage and its working principle. (a) Exploded view of PDS. (b) Magnified view of media layer.

III. STRUCTURE OF ELECTROMAGNETIC MICRO X-Y STAGE

To develop a data storage device, a certain range of relative motion between probe and media is desired. In PDS, we believe that media scanning scheme is more appropriate rather than the media rotating scheme. Therefore, we aim at the design of media scanning method which has two-axis planar motion. Two kinds of representative driving forces are generally used in MEMS actuators, which are electrostatic and electro-magnetic forces. The generated force of electromagnetic actuator is generally greater than that of the electrostatic actuator. In PDS, the electromagnetic method is preferable because the objective media platform should have much heavier mass and larger scanning stroke if considering the large data capacity.

Fig. 2 shows the structure of PDS with an electromagnetic x-y stage (here, the signal processing module I and II are not shown) and working principle of x-y stage. As shown in Fig. 2 (a), rare-earth permanent magnets (REPM) are positioned in top and bottom layer, and media layer and multi-probe layer is placed in the middle of assembled structure. For constructing the close-looped magnetic circuit yokes are attached at the outside of middle layer. By doing so we can minimize the magnetic stray field, and hence we can get maximum driving force from limited current source. The media layer is made of two substrates; media and glass substrates. The media substrate with a thickness of 250 μm is bonded to the Pyrex glass substrate with a thickness of 300 μm.

Looking at the detailed structure of x-y stage, media platform that is 5×5 mm^2 is prepared at the center of the stage, and a pair of "L" shaped flexure is designed at the four corners, as shown in the Fig. 2(b). To prevent the rotational motion of stage, especially yawing motion, 4 stiffeners are interconnected between the flexures.

The working principle is very simple; The driving forces arise from "Lorentz force". Details of the generation of electromagnetic forces are depicted in magnified view of Fig. 2(b). Magnetic field B(z) is formed by the upper and lower permanent magnets, and by applying current to the coil in the depicted direction the output force $F_L(x)$ is generated. Based on this configuration, this device has 2-axis planar scanning motion.

