PZT Driven Silicon XY Microstage for Multiprobe Data Storage

著者	MOHD FAIZUL BIN MOHD SABRI
号	54
学位授与機関	Tohoku University
学位授与番号	工博第4181号
URL	http://hdl.handle.net/10097/61806

	もはまど　ふぁいずる　びん　もはまど　さぶり
氏　名	MOHD FAIZUL BIN MOHD SABRI
授与学位	博士（工学）
学位授与年月日	平成２１年９月９日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）機械システムデザイン工学専攻
学位論文題目	PZT Driven Silicon XY Microstage for Multiprobe Data Storage （マルチプローブ高密度記録のためのＰＺＴ駆動シリコンＸＹマイクロステージ）
指導教員	東北大学教授　小野　崇人
論文審査委員	主査　東北大学教授　小野　崇人　東北大学教授　羽根　一博 東北大学教授　高　偉　東北大学教授　江刺　正喜

論文内容要旨

Nanotechnology is the final frontier in the ever shrinking electronics world. The impact of its application on society is far-reaching, as the reduction in size comes with and improvement in performance, thus making many electronics products accessible to the average consumer. There are now many portable applications, such as portable media players, disk drives, and games players. In the field of data storage applications, the challenge is to achieve high storage densities, in excess of 1 Tb/in^2. The leading technologies in the data storage field, optical data storage and magnetic data storage encounter limitations in this respect, through the optical diffraction and paramagnetic limit, respectively. Although efforts are being made to resolve these limitations, another contender for high density data storage technology is probe based data storage.

Probe based data storage operates on the principle that an array of read/write tips are used to deform a writable substrate in order to store and retrieve data. The array of read/write tips allow faster access of data through parallel transmission, typically enabled through a translational or rotational motion using a microstage. A microstage, or micropositioning device, is used in many current technological applications, such as examples in semiconductor manufacturing, scanning probe applications, optical fiber positioning and alignment, and chemical and biotechnology industries.

The purpose of this thesis is to feature a microstage design intended for application within a probe based data storage system. The performance of the microstage is crucial in determining the final performance of the overall data storage system, as the microstage provides a limitation to the data access rate of the system.

The specifications for the microstage design are as follows:

- A resolution of at least 25 nm, to match a data pitch of at least 25 nm, in order to achieve a 1 Tbit/in^2 storage density.
- A travel range of 80 - 100 μm, in order to match the current typical size for the cantilever array which in 80 - 100 μm pitch.
- A transfer rate of the multiprobe data storage system of the order of tenfold MByte/s, comparable to the data transfer rate for common storage systems.
- High accuracy and repeatability.
- Low power
- Low cost and size, and ease of fabrication

In order to fulfill the above specifications, a hybrid translational XY microstage design comprising of PZT actuators mounted onto a silicon base was designed. Piezoelectric actuators were chosen over other more popular choices such as electrostatic and electromagnetic actuators, as they are excellent candidates for large force, small displacement applications where higher voltages are available. Furthermore, electrostatic actuators have the disadvantage of large overall dimensions due to its comb structure, whilst electromagnetic actuators are in the form of three dimensional coils which are difficult to fabricate.

The "PZT" family of materials are an attractive group of piezoelectric material, and is the most commonly used piezoelectric ceramics. It comprises of a lead zirconate/lead titanate mixture, offering greater sensitivity and higher operating temperatures compared to other piezoelectrics. PZT material actuators have the advantage of high resolution which is critical for such a small pitch of the 25 nm required for data access. In addition, the resonance frequency of PZT is of the order of kHz, thus potentially allowing high data access rates. PZT also requires relatively low power to operate, and has a high power density which allows for a high effective force for its relatively small size. However, typical of piezoelectric materials, PZT has a low effective actuation, only about 0.1% of its actual size, and therefore an amplification mechanism needs to be incorporated in order to amplify the displacement of the microstage. Furthermore, for the purpose of this thesis, a stacked actuator type, comprising of alternate layers of PZT material and nickel, was chosen in order to maximize its actuation capabilities.

The design of this hybrid XY microstage comprises of three main components including a silicon base, the stacked PZT actuators and its amplification mechanism, and capacitive sensors. A silicon base of dimensions 20×20×0.4 mm was chosen as the substrate for the microstage, as silicon is advantageous for micromechanical applications due to its Young's modulus and high yield strength similar to stainless steel. It is also an extremely robust and stable material. More importantly, silicon is already an established substrate material for integrated circuit fabrication, and thus the fabrication of this microstage will be facilitated by employing standard silicon fabrication processes, which will also lower the production costs.

For the purpose of this thesis, a stacked actuator type, comprising of alternate layers of PZT material and nickel, was chosen in order to maximize its actuation capabilities. This actuator was placed in a rhombus-shaped amplification structure, called the Moonie amplification structure, in order to further amplify the displacement of the microstage. For completion of the design, capacitive sensors were fabricated on glass substrates and incorporated. This component is used to sense the displacement of the microstage, for the purpose of closed loop control.

