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論 文 内 容 要 旨

1. Introduction

The giant magnetoimpedance (GMI) effect has been widely investigated due to its potential application in sensor elements. The GMI effect is studied in wires, ribbons or single layered thin films, and multi-layered thin films. Multi-layered thin films show a noticeable increase in the GMI effect. The GMI sensor element shows high MI effect with transverse magnetic anisotropy. However, it is difficult to induce magnetic anisotropy in transverse direction of the element due to a large demagnetizing field. Therefore, the focus of this thesis work is to explore simple and effective methods to control the direction of the magnetic anisotropy and to fabricate magnetic anisotropy which rapidly reacts to a weak external magnetic field for sensor applications. I proposed an original method to induce and control magnetic anisotropy using the inverse-magnetostrictive effect (also known as the Villari effect) and residual stress, which is generated by different thermal expansion coefficients between layers in the multi-layered structure. The proposed method was verified by Finite Elements Method (FEM) simulations and experiments. I also investigated the variation of magnetic properties with changes in the geometry of the elements as well as magnetic materials for inducing magnetic anisotropy whose direction can be changed by a weak external magnetic field. Based on the proposed method, the prototype sensor elements were manufactured. The performance of the prototype sensor elements was examined. It showed impedance variation by applying a weak external magnetic field. The results confirm that the proposed method to induce magnetic anisotropy is effective. Furthermore, the fabricated sensor elements work as a magnetic sensor.

2. Methodology of Direction Control in Magnetic Anisotropy

The inverse-magnetostriction effect is the change in anisotropy direction of a material when subjected to a mechanical stress. The thin film consists of a magnetic layer and a conductive layer. In the case of a multilayer structure, the direction of bending is determined by the combination of the thermal expansion coefficients between the layers, as shown in Fig. 1.

First, when the thermal expansion coefficient of the upper layer is larger than that of the lower layer, the thin film bends upwards, as shown in Fig. 1(a). On the other hand, when the thermal expansion coefficient of the upper layer is smaller than that of the lower layer, the bending shown in Fig. 1(b) is generated. Using the inner stress that is generated by the difference in thermal expansion coefficients between the magnetic and conductive layers, I can control the direction of anisotropy in the magnetic layer of a magnetostrictive material. $Fe_{72}Si_{14}B_{14}$ was used for the magnetic layer, as this is a soft and magnetostrictive material. Therefore, the direction of anisotropy in the $Fe_{72}Si_{14}B_{14}$ thin film can be controlled according to the direction of inner stress by inverse- magnetostriction effect.

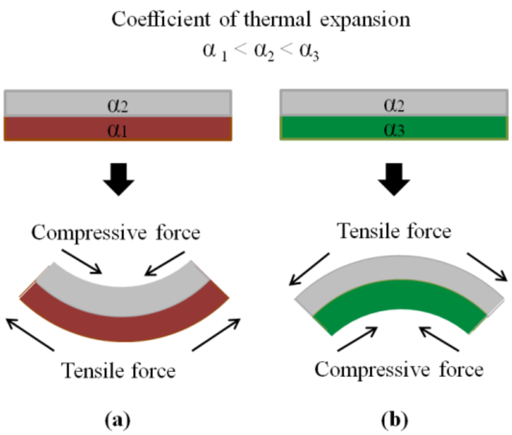

Figure 1. Bending direction in the multilayer structure according to changes in the combination of thermal expansion coefficients between layers