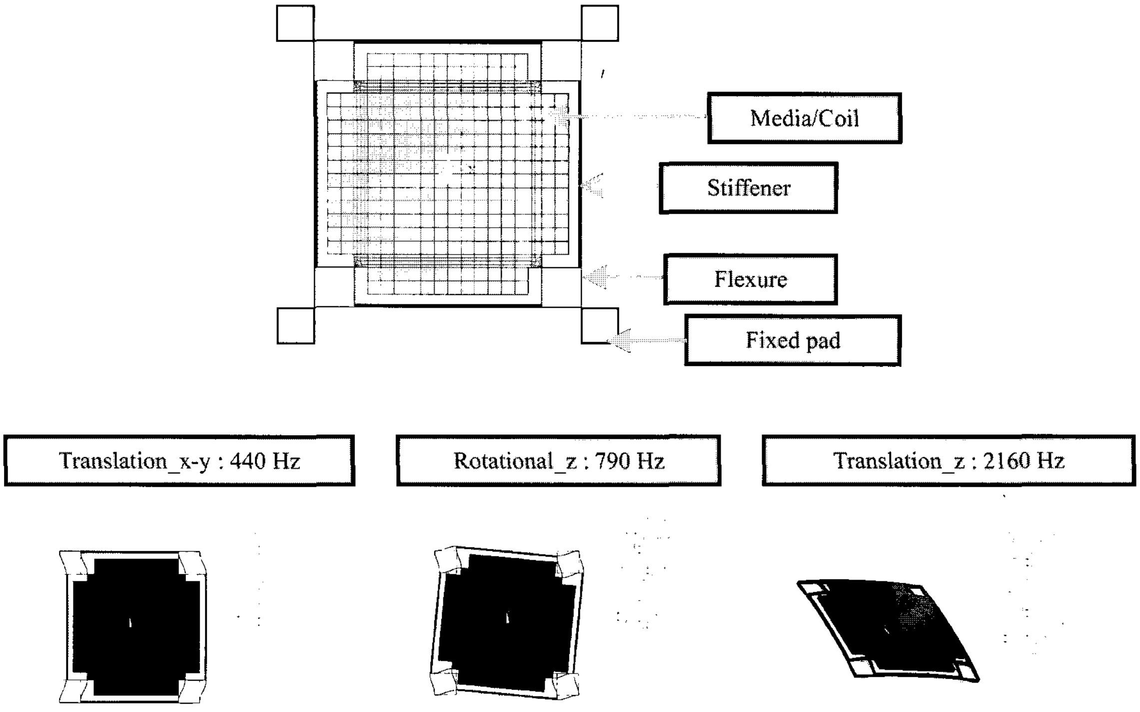


Fig. 3. Modal analysis by finite element method (FEM).

For the portable use of the PDS, it is essential to reduce power consumption of x-y stage. For this purpose, 'Damascene process' [16-18] used for IC process is adopted to form a thick copper coil inside silicon body of x-y stage. This copper filling process has advantages of significantly low resistance and low fabrication cost. As the copper coil is thicker, the power consumption of x-y stage that is a crucial factor for the portable applications becomes lower. In our design, each copper coil has 100 turns and its line-and-space, thickness and total length are 5 μm, 30 μm, and 1 m, respectively.

IV. MODAL ANALYSIS OF MICRO X-Y STAGE

The mode shape analysis of the proposed structure using finite element method (FEM) analysis package, ANSYS[R] 5.6., has been performed. Through this analysis, the stiffness of flexural structure and required current for obtaining the desired motion and deflection have been estimated. Unfortunately, due to the poor aspect ratio, in which slender and thin and wide components are mixed in the same body, it was inevitable to use very fine elements when generating a meshed model. Consequently the meshed model required a large number of mesh elements and long computation time. Meshed model for FEM analysis is shown in Fig. 3. Through the numerical analysis we found 10 natural vibration modes. Several modes are repeated because the structure has symmetric shape. So we classified 5 distinctive modes below 13 kHz frequency range. These modes and features are summarized in Table 1.

Table 1. Summary Of Vibration Modes And Its Feature.

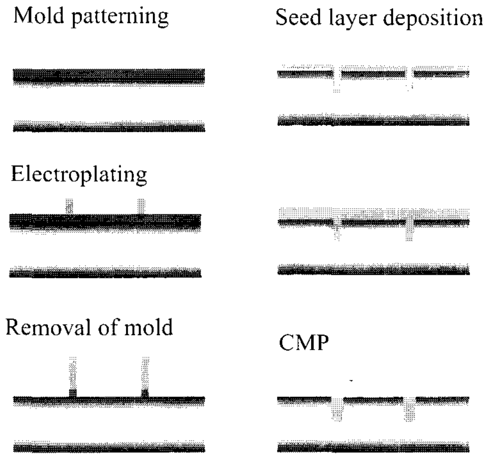
Frequency	Mode Description	Repetition
440 Hz	Planar motion in x, y direction	2 modes
790 Hz	Yaw motion in vertical axis	Single mode
2160 Hz	Translation motion in vertical axis	Single mode
3790 Hz	Coupled roll and pitch motion	2 modes
12.7 kHz	Local mode at stiffener	4 modes

Key issue in structure design is the separation of uncontrollable modes from controllable ones. In our case only the x and y motions are controllable. Therefore uncontrollable modes have to be put as high as possible far from the x and y modes. The yawing mode is two times higher than x, y translation modes.