The design and fabrication of this hybrid XY microstage is approached from three different angles – analytical calculations, FEM simulation, and fabrication and experimental testing. Analytical calculations are used as a first approximation to determine the operating parameters for the microstage. FEM simulation is then used as a tool to predict and optimize the operation parameters, as it is better suited to model the complex geometry of the microstage, compared to analytical calculations. Finally, the device is fabricated and experimentally tested to confirm its performance.

The analytical calculations for the microstage are mainly concerned with calculating the stiffness of the key components of the amplification mechanism, in order to obtain a value for the resonance frequency of the microstage. In particular, hinges and support springs within the amplification structure are critical in determining the resonance frequency. Qualititatively, these components need to be flexible enough to allow for movement, yet be rigid enough to withstand breakage. In addition, a higher overall spring constant for the system will result in a higher resonance frequency, but a stiffer system will limit the displacement of the stage. A tradeoff between these two factors will be taken into consideration when determining the dimensions of the hinge and support spring in this microstage design.

Finite Element Method (FEM) is used to simulate the behaviour of the microstage, in order to obtaining its operating parameters, such as displacement, amplification factor, and blocking force. Furthermore, the amplification factor and blocking force may be obtained as a function of Moonie angle, and this information will be further utilized in order to identify the optimum Moonie angle required for maximum amplification.

The fabrication process for the microstage provides a particular challenge, at the microstage is a hybrid structure comprising of a electro-mechanical component, i.e. the PZT actuator, incorporated onto a silicon substrate. The fabrication processes for the key components, the microstage and PZT actuator, are implemented using standard semiconductor fabrication processes. Two variations of the microstage were produced, each containing a different type of PZT actuator – one containing modified commercial actuators, whilst the other contained laboratory-made actuators. The fabrication of the PZT stacked actuator was especially challenging, and some innovations were introduced to the fabrication method in order to obtain well-formed alternating stacks of PZT and nickel material. Fabrication of the stacked structure of the PZT actuator involves depositing nickel material into high aspect ratio PZT grooves. The integration of the PZT actuators onto the silicon microstage involves specially designed microassembly processes, to ensure precise and repeatable positioning of the actuators into their respective positions.

The overall performance of the two types of microstage, i.e. containing modified commercial actuator and fabricated actuator, was carried out. These experimental results were then compared with the analytical and simulation results. The values for displacement, amplification and resonance frequency closely correspond to the values predicted by analytical calculations or simulation, thus validating each of these approaches as tools in predicting the performance of the microstage. It is demonstrated for the microstage containing modified commercial actuators, that its amplification factor closely corresponded to the value predicted by simulation, of about 18, thus resulting in displacements of 82 μm and 60 μm at an applied voltage of 70 V for the X and Y directions, respectively. This observation demonstrates that the microstage design containing Moonie amplification structure is effective in providing a high amplification for the small stroke of the PZT actuator. In addition, investigation of the microstage experimental resonance frequency was carried out for the two different types of microstage. The microstage contanining modified commercial actuators produces resonance frequencies of 361 Hz and 642 Hz in the X and Y directions, respectively. Whilst an order of magnitude lower than the PZT's intrinsic resonance frequency, this value of the microstage resonance frequency can be further improved through better design of the microstage. On the other hand, the resonance frequency for the microstage containing fabricated actuators produced a resonance frequency of 456 Hz in the X direction. This value is higher than the value of resonance frequency for the microstage containing the modified commercial actuators. This is due to the lower mass of the fabricated actuator. This resonance frequency of 456 Hz in the X direction also corresponds well with the analytical calculations which takes into consideration the mass of the inner stage which is responsible for motion in the X direction. In addition, the stored energy and efficiency of the microstage was obtained, as well as the cross-talk behaviour in the in-plane and out of plane directions.

The performance of the microstage is evaluated against the initial design specifications, using the performance of the microstage containing modified commercial actuators as a reference. The high resolution of at least 25 nm is achievable through the choice of PZT actuator, which allows precise positioning, with the aid of a control loop to compensate for the PZT's inherent hysteresis effects. The choice of PZT actuator also enables highly accurate and repeatable actuation, with a confidence interval of ±1 μm obtained through standard deviation of the displacement measurements. In addition, the cross-talk for in-plane motion is limited to 1% or less of the overall displacement. A travel range of 100 μm is within practical reach, as the current microstage employing modified commercial actuators is capable of displacement of approximately 80 μm at 70 V, and may be improved through the use of a higher stroke actuator or an improvement in the amplification mechanism. The power consumption of the microstage is considered to be lower than that containing electrostatic actuators. The overall microstage dimensions of 20×20×0.4 mm qualifies it for miniature applications, although it may be currently limited to non-portable data storage applications, due to the fragility to some of the components of the microstage. The overall production costs are lowered through the use of standard semiconductor processes, which also allows convenient fabrication. Innovations and improvements have been made within the fabrication process, especially with respect to fabrication of the PZT actuator and microassembly processes to integrate the hybrid structure.