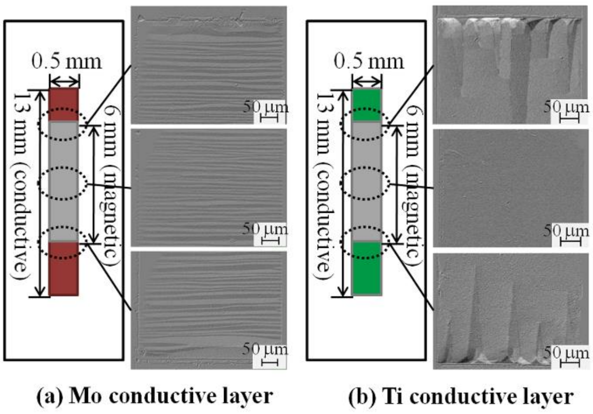

Figure 2 A result of the magnetic domain observation in the magnetic layer

2.1. Fabrication of Thin Film

The fabricated thin-films consist of magnetic layer and conductive layer. $Fe_{72}Si_{14}B_{14}$ (coefficient of thermal expansion: $6.5x10^{-6}/K^{-1}$) was used for the magnetic layer. Titanium ($8.3x10^{-6}/K^{-1}$) and molybdenum ($5.4x10^{-6}/K^{-1}$) were used for conductive layer. These thin-film layers were deposited by RF sputtering on the glass substrate which has 150 μm thickness. The thickness of the magnetic and the conductive layers are 0.7 and 2 μm, respectively, and they are insulated by 0.25 μm thick SiO_2. The lift off method was used for the fabrication. After the fabrication, I annealed the thin-films to release the local stress, which was induced during the deposition, in rotating-field of 0.3T at 360℃ in 2 hours.

2.2. Experimental Results

The magnetic domain patterns of fabricated thin films were observed by Kerr-microscope. Figure 2 shows the induced magnetic domain patterns on the magnetic layer. When the thermal expansion coefficient of magnetic layer ($Fe_{72}Si_{14}B_{14}$) is larger than conductive layer (Molybdenum), the in-plane uniaxial magnetic anisotropy was induced along the transverse direction by the generated inner stress as shown in fig. 2(a). In contrast, when the thermal expansion coefficient of magnetic layer ($Fe_{72}Si_{14}B_{14}$) is smaller than conductive layer (Titanium), the transverse direction magnetic anisotropy was not induced in the magnetic layer as shown in Fig. 2(b). As the results, direction of the uniaxial magnetic anisotropy could be controlled by difference of thermal expansion coefficient between magnetic and conductive layer.

3. Influence of Ratio of the Thickness on Anisotropy Field

I will introduce the dependence of magnetic anisotropy on the ratio of the thicknesses between the two layers to develop a GMI sensor element with a high, and adjustable, sensitivity. The generated total anisotropy field ($H_{k(t)}$) in the magnetic layer depends on the shape anisotropy ($H_{k(s)}$) and the induced anisotropy ($H_{k(i)}$). For control of the anisotropy field, I change the thickness of the magnetic layer. The $H_{k(s)}$, the $H_{k(i)}$ and the generated bending stresses are numerically analyzed. In addition, the $H_{k(t)}$ is obtained experimentally. Based on this, I investigate the relationship between induced anisotropy and the ratio of thickness.

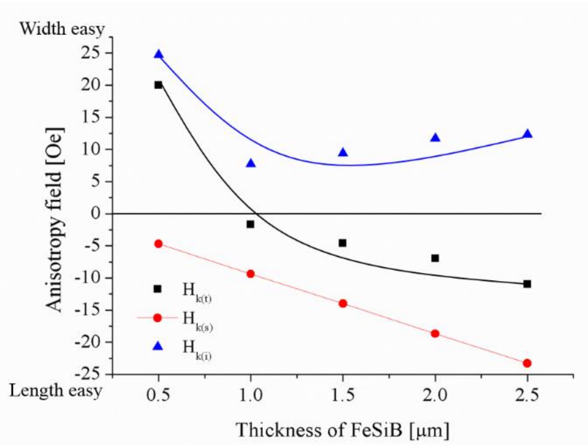

Figure 3 Analysis of the magnetic anisotropy: Hk(t), Hk(s), and Hk(i)