V. FABRICATION

A. *Copper filling technique in high-aspect-ratio silicon trench*

To fabricate an electromagnetic x-y stage with large displacement, it is very important to fabricate the coils with low resistance. In our work, the copper coils of high aspect ratio are electroplated inside the deep silicon trenches. This method is appropriate for fabricating a low resistance coil because the silicon trench used as a mold for high aspect ratio copper coil can be easily fabricated by inductively coupled plasma reactive ion etching (ICP-RIE) with high resolution. So far, the patterned micro-molds using AZ4562 [19] and SU–8 [20] have mainly been used to fabricate electromagnetic devices with high aspect ratio copper coil. However, there are some significant drawbacks that are not easy to be solved; 1) fabrication of a high aspect ratio mold, 2) compatibility with the subsequent processes for MEMS devices, 3) removal of the mold after electroplating, especially in case of SU-8. Thereby, in our work, we propose a new MEMS coil fabrication technique using 'Damascene process'. Schematics of the conventional and our fabrication process of copper coil by electroplating are shown in Fig. 4(a) and (b), respectively. In our fabrication process, the silicon trenches are fabricated by using ICP-RIE and thermally oxidized for isolation between copper coil and silicon substrate. An Au/Cr for seed layer are deposited on the whole surface by DC sputtering method. Then, copper is electroplated uniformly inside the silicon trenches which are covered by the seed layer. Subsequently, chemical mechanical polishing (CMP) process is performed to remove the copper layer electroplated on the stage surface and make the surface be flat. This flat surface after copper CMP process makes the stage be easily assembled with the multi-probe array. When the coil is fabricated by using the conventional method shown in Fig. 4(a), the coil protrudes from the surface of media platform, and, as a consequence, it is very difficult to assemble the multi-probe array with the x-y stage because of the geometrical inference between them. An experimental equipment for copper electroplating is shown in Fig. 5. As anode, two copper bars containing 0.004~0.006 % P is used. The precursor solution is circulated by pump and air bubbles are used for the agitation of solution. The strong agitation is an important factor to have uniform copper deposition inside the deep silicon trenches without forming any void. In order to suppress the formation of any voids that could be caused by excessive copper deposition at the entrance of trench where the electric field is strongly concentrated, the composition of electrolyte, i.e. concentration of copper ions in acid-copper sulfate electrolytes and amount of additives (brightener, starter, etc.), and the applied current density should be properly controlled [17]. According to our experimental results, firstly, it is very crucial to select a proper brightener which consists of the crystal growth inhibitor, pit inhibitor, leveler, and inhibitor of thermal decomposition. Secondly, lowering the density of copper ion to be balanced with amount of sulfuric acid is also important. Finally, it is observed that lower current density result in less voids in copper coil. Fig. 6(a) shows a photograph of fabricated silicon trench with Au/Cr seed layer. As an example, copper coils of which entrance got blocked due to improper setting of the experimental parameters for electroplating are shown in Fig. 6(b). We have conducted numerous experiments to explore the optimal values with varying experimental parameters. Fig. 6(c) shows the photograph of copper coil filled in the silicon trench without any voids under optimal conditions, which are summarized in Table 2. Electrical properties of the fabricated copper films were characterized. An electroplated copper film (5 μm in thickness) shows an electrical resistivity of 1.8 μΩ-cm., which is close to the value of bulk copper material.



(a) (b)

Fig. 4. Fabrication process to form copper coil. (a) Conventional method. (b) Copper filling method.