Whilst the performance of the microstage containing modified commercial actuators has successfully fulfilled the design specifications outlined at the beginning of this thesis, the performance of the microstage containing fabricated PZT actuator has demonstrated some advantages. First, the fabrication processes employed in producing the stacked PZT actuators are a significant challenge, and successful fabrication indicates that standard MEMS fabrication processes can be used to fabricate these stacked PZT actuators. Second, the mass of the fabricated actuators are less than the modified commercial actuators. This results in a higher resonance frequency and less crosstalk, especially in the Z direction; for the microstage containing the fabricated actuators, compared to the microstage containing modified commercial actuators.

In conclusion, the design specifications which served as the motivation for this thesis, have been fulfilled, thus demonstrating that this design is feasible for probe based data storage applications. This current design provides a good basis to for further improvements to the microstage design in realizing high density probe based data storage, for example to provide a larger travel range, and higher resonance frequency. In addition, this work has involved the discovery a number of innovations in the device fabrication process. These innovations include the fabrication of precise structures using MEMS fabrication methods, precise integration hybrid MEMS components onto the silicon base using a thick photoresist pattern, and reliable electromechanical bonding using Nickel electroplating.

As a final analysis, the performance of this microstage can be compared with another commercial microstage also employing PZT actuators, which provides a benchmark of the performance. A minimal compact scanner produced is of dimensions 45×45×6 mm, and has displacements 15 μm in both the X and Y directions. In comparison, this microstage design is of much smaller dimensions of 20×20×0.4 mm, and yet provides a much higher displacement, thus demonstrating the effectiveness of this design.

論文審査結果の要旨

半導体微細加工技術を発展させたマイクロ加工技術を用いると，さまざまな機能を集積化した小型のデバイスが実現できる．近年，携帯機器で使われる高密度記録装置のために，マルチｱプローブ型の記録方式が提案され，そのトラッキング制御のために小型の XY マイクロステージが必要とされている．この応用のための XY マイクロステージは，小型でありながら，大きな変位と高速の駆動特性を有する必要がある．これまでに，マイクロ加工技術を用いた静電式や電磁式のマイクロステージの報告があるが，静電式では駆動力が小さいためアクチュエータのサイズが大きく，電磁式では小型化が困難であるなどの問題がある．PZT などの圧電材料を用いたアクチュエータはエネルギー密度が最も大きく，小型でも大きな力を発生できる特徴を持つが，一般にそれ自体の加工が困難である．本論文は，マイクロ加工技術を用いて積層 PZT アクチュエータを集積化したシリコン XY マイクロステージに関する研究をまとめたもので，全編 8 章からなる．

第 1 章は序論であり，研究背景や目的について述べている．

第 2 章では，マルチプローブ型記録方式，およびこれに必要なポジショニング機構について述べ，その原理と性能の関係について論じている．

第 3 章では，ピエゾアクチュエータの種類，構造やその特性についてまとめ，設計について論じている．この設計論を展開し，大きな変位を得るための構造の最適化手法について述べている．これは，ピエゾアクチュエータを用いた小型 XY マイクロステージの駆動性能の向上のために重要な知見である．

第 4 章では，ムーニー型の変位拡大機構を内蔵した圧電駆動型の XY マイクロステージを提案し，その設計とその基本性能について論じている．提案するシステムは，高密度記録のトラッキング用ステージに必用な機能をコンパクトにまとめたもので，有効かつ重要な成果である．

第 5 章では，ムーニー型の変位拡大機構およびマイクロステージの駆動特性および周波数特性について，有限要素法を用いた解析結果についてまとめている．設計した変位拡大機構は小型でありながら大きな変位拡大率が得られることが示されており，実用化にむけた重要な成果である．

第 6 章では，積層型ピエゾアクチュエータおよび XY マイクロステージの作製方法についてまとめている．シリコンの機械構造を反応性イオンエッチングにより精密に加工し，積層型ピエゾアクチュエータをフォトリソグラフィーと電界メッキにより精密にアセンブルする新しい加工方法について述べている．提案している加工方法は，異種要素を集積化した小型システムを実現するために有用な技術であり，重要な成果である．

第 7 章では，作製した積層型ピエゾアクチュエータおよび XY マイクロステージの駆動性能の評価結果をまとめている．XY マイクロステージは，70V の駆動電圧で最大 80μm 変位し，400Hz 以上の共振周波数を有することが実験的に示されている．これは圧電駆動の XY マイクロステージを実現するために非常に重要な知見である．

第 8 章は結論である．

以上要するに本論文は，半導体微細加工技術を用いて圧電駆動型の XY マイクロステージのプロトタイプを開発して有効な成果を得たものであり，機械システムデザイン工学および精密工学の発展に寄与するところが少なくない．

よって，本論文は博士(工学)の学位論文として合格と認める．