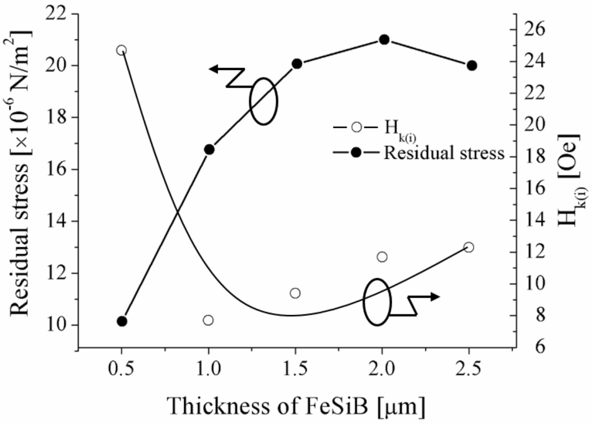

Figure 4 Relationship between bending stress and induced magnetic anisotropy

As the experimental results, The generated magnetic anisotropy ($H_{k(t)}$) was determined by using the shape ($H_{k(s)}$) and the induced ($H_{k(i)}$) anisotropies. According changes in the ratio of the thickness, the neutral plane which has stress free was changed. As the result, different amount of stress was produced in the magnetic layer by the different thickness ratio. However, the $H_{k(i)}$ is the major factor to decide $H_{k(t)}$, as shown in Fig. 3. The $H_{k(i)}$ has an intimate relationship with the bending stress generated by the difference in the thermal expansion coefficients between the two layers. Thus, I numerically calculated the amount of bending stress for various thicknesses of the magnetic layer. These variations of the bending stresses influence the induced anisotropy ($H_{k(i)}$), and the $H_{k(i)}$ is inversely proportional to the bending stress, as shown in Fig. 4. Consequently, the ratio of the thicknesses between the magnetic and the conductive layers is a very important factor in deciding the magnetic anisotropy for our proposed method to control the magnetic anisotropy.

4. Influence of Magnetostriction Constant on Anisotropy Field

For reduction of anisotropy field (H_k), I controlled the generated stress according to varies in the geometry of element. However, it is not enough to reduce H_k for high sensitivity of MI sensor element. Besides, there is a limitation to control geometry of the thin film. As the reason, much more need of consideration to change magnetostriction constant because the generated magnetoelastic energy has relations not only stresses but also a magnetostriction constant. For the investigation of the effect of the magnetostriction constant, I used two materials: FeSiB and CoFeSiB in magnetic layer. The magnetostriction constant decreases according to increase cobalt content.

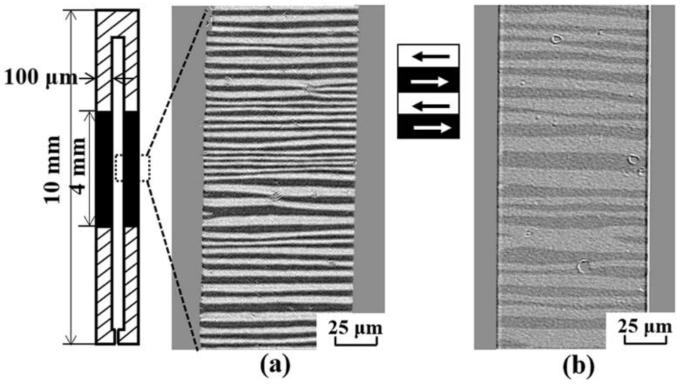

Figure 5 Results of magnetic domain observation (a) FeSiB magnetic layer. (b) CoFeSiB magnetic layer

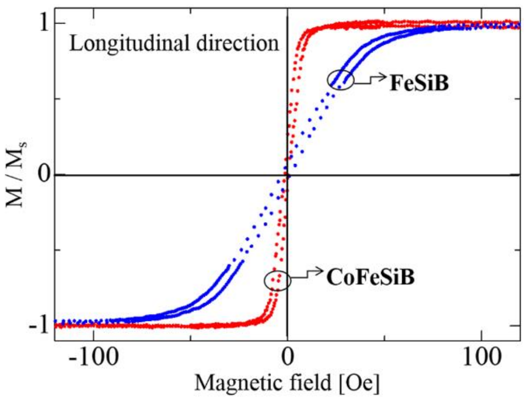

Figure 6 Magnetization curves according to changes in magnetostriction constant.