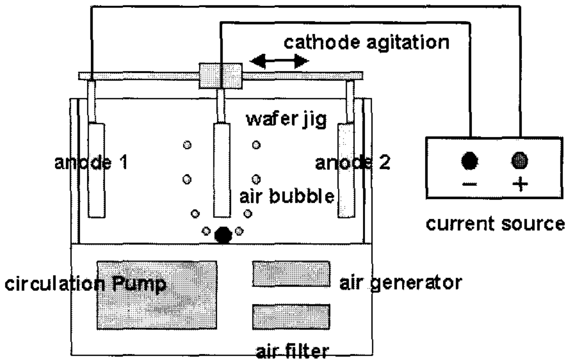


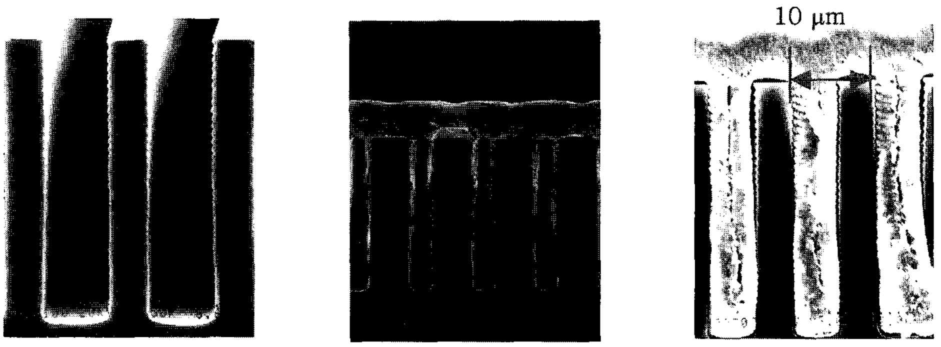
Fig. 5. Schematic diagram of electroplating equipment.

Table 2. Composition Of Electrolyte For Copper Electroplating.

Composition	Range	Optimal Conditions
$CuSO_4$-$5H_2O$	40 · 72mg/L	50
H_2SO_4	100ml/L	100
Starter	10ml/L	10
Brightener	13~20ml/L	16
HCl	0.12 ml/L	0.12
Current density	5~20mA/cm^2	7
Temperature	20~50°C	25

B. *Fabrication process of micro x-y stage*

Fig. 7 shows the fabrication process of micro x-y stage. (1) By using ICP-RIE, silicon wafer is dry-etched to form silicon trenches (5 µm in width, 30 µm in thickness). (2) The wafer is thermally oxidized with a thickness of 2000 Å for isolation between silicon substrate and copper coil to be deposited later. (3) The backside silicon is wet-etched (50 µm in depth) using tetra methyl ammonium hydroxide (TMAH) to separate the silicon moving part from glass substrate which will be bonded to the silicon substrate in the subsequent process. (4-5) The silicon wafer is anodically bonded to glass substrate (Pyrex 7740). Before performing the anodic bonding process, the backside oxide layer was removed while the front side was being covered with thick resist. (6) A 500 Å Cr as adhesion layer and 2000 Å Au as seed layer are deposited on the overall front side by sputterring method. (7) Copper is electroplated to fill the silicon trench. (8) The top surface is planarized by CMP process which removes the overplated copper on silicon wafer. (9) The polyimide (PI 2721, HD Microsystems) layer is coated to electrically isolate the copper coils from the electrodes which connect ends of coil to outer pad for wire bonding. Then, the polyimide is patterned by UV lithography to open the contact area to electrodes and cured at 300 °C. (10) An Au/Cr (3000 Å / 500 Å), which acts as an electrode, is deposited by sputterring method and patterned by wet etching. (11) The final process is the deep dry-etching through the silicon wafer to define flexures and moving part. Thick resist is used as the etching mask during dry-etching process by using ICP-RIE. After completing the processes described above, the wafer is diced under the passivation of devices using resist and the resist is removed by PR remover and O_2 asher. Fig. 8(a) shows an optical photograph taken after the process step (8), i.e.,



(a) (b) (c)

Fig. 6. SEM images showing silicon trench and copper coil. (a) Silicon trench with seed layer. (b) Entrance blocking of Silicon trench (J = 10 mA/cm^2, Cu_2^+ = 18 g/L, where J and Cu_2^+ denote current density and copper ion density, respectively). (c) Silicon trench filled with copper (J = 10 mA/cm^2, Cu_2^+ = 18 g/L).

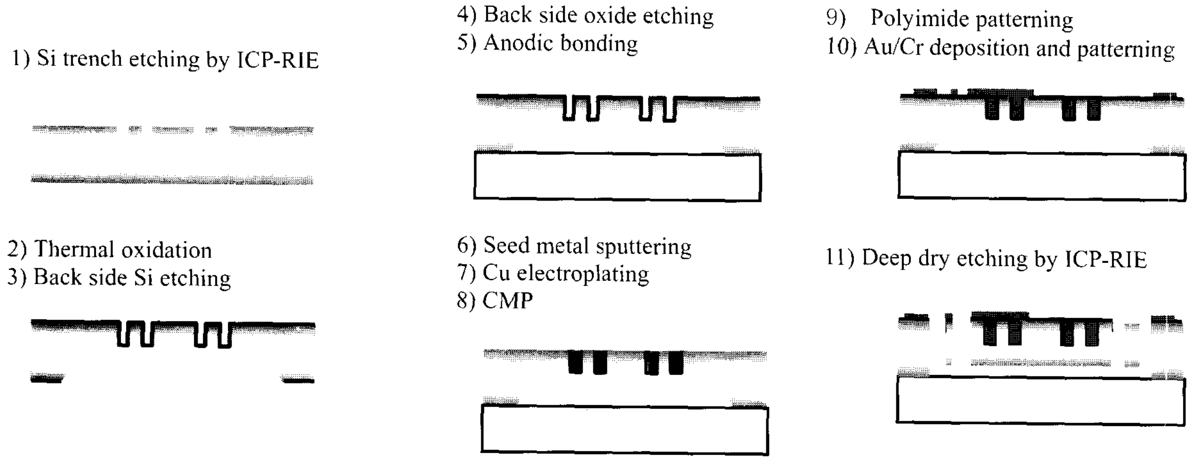


Fig. 7. Fabrication process of micro x-y stage.

copper CMP process. It is shown that the overplated copper was clearly removed by CMP and the copper coil with 5 μm line-and-space was filled successfully in silicon trench. Fig. 8(b) shows the polyimide pattern after the above process step (9). The thickness of polyimide film after 300 °C curing was about 4.5 μm. The copper coil was uniformly covered by polyimide except the contact open area for copper wiring toward outside. During patterning of this polyimide, spray developing method was adopted. Fig. 9 shows a x-y stage which is assembled with only bottom magnets and PCB. In the PCB, four slits are formed to install 4 permanent magnets and they are manually assembled.

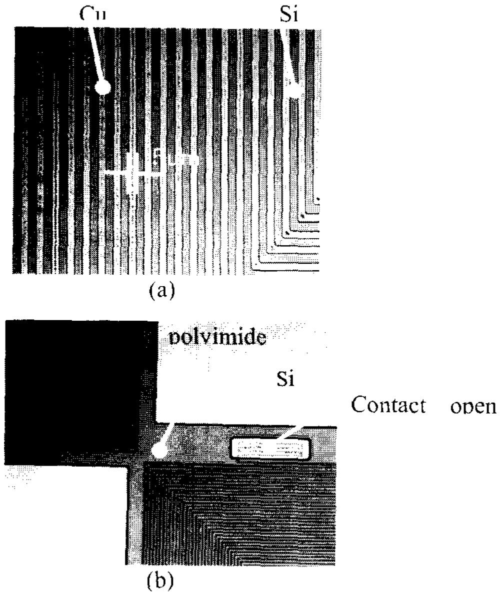


Fig. 8. Photographs after fabrication step 8 and 9. (a) After copper CMP (process step 8). (b) After patterning of polyimide (process step 9).

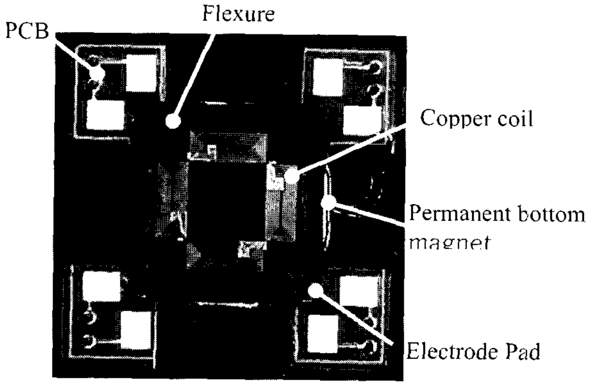


Fig. 9. Photograph of assembled x-y stage with bottom magnets.

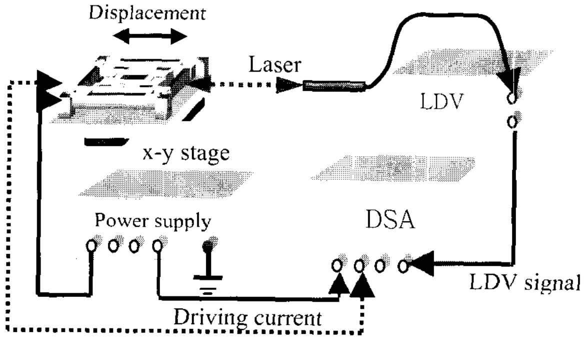


Fig. 10. Schematic diagram of LDV measurement set-up.

VI. MEASUREMENT RESULTS

The static and dynamic characteristics of the fabricated x-y stage were measured by using laser doppler vibrometer (LDV). Fig. 10 shows the schematic diagram of the measurement set-up. For the convenience of the measurement, the top magnets were removed and only the bottom magnets were employed. The measured dynamic characteristic was analyzed using dynamic signal analyzer (DSA). Fig. 11 shows the measured static displacements in both cases of actuating single coil and double ones in x direction. The measured DC gain was 0.16 μm/mA and the maximum displacement was 42 μm at a driving current of 180 mA. The nonlinear characteristic was shown at the range of driving current larger than 120 mA. Measured displacement was a quarter of the simulated value. The reason why the DC gain became smaller mainly came from the absence of the top magnets and yokes which are essential for the close-looped magnetic field and also from the possibility of the alignment error between the magnets and coils. The frequency response of stage measured by DSA is shown in Fig. 12. The natural frequency of translational x mode was about 325 Hz and that of the rotational mode were observed at 610 Hz. The reverse-tapered flexures of x-y stage during ICP-RIE process made the natural frequency of fabricated device became lower than the simulated value. The average flexure width of the fabricated stage was measured to be about 17.5 μm while the designed flexure width was 20 μm. To confirm the cause of the natural frequency being lower, we recalculated the natural frequency of the stage by using the measured flexure width. Its value was 340 Hz. This value is fit well to the measurement results. LDV measurement in y direction was also done and the natural frequency of it was 345 Hz. The difference of natural frequencies in the x and y directions is caused by the non-uniform etching process during the ICP-RIE process.

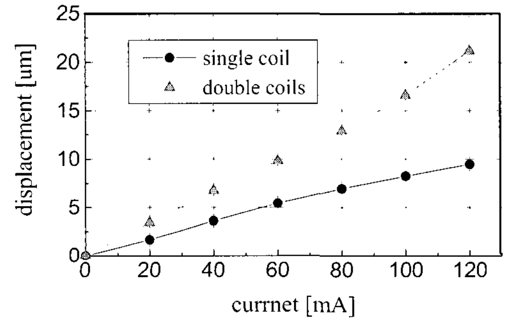
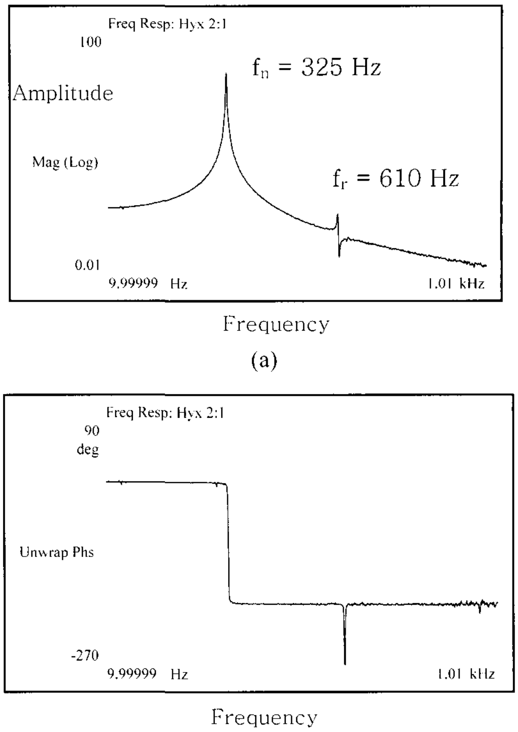


Fig. 11. Plot of static displacement versus driving current.



(a)

(b)

Fig. 12. Frequency responses of micro *x-y* stage. (a) Amplitude. (b) Phase.

VII. CONCLUSIONS

In order to overcome the limitation in areal density of magnetic recording called superparamagnetic phenomenon, it is needed to develop a new type of storage. For the increasing demands for portability and large storage capacity, the next generation data storage should have compact size like semiconductor devices and have high areal density above several hundred Gb/in^2. New media scanning device whose function is the same as the voice coil actuator and spindle motor in hard disk drives is also required. The scanning device should have large displacement and very small power consumption for portable usage.

In this paper we proposed a new electromagnetic micro x-y stage for probe-based data storage (PDS). For large storage capacity, the x-y stage should have large displacement corresponding to the pitch of multi-probe array. For these reason the electromagnetic driving method was adopted. To reduce the power consumption in electromagnetic x-y stage, a thick copper coil was fabricated using 'Damascene process', which was developed for three-dimensional wiring process for IC. The power consumption of the fabricated x-y stage was several Watts higher than the simulated value. Such discrepancy came from the incomplete assembly in measurement. So we analyzed that the electromagnetic field induced by the bottom magnets is about one third of fully assembled device. In order to accomplish the desired design targets, following efforts are underway: fabricating the x-y stage with a media platform whose thickness is less than 50 μm and assembling the whole device layers with MEMS magnets [21]. The reduction of the power consumption down to several tens of mW as well as the fabrication cost and the size of the PDS is expected to be achieved in the near future.

ACKNOWLEDGMENTS

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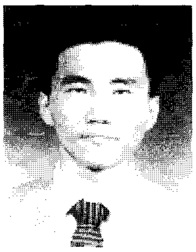
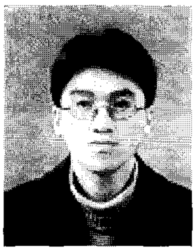
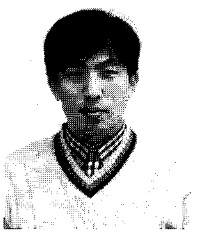


Jae-joon choi received the B.S. degree in electrical engineering from Yeungnam University, Korea, in 1993, the M.S. degree in precision mechanical engineering from Tohoku University, Japan, in 1995, and the Ph.D. degree in mechatronics and Precision Engineering from Tohoku university, Japan, in 1998. From 1998, he has been a Researcher in MEMS LAB at Samsung Advanced Institute of Technology (SAIT), Korea. His research interests is in the area of storage device with MEMS technology.



Hongsik Park received the B.S. ('97) and M.S. ('99) degree of electronic engineering from Kyungpook National University, Korea respectively. From 1997 he has worked in MEMS Lab. at Samsung Advanced Institute of Technology (SAIT), Korea. His research interests include MEMS actuators and storage device with MEMS technology.



Kyu Yong Kim received the B.S. ('89), M.S. ('91), and Ph.D. ('95) degree of mechanical engineering from Yonsei University, Korea respectively and consecutively. Form 1995 he joined the Samsung Advanced Institute of Technology (SAIT) as a research staff. His research interests are focused at active control system design and vibration analysis for storage devices.

Jong Up Jeon received the B.S. degree in machine design and production engineering from Seoul National University, Korea, in 1986, the M.S. degree in mechanical engineering from Korea Advanced Institute of Science and Technology (KAIST), Korea, in 1988, and the Ph.D. degree in precision machinery engineering from the University of Tokyo, Japan, in 1997. From 1988 to 1992, he was a Researcher in the Robotics and Fluid Power Laboratory at Korea Institute of Science and Technology (KIST). From 1995 to 1997, he was a Researcher in the Higuchi "Ultimate Mechatronics" Project, Kanagawa Academy of Science and Technology (KAST), Kanagawa, Japan. He is presently a Project Manger at Samsung Advanced Institute of Technology, Korea. His research interests are in the area of mechatronics, robotics, automotive control applications, active magnetic bearings, electrostatic levitation, MEMS actuators and nanotechnology.