As shown in Fig. 5, the domain pattern was approximately 3.4 μm and 6.6 μm wide in the FeSiB and CoFeSiB layers, respectively. In comparison with the FeSiB layer, the width of the domain pattern in the CoFeSiB doubled with decreases in the magnetostriction constant. These domain patterns showed that the generated energy of strain induced magnetic anisotropy in the magnetic layer decreased as the magnetostriction constant was reduced. The FeSiB and CoFeSiB layers were saturated at 80 Oe and 10 Oe, respectively. The sample using CoFeSiB for the magnetic layer reached saturation more rapidly than the one using FeSiB. These features indicate that higher sensitivity can be obtained by decreasing the magnetostriction constant.

5. Conclusion

This work verified the proposed mechanism of inducing transverse magnetic anisotropy utilizing inverse-magnetostrictive effect with changes in difference of thermal expansion coefficient between the two layers. I strongly anticipate this study is helpful to improve sensitivity of the MI sensor.

論文審査結果の要旨

軟磁性薄膜を利用したデバイスはセンサ応用を中心に広い分野で用いられており，そのため磁性薄膜の特性を使途に合わせて制御することは極めて重要な技術である．特に磁気異方性の制御は，例えばセンサの感度を決定づける要因となりうるため，極めて重要である．従来薄膜磁性材料の異方性制御手法として，磁界中での成膜やひずみ印加下での熱処理等の手法が提案されているが，低い再現性や高コストなどの問題点が多く，新たな手法の確立が必要とされている．本論文は，軟磁性薄膜の異方性制御手法として，逆磁歪効果を利用した磁気弾性エネルギー制御により磁気異方性を制御する手法を新たに確立するとともに，それを利用したセンサ応用に関して検討したもので，全編７章からなる．

第１章は緒言であり，本論文の背景と目的を述べている．

第２章では，磁気センサー一般に関して原理や感度の現状をまとめ，特に磁気インピーダンス(MI)センサと呼ばれる磁気センサについてその特性向上のための指針を理論的に整理することで，必要とされる薄膜磁性材料の特性を明らかにしている．

第３章では，薄膜磁性材料の磁気異方性制御手法として，積層した異種の膜の熱膨張率の差を利用した応力導入により磁気異方性を制御する新たな手法の提案を行った．磁性薄膜材料の持つ磁歪特性を活用し，異種の薄膜と積層して熱処理を行うことで異方性を誘導できることを実験と理論の両面から明らかにした．これは，薄膜磁性材料の異方性制御技術として本論文で初めて提案するもので，プロセスが簡易であることから工業的にも優れた手法であり，重要な成果である．

第４章では，第３章で提案した異方性制御技術における異方性強度と薄膜形状の関係について明らかにしている．磁性薄膜ならびに積層する薄膜の形状と誘導される磁気異方性強度の関係を詳細な実験により明らかにするとともに，材料力学に立脚した理論的応力評価結果が実験結果と良好な整合性を持つことを明確にした．この結果は，所望の異方性を得るための設計指針を明確化するものであり，高く評価される．

第５章では，第３章で提案した異方性制御技術に立脚した材料選択手法を提案している．組成の制御により磁性薄膜材料の磁歪定数を変化させ，それにより誘導される磁気異方性を制御するものである．これによりMIセンサの高感度化に必要な均一かつ弱い磁気異方性を誘導することを可能とした．これは，高感度センサ実現のために極めて重要な技術である．

第６章では，本論文で提案した異方性制御手法を利用して磁気センサを試作し評価している．磁気異方性を広い範囲で制御した磁性薄膜でセンサを試作し，その特性を詳細に検討した結果，センサのインピーダンスが磁気モーメントの高周波磁化変化理論に立脚して変化していることを明らかにし，2.5 %/Oeの感度を実現するとともにさらなる高感度化のための提案を行っている．これは，本論文で提案した異方性制御手法が高感度センサ実現のために有効であることを示すもので，極めて価値の高い結果である．

第７章は結言である．

以上要するに本論文は，薄膜磁性材料の磁気異方性制御技術として逆磁歪効果を用いる手法を新たに提案するとともに異方性強度を決定づけるパラメタを明らかにし，磁界センサの高感度化のための手法を明確化したものである．この成果は，磁性材料開発ならびに磁気センサ開発に大きく貢献するとともに，電気工学，磁気